Smart Buildings: Using Smart Technology to Save Energy in Existing Buildings

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Executive Summary

Smart buildings use information and communication technologies (ICT) to enable automated building operations and control. They can enhance occupants' comfort and productivity while using less energy than a conventional building. Whereas conventional buildings have systems operating independently, smart buildings use ICT to connect building systems together to optimize operations and whole-building performance. Smart buildings also allow operators and occupants to interface with the building, providing visibility into its operations and actionable information. In addition, smart buildings can communicate with the power grid, a feature that is becoming increasingly important for utility demand response deployment. Although the greatest penetration of smart technologies in existing buildings has been in offices, their use is growing steadily in all buildings types.

This report is aimed at energy efficiency program designers and administrators who are interested in the cost-effective energy savings that smart buildings achieve. Building operations teams (including IT personnel) may also find it useful. We describe the functions and applications of smart technologies in existing commercial buildings, how they differ from conventional technologies, and how much energy they can save. We then offer case studies of utility energy efficiency programs that use smart technologies, and we conclude with recommendations for expanding these programs.

TECHNOLOGIES

A number of smart technologies can improve building operations.

HVAC. Smart heating, ventilation, and air conditioning (HVAC) systems use multiple sensors for monitoring and control. Software interprets information from various sensor points to optimize the HVAC system's operation while improving occupant comfort. Smart HVAC controls can limit energy consumption in unoccupied building zones, detect and diagnose faults, and reduce HVAC usage, particularly during times of peak energy demand.

Lighting. Smart lighting consists of advanced controls that incorporate daylighting and advanced occupancy and dimming functions to eliminate overlit spaces. Luminaire light-level controls are rapidly developing and gaining market recognition. Demand-response programs are incentivizing step and continuous dimming control. Smart lighting systems can be controlled wirelessly and scheduled into lighting management systems. Wireless controls facilitate easier retrofits, while lighting management platforms let users access controls through web-based dashboards.

Plug loads. Plug loads include the hundreds of types of portable office and miscellaneous equipment in buildings. In existing buildings, smart plug load controls consist of auto-controlled receptacles and power strips that rely on time scheduling, motion sensing, or load detection to completely cut off power to equipment that is not in use. Some smart power strips can sense the primary load, such as a computer, and operate peripheral devices accordingly. For centralized control, plug load schedules can be programmed into lighting and building management systems (BMS).

Window shading. Smart window systems manage the amount of solar heat and daylight that enters the building. Systems consist of passive and active window glazing and films that respond to changes in sunlight or temperature, and auto-controlled shades that are scheduled to operate at specific times of the day to control light levels and solar heat gain. In retrofits, smart shading technologies have the greatest energy-savings potential in buildings with untinted, single-pane windows.

Automated system optimization. Whereas a traditional building automation system (BAS) relies on preset schedules and set points for building operations, automated system optimization (ASO) relies on real-time feedback. ASO uses ICT to collect and analyze building systems' operational and energy performance data and make anticipatory changes in operations based on external factors such as occupancy patterns, weather forecasts, and utility rates. Cloud-based remote building monitoring is growing in popularity. This approach lets building operators (or third-party energy service vendors) monitor building performance through web-based energy management platforms.

Human operation. Operators can interface with a smart building through *computer dashboards*—user-friendly interactive displays of building operations and energy use. Dashboards allow the building operator to analyze all building data centrally and receive alerts on faults detected by the ASO. Operations personnel, including IT specialists, will apply training in network management, data analysis, and smart technology. As for building occupants, they can use mobile apps to control some workspace functions such as lighting. Apps can also display individual occupants' energy use and recommend ways to reduce consumption.

Distributed energy resources. Distributed energy resources (DER) consist primarily of energy generation and storage systems placed at or near the point of use and provide power independent of the grid. Examples of DER include combined heat and power, solar photovoltaics and other renewables, and battery and thermal storage. DER relies on communications and control devices for efficient energy dispatch; adding a smart inverter to the DER gives it smart functionality. *Smart inverters* are software controlled and help manage onsite energy generation and storage. They allow for continuous two-way communication between the DER and the electric grid and can immediately respond to load signals, electricity rates, demand response events, and power outages.

ENERGY SAVINGS, COST EFFECTIVENESS, AND NONENERGY BENEFITS

As shown in table ES1, individual smart technologies offer substantial energy savings.

Table ES1. Smart technology energy savings

System	Technology	Energy savings
HVAC	Variable frequency drive	15–50% of pump or motor energy
HVAC	Smart thermostat	5–10% HVAC
Plug load	Smart plug	50–60%
Plug load	Advanced power strip	25–50%

System	Technology	Energy savings
Lighting	Advanced lighting controls	45%
Lighting	Web-based lighting mgmt system	20–30% above controls savings
Window shading	Automated shade system	21–38%
Window shading	Switchable film	32–43%
Window shading	Smart glass	20–30%
Building automation	BAS	10–25% whole building
Analytics	Cloud-based energy information system (EIS)	5–10% whole building

Sources: Hydraulic Institute, Europump, and DOE 2004; DOE 2016b; Boss 2016; GSA 2012; BEEx 2015; Lutron 2014; InvisiShade 2016; SageGlass 2016; RavenWindow 2016; Gilliland 2016.

Smart buildings save energy by automating controls and optimizing systems. Whereas an upgrade to a single component or isolated system can result in energy savings of 5–15%, a smart building with integrated systems can realize 30–50% savings in existing buildings that are otherwise inefficient. Savings can reach 2.37 kWh/sq. ft.

As shown in table ES2, smart technologies exhibit a range of energy savings in various commercial building subsectors.

Table ES2. Commercial building subsector energy savings from smart building technologies

Building type	Floor area (sq. ft.)	Smart building technology	Average energy consumption (kWh/year)*	Percent savings	Average savings (kWh/year)
Education	100,000	Occupancy sensors Web-based lighting control management system	190,000	11%	20,900
Office	50,000	Lighting controls Remote HVAC control system	850,000	23%	200,000
Hotel	200,000	Guest room occupancy controls	4,200,000	6%	260,000
Laboratory	70,000	Air quality sensors Occupancy sensors Real-time ventilation controllers	980,000	40%	390,000
Hospital	120,000	Lighting controls + LED upgrade Data analytics software package	7,900,000	18%	1,400,000

Sources: See Appendix A.

The purchase cost, energy savings, and payback of smart technologies varies widely across technology types. For technologies that cover the whole building in one application, such as an advanced BAS, installation costs are lower for larger buildings than for smaller ones, due to the square footage covered by the application. Thus, advanced BAS are more cost effective in larger buildings. Technologies that are applied redundantly throughout a building, such as smart thermostats, are more cost effective in smaller buildings. Advanced controls and sensors have declined in price as they have become smaller and embeddable. The wireless capability of smart controls and sensors makes them retrofit friendly; they can also have lower installation and commissioning costs than wired devices.

Smart building owners and tenants enjoy nonenergy benefits along with the energy savings. Tenants are increasingly demanding flexible, controllable workspaces, and some building owners are installing smart technologies to attract and retain tenants. In addition, improved indoor air quality and temperature control can lead to greater worker productivity.

BARRIERS TO PREVALENCE

Upfront purchase costs are the leading barrier to investments in buildings, and smart building technologies are no exception. It is all too common for building systems to undergo upgrades only at the point of failure; the upfront purchase costs of some smart building technologies discourage more timely upgrades. Investment costs are especially challenging for owners of small- and medium-sized buildings, who generally have less capital to work with to make improvements. In addition, the financial and insurance industries have yet to accept the valuation of smart building features for accurate appraisal and underwriting.

Smart buildings face a number of other barriers. Building operators are confronted with a steep learning curve. Buyers may be reluctant to invest due to concerns over the premature obsolescence of new technology. The industry has yet to standardize a communications protocol for interconnecting smart devices. Smart buildings may centralize the control and monitoring of security, access, and safety systems, giving rise to concern that such systems will be the target of cybersecurity threats. Finally, a lack of customer awareness and gaps in workforce skill sets also affect the proliferation of smart technologies. If these technologies are to proliferate in the market, the building industry must better understand smart buildings' value proposition and begin to shift the building operator culture.

SMART BUILDING PROGRAMS

Smart technologies that are often incentivized through prescriptive utility energy efficiency programs include advanced occupancy and vacancy controls that work with lighting and HVAC systems, daylighting controls, smart power strips and smart plugs, and BMS. For windows, incentives are sometimes in place for passive shading technologies such as smart films and screens.

Some pay-for-performance and demand response programs have begun including sensors, meters, inverters, and analytics software in their portfolios to show how a building is performing in real time and to identify energy-savings opportunities. These enabling technologies can verify the kilowatt-hours (kWh) saved from energy efficiency measures as required for performance programs; they also allow customers to participate in demand response events. Some utilities have recently rolled out or plan to roll out smart inverter programs, with incentives paying for kilowatts of generation from DER.[1] And a few programs are starting to pay not only for hardware but also for ongoing third-party services to monitor and suggest operational improvements to buildings.

A smart building can improve traditional evaluation, measurement, and verification accuracy by collecting building systems' energy performance data in real time at more frequent intervals. This enables the continuous quantification of energy savings and gives program managers real-time feedback on project performance.

RECOMMENDATIONS

For smart technologies to proliferate in the commercial buildings market, building owners and operators must understand their value proposition. Incentivizing smart technologies through energy efficiency programs could help expedite their uptake. Further, packaging them with common energy efficiency measures might allow them to piggyback on known energy savings and the quicker paybacks of standard measures. Packages also present an opportunity to integrate interdependent measures in a single installation.

Pay-for-performance programs offer incentives for actual kWh saved. Such programs can use smart technologies and post-retrofit energy data to verify savings and validate cost effectiveness. These programs can also offer incentives aimed at the upfront and continuing costs for commissioning, remote monitoring, and optimization services.

The industry would benefit from further demonstrations that measure energy saved through building automation and analytics in commercial building retrofit projects. As with many emerging technologies, relatively few studies have been completed on smart buildings, and incentives are still generally lacking for whole-building measures such as holistic building analytics platforms. Further research and technology demonstrations are needed to address the current gap in incentives and to explore the benefits of smart commercial buildings and the barriers to market transformation. ACEEE is planning a 2017 study that will focus on a few key market segments.

[1] Smart inverters permit continuous two-way communication and power transfer between DER and the grid.

Introduction

Commercial buildings represent 18% of US primary energy consumption and carbon dioxide emissions and 36% of all US electricity use (EIA 2015; EIA 2017). Although the average total energy use per square foot has declined approximately 10% over the past decade, total electricity consumption in commercial buildings has been steadily climbing (EIA 2016). Electricity now accounts for 61% of all energy consumed in commercial buildings, while natural gas accounts for 32%. The breakdown in end-use electrical consumption is as follows: heating, ventilation, and air conditioning (HVAC) 33%, miscellaneous loads 32%, lighting 17%, and refrigeration and cooking 18% (EIA 2016).

Commercial buildings can save energy by using advanced sensors and automated controls in HVAC, plug loads, lighting, and window shading technologies, as well as advanced building automation and data analytics. Buildings that have advanced controls and sensors along with automation, communication, and analytic capabilities are known as *smart buildings*. In a fully-fledged smart building, the building systems are interconnected using information communications technologies (ICT) to communicate and share information about their operations. Smart building technologies can provide facilities operators with the tools to anticipate and proactively respond to maintenance, comfort, and energy performance issues, resulting in better equipment maintenance, higher occupant satisfaction, and reduced energy consumption and costs.

> A *smart building* is a supersystem of interconnected building systems. Like the Internet, it connects individual computer networks into one larger supernetwork (BEI 2011).

Smart buildings represent a new and potentially enormous opportunity to save energy. The global market for connected devices in commercial buildings has grown steadily since ACEEE first focused on them in 2013 (Rogers et al. 2013).[1] Approximately 206 million connected devices existed in commercial buildings worldwide in 2015, and this number is expected to triple by the end of 2017 (Gartner 2015a). Both retrofits and new commercial building designs are increasingly implementing smart technologies.

This report is aimed at energy efficiency program designers and administrators who are interested in the cost-effective energy savings that smart buildings achieve. We describe the functions and applications of smart technologies in existing commercial buildings, how they differ from conventional technologies, and how much energy they can save. Among the smart technologies that exhibit savings, we prioritize the best opportunities in various types of commercial buildings. We then describe utility energy efficiency programs using smart technologies and conclude with recommendations for expanding these programs.

Study Methodology and Scope

ACEEE conducted research for this report through a literature review and expert interviews. The literature reviewed included articles, reports, and case studies. Experts

[1] ACEEE research on intelligent efficiency has focused on smart technologies that effectively save energy costs.

interviewed included utility program administrators, smart technology manufacturers, and smart building practitioners. We used a combination of reported data, facts, statistics, and anecdotal evidence to formulate our conclusions and recommendations.

Our study focuses on existing commercial buildings, including office, retail, education, laboratory, healthcare, and hospitality properties. Residential homes and commercial new construction are not emphasized. Multifamily buildings are not explicitly included in the scope of this paper, but many of the energy-saving benefits of smart buildings could apply to multifamily common areas. Our study looked at buildings with significant occupancy, so data centers and warehouses are not included.

For simplicity's sake, we divided commercial buildings into two size categories: large (greater than 100,000 square feet, such as a high-rise office building) and small and medium (100,000 square feet or smaller), such as your local bank branch. As figure 1 shows, while large buildings represent just 2% of US commercial buildings, they represent nearly 35% of the US commercial building stock floor area, and they are more likely to have smart building technology components installed than smaller buildings (EIA 2016). Nonetheless, we place a slightly greater emphasis on small and medium buildings because they represent nearly 98% of US commercial buildings and typically lack smart building technologies; they therefore represent a large opportunity.

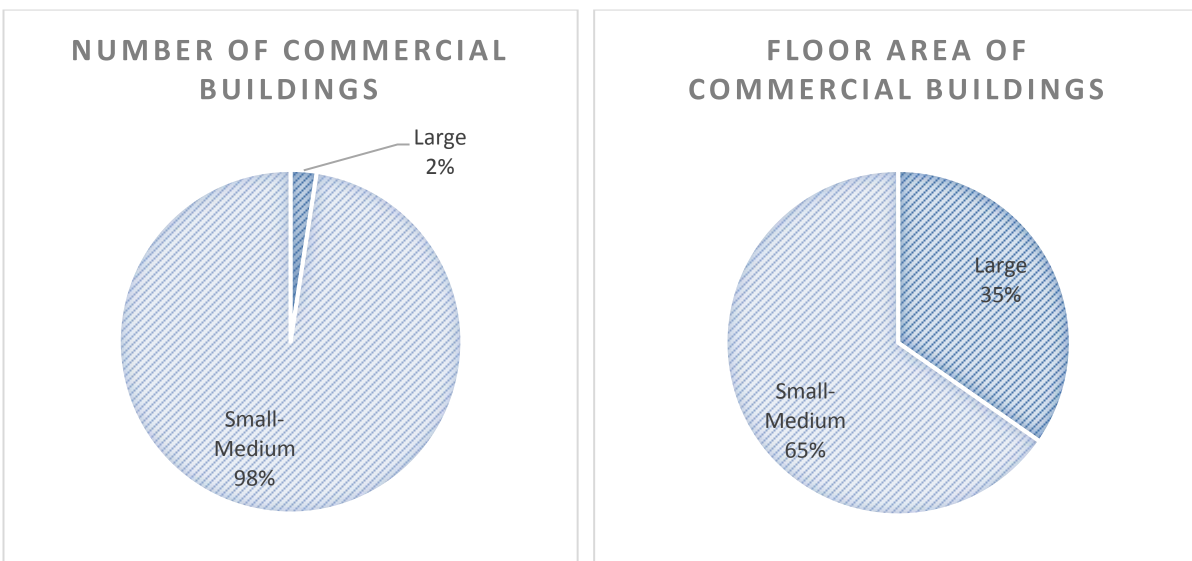
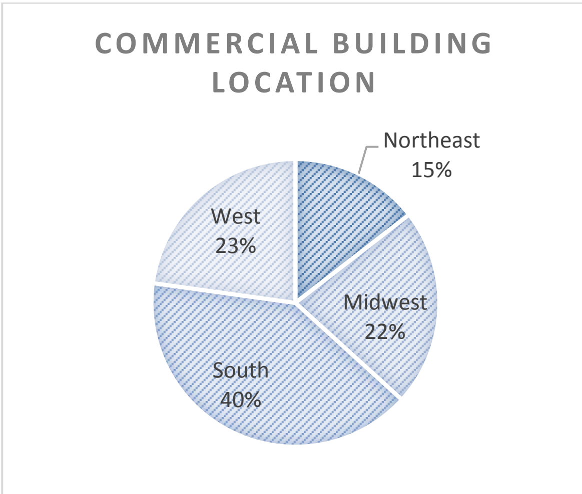


Figure 1. The number of US commercial buildings by size (left) and the floor area of US commercial buildings (right). ***Source:*** **2012 CBECS Survey Data.**

This paper's scope is the entire US commercial building stock, including about half of all buildings aged 35 years or older (i.e., those constructed pre-1980) and half of the newer buildings (i.e., those constructed after 1980). Building age is strongly correlated with the types of building construction and installed equipment, which has implications for the types of building data that can be collected and the processes that can be made smart.

Each US region is included in our analysis. The South has the greatest number of commercial buildings (around 40% of the total stock), while the West and Midwest represent about 23% and 22%, respectively, and the Northeast represents the remaining 15% (EIA 2016). These regional distinctions are important, as each region has unique weather patterns, income levels, building stock, and available utility programs. Figure 2 shows US commercial building locations.



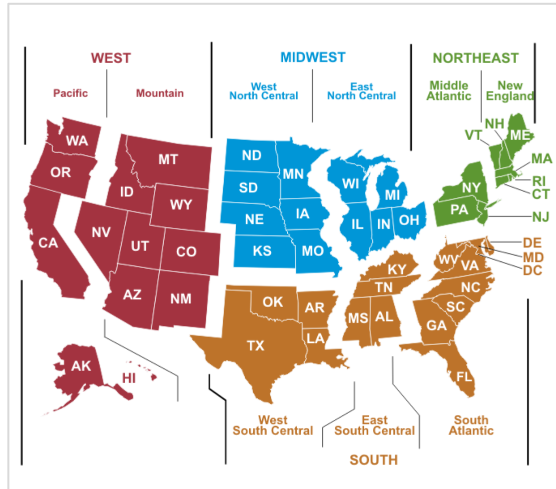


Figure 2. US commercial building regional locations. *Sources*: 2012 CBECS Survey Data and CBECS US Census Regions and Divisions.

Smart Building Technologies

Smart buildings include efficient technologies with automated controls, networked sensors and meters, advanced building automation, data analytics software, energy management and information systems, and monitoring-based commissioning (MBCx). In the following, we examine these key building systems and technologies. We also discuss advances that have led to smart components and systems, market growth and trends, and performance and costs.

We examine the following opportunities for smart technologies:

- HVAC systems
- Plug loads
- Lighting
- Window shading
- Automated system optimization
- Human operation
- Connected distributed generation and power

Figure 3 gives an overview of these interconnected systems.

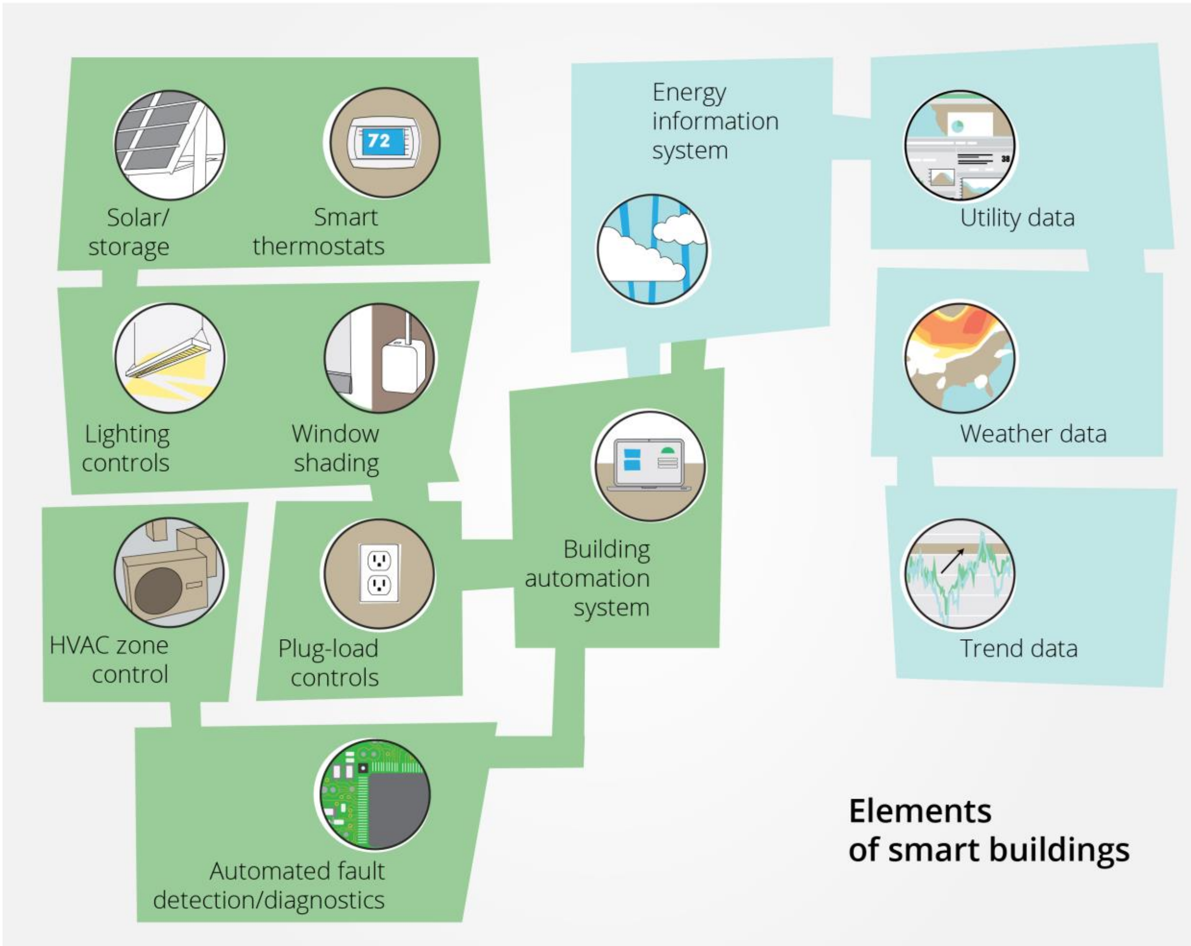


Figure 3. Overview of smart building technologies

HVAC SYSTEMS

It takes an enormous amount of energy to condition air and then distribute it throughout a building; not surprisingly, HVAC equipment typically consumes at least 40% of a commercial building's energy (EIA 2016). Many buildings' HVAC systems consume even more energy than that, as roughly one-third of them are oversized for the space they serve (Haynes 2016). Using controls to properly manage HVAC operation is an essential part of saving energy in a building. However building operators frequently manage HVAC operations through trial-and-error adjustments in reaction to occupant comfort feedback—sometimes relegating energy savings to a much lower priority.

Smart HVAC systems have the potential to greatly reduce energy consumption while maintaining or even improving occupant comfort. Smart building software interprets information from a variety of HVAC sensor points and maintains that information in real time, in a cloud-based system that is remotely accessible. Engineers develop algorithms within the smart building software that use the database information to optimize the monitoring and control of HVAC systems. These advanced controls can limit HVAC consumption in unoccupied building zones, detect and diagnose faults, and reduce HVAC usage during times of peak energy demand.

Using Sensors to Optimize Operations

Sensors are devices that sense a physical stimulus and convert it into a signal. One example of a sensor that provides HVAC systems with useful data is a *duct static pressure sensor*, which measures the amount of resistance against the air flowing through a duct. HVAC fans must work harder to overcome greater resistance in ducts, so reducing static pressure saves energy. A duct static pressure sensor contains a sensing element that reacts to physical changes—in this case, static pressure. The sensor transmits an electrical signal that indicates a change in duct static pressure. Building operators can use these static pressure readings to control the HVAC systems to operate at a particular duct static pressure, and can even use the measurement to identify HVAC system faults (Dunn 2015).

The falling cost of sensor technologies is a key catalyst of smart HVAC. In 2004, a basic Internet of Things (IoT) sensor—such as your phone's little gyroscope sensor—cost $1.30 on average; by 2014, a basic sensor's cost averaged less than $0.60 (Goldman Sachs 2014). With lower technology costs and the increasing availability of wireless technologies, it is now easier than ever to cheaply obtain sensor readings for various HVAC components. Further, recent advancements in data storage and cloud computing make it possible for building operators to access the multitude of HVAC data points, such as temperature, pressure, flow rate, and gas concentration.

One of the largest energy efficiency benefits of smart building HVAC controls is found through optimizing the amount of conditioned (i.e., heated or cooled) air supplied throughout a building. Although it may seem like a simple concept, this goal can be achieved in various ways. For example, a whole-building ventilation controls system, with smart capability, senses the amount of carbon dioxide (CO_2) in occupied areas of the building and can modulate the amount of airflow in one area without starving or over-ventilating another. This can save considerable energy in heating and cooling and ventilation fan operation. In addition to controlling HVAC operation based on CO_2 levels, smart controls can optimize airflow using data provided by occupancy, temperature, humidity, duct static pressure, and air quality sensors.

Small- and medium-sized buildings may not have the funding to invest in whole-building HVAC control systems and may be more inclined to install smart controls directly on HVAC equipment. For example, the Pacific Northwest National Laboratory evaluated the effectiveness of rooftop units (RTUs) retrofitted with advanced controllers equipped with multi-speed fan, economizer, and demand ventilation controls. The study found approximately 50% electricity savings for RTUs with a three-year payback, even in regions with low electricity prices (Wang et al. 2013). This smart RTU technology was deemed so successful that is was subsequently included in California's Title 24 and DOE's RTU manufacturing standard.

Smart HVAC systems can also support sophisticated data analysis. Historically, building operators of a typical commercial building have been limited to reviewing rudimentary energy bill data. This form of data analysis is limited because the operator has reduced visibility into actual systems performance and interactions, often relying on month-old whole-building meter data. Armed with smart building data analytics, building operators can review historical building occupancy and usage on a granular level, receive performance data in real time and fine-tune the HVAC controls accordingly, thereby avoiding wasted HVAC usage.

UC Irvine Laboratory Ventilation

Facility managers and energy engineers at the University of California (UC) Irvine realized that the best way to reduce energy consumption on campus was to target the biggest energy users: laboratories.

Stringent ventilation requirements for laboratories drive energy-intensive operations; many operate HVAC systems 24/7 regardless of occupancy. After installing an array of smart sensors and controllers, the UC Irvine team was able to obtain accurate measurements of potentially harmful air contaminants. Instead of relying on the default laboratory air-change rate, building operators were able to base their air-change rates on real-time air contaminant measurements. This reduced the number of air changes per hour (ACH) by one-third during normal operation (without compromising occupant safety) and by half when the zone was unoccupied.

Combined with other minor efficiency upgrades (e.g., lighting and exhaust fan controls), these real-time, demand-based ventilation controls helped reduce the energy consumption of 10 different UC Irvine laboratories by more than 60% on average (Brase 2013).

Controlling Multiple Zones

Optimizing the use of conditioned air is one of the most effective applications of smart building equipment, especially in multi-zone systems. For example, a multi-zone variable air volume (VAV) system with six VAV boxes could use smart controls to more effectively condition each of the six zones.[2] With sensors installed in each office area, each VAV box can be programmed to cycle back or shut off completely when the corresponding space is vacant. If most of the employees are out of the office, the smart controls can reduce or shut off conditioning to any or all of the six zones to save energy. An example of a less efficient alternative is a whole floor with a constant air volume (CAV) system served by one air-handling unit.[3] In this case, control options are limited to cycling back or turning off the airflow on the entire floor, and the flexibility of zone control is lacking.

Adobe Headquarter Neighborhoods

Adobe remodeled its headquarters into an open-office layout called *neighborhoods*. By shutting down HVAC (and lighting) to neighborhoods unoccupied for more than 15 minutes, Adobe eventually achieved a 65% reduction in energy consumption, even as it increased the number of employees from 80 to 135 (PG&E 2013). By investing in thousands of timers, sensors, and VAV boxes to control the flow of conditioned air to individual zones, Adobe was able to implement this creative and energy-efficient solution.

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[2] A VAV system typically contains variable frequency drives (VFDs) on its fan, which can modulate the supply of airflow between 0% and 100% as needed, which can greatly reduce air handling unit energy consumption.

[3] A CAV system typically distributes air using constant fan speed.

Hotel rooms, which could be considered individual zones, offer a unique application for zone control energy savings. Hotel room HVAC units typically remain set at whatever temperature the guest or cleaning staff last selected, thus conditioning unoccupied guest rooms. This can waste hundreds of thousands of kWh of electricity and tens of thousands of dollars in energy costs each year. Connecting guest room vacancy controls and HVAC system controls allows hotels to set back the temperature when the room is vacant. Of course, building operators must balance these energy-saving measures with occupant comfort to ensure that guests do not experience discomfort when they return to their rooms. Navigant estimated that only about 30% of the global hospitality industry currently uses room-based energy management systems to reduce HVAC consumption (Pacelle and Bloom 2014). This figure is likely even lower in the United States, because relatively few US hotels contain smart HVAC controls compared to hotels in many parts of Asia and Europe.

Conrad Hotel

The Conrad Hotel, located in Chicago, saved more than 450,000 kWh/year by installing automated HVAC controllers, infrared motion detectors, and wireless door switches. These technologies let Conrad staff manage the temperature of its 352 HVAC units when rooms are unoccupied. Thanks to a custom utility incentive from Commonwealth Edison (ComEd), the project payback was estimated at 1.5 years, with annual energy savings of more than $35,000 (ComEd 2012).

Fault Detection and Diagnostics

Leaks, blockages, and deterioration are routine occurrences in HVAC system equipment. If these faults go undetected for an extended time, even the most efficient equipment can waste a considerable amount of energy. Often these faults go undetected until routine maintenance is completed or the fault's effect is noticed in the building—which could be days, weeks, or months after the fault occurs. In contrast, even the most rudimentary smart capability enables operators to immediately spot abnormalities, proactively remedy faults, and prevent system failure.

Tower Company Detects and Diagnoses Cooling Tower Fault

Aquicore, a Washington DC-based energy management software and analytics company, helped the Tower Company identify a relatively simple fault in one of its office building's cooling towers. After installing a wireless web-enabled water consumption submeter on the cooling tower, the engineering team began receiving regular reports on cooling tower water consumption. When the vice president of engineering noticed unusually high cooling tower usage on a Sunday—a day when the building is typically unoccupied—it led to the discovery of a faulty electronic float inside the cooling tower. This discovery, along with minor cooling tower maintenance, allowed the team to reduce the entire building's water consumption by 45% (Aquicore 2016). By discovering this fault and curtailing the cooling tower's weekend usage, the team significantly reduced the equipment's energy consumption.

HVAC system performance naturally degrades over time; this can go unnoticed by the owners or occupants and result in years of wasted energy. One of the greatest values of adding smart building equipment is the ability to detect and prioritize faults. Automated fault detection and diagnostics (FDD) can include a combination of sensors and algorithms to compare the expected operating condition of the equipment or system to actual performance. For example, in RTUs, having stuck air dampers is one of the biggest potential energy wastes: dampers stuck open allow unchecked infiltration of outside air, while dampers stuck closed fail to provide adequate ventilation (or to take advantage of free cooling, in the case of economizing dampers). Automated FDD ensures that dampers close fully by running the RTU at 100% with the damper signaled *opened* and measuring the temperature difference between the outside air and the mixed air inside the RTU, which should be almost identical after running this test. If the temperature differs by more than a few degrees, the system detects a fault: the damper is not modulating properly. Similarly, to verify that the damper opens fully, the algorithm again dictates that the RTU runs at 100% capacity, with the damper signaled *closed*. If the return air temperature and the mixed air temperature differ by more than a few degrees, then the system creates another fault (Katipamula et al. 2015).

Although it is common for HVAC equipment to signal some faults, smart building equipment can often more accurately diagnose what the fault is and, in limited cases, why it occurred, enabling prioritized attention to faults and expediting their remedies, resulting in less wasted energy. The Switch Automation smart building platform views traditional fault detection as analogous to a vehicle's "check engine light": the light is valuable in that it indicates an issue with the vehicle, but it does not provide any insight into the nature of that issue (Swenson 2016). Many buildings face the same problem with traditional methods of HVAC fault detection: they make it apparent that something has malfunctioned, but determining the exact problem requires an investment of time and money.

Persistent Fault Detection in a Charlotte Office

Abundant Power's automated fault detection platform helped analysts discover that approximately 80% of the water-source heat pumps in the office at 330 S. Tryon in Charlotte, North Carolina, began operating at midnight every night, despite the fact that they were scheduled through the BAS to turn on at 7:00 a.m. The analytics platform identified the specific faulty units, and the controls contractor corrected the issue remotely. Or at least that was the initial attempt. Soon after the apparent fix, follow-up data verification analytics showed that 60% of the units still started up at midnight. It took the controls contractor two more attempts to finally resolve the issue. Not only did remote fault correction save the time and money of a technician's travel to the site, but the persistent automated follow-up saved an estimated 120,000 kWh at an operational cost of $9,000 per year (S. Smith, chief executive officer, Abundant Power, pers. comm., January 17, 2017).

Installing the right FDD system can help users uncover specific problems, without overwhelming them with unnecessary alerts. One effective approach is the rule-based HVAC FDD program, which uses rules to determine if HVAC equipment is interacting appropriately. For example, if data points show that a chiller is sending warm water to an air handler, the system generates faults for all the equipment involved, including the chiller, the air handler, and the VAV box overheating the space. However, because the system's rule-based programming identifies the chiller as the likely root source of the error, the system suppresses the VAV box and air handler faults (Sinopoli 2015). For building operators, automated and prioritized faults let them spend their time solving other problems, rather than having to act like detectives every time they receive an HVAC fault alert.

Smart building fault detection can also let building operators and maintenance contractors remotely diagnose and evaluate specific issues, avoiding the time and cost required to send technicians onsite. Additionally, if the FDD system connects to an equipment supplier database, the system can identify and order the required replacement part. In some cases, FDD can even predict failure and ensure that the component is shipped to the building before the failure even occurs (Sachs and Lin 2010).

Intelligent Demand Management and Response

In addition to reducing HVAC operations during unoccupied periods and efficiently detecting and diagnosing faults, smart buildings can curtail HVAC use during periods of peak demand through demand management and response. In many areas of the United States, current demand response programs could be considered rather unintelligent, with utilities typically using a fax, phone call, or email to ask users to reduce loads during peak demand times. In response, users might arbitrarily adjust HVAC temperature set points, which leads to inconsistent reductions and makes it difficult to validate the extent to which energy demand was actually reduced (S. Klann, executive vice president, Intelligent Buildings, pers. comm., June 13, 2016).

Direct communication between smart buildings and the local utility could help manage building energy demand on a daily basis. Intelligent demand management and response could allow buildings to automatically respond to fluctuating electricity demand and reduce peak usage, helping building owners avoid paying elevated utility prices. With electricity demand expected to increase by as much as 40% by 2030, smart buildings may become a key component of the current transition to a smart interconnected grid system (Memoori 2016).

Today, however, intelligent demand response faces compatibility challenges in communications between electricity producers, utilities, and consumers. To address these issues, the Open Automated Demand Response (OpenADR) Alliance is attempting to "standardize, automate, and implement" automated demand response programs (OpenADR 2016). Efforts like OpenADR and advances in smart building technology are helping to pave the way for widespread implementation of real-time demand response, which may facilitate the transition to smart grids in the future.

PLUG LOADS

A *plug load* is the amount of energy drawn by a device plugged into an electrical outlet. Plug loads constitute a substantial portion of electrical demand in commercial buildings (NREL 2015). A *phantom load* is the electricity that flows through plugged-in devices even after they are turned off. However recent improvements in technology enable devices with low-power modes, significantly reducing the energy consumption of phantom loads. Devices include the hundreds of types of office and miscellaneous equipment that provide much of a building's functionality, but do not constitute a major end use. In an office building, typical plug load equipment includes computers, monitors, and imaging and networking devices.

The primary equipment in a university laboratory—e.g., freezers and refrigerators, incubators, grow lights, etc.—is much different than that in an office. Stanford University conducted a plug load study of 220 campus buildings in 2014 and determined that laboratory equipment consumes 50% of total plug load electricity, accounting for 11% of total campus electricity consumption (Hafer 2015).

Currently, plug loads make up 5% of primary energy consumption in US commercial buildings (GSA 2016). However, as HVAC and lighting systems become more efficient, plug loads represent a growing proportion of total building energy use. Although they are typically one of the last end uses considered for energy conservation, plug loads alone can contribute up to 50% of total energy use in high-performance buildings (NREL 2015).

Until recently, plug loads have remained a largely unregulated building load. ENERGY STAR product certification and the DOE's Appliance and Equipment Standards Program set minimum energy conservation standards for end-use products. Since 2009, DOE's program has issued 44 new or updated standards (DOE 2017). ASHRAE, the International Green Construction Code, and California's Title 24 have standards in place requiring some portion of receptacles to be automatically controlled by timer, occupancy, or other control-type switches. Separate wiring and submetering of plug load circuits are also required in buildings with specific size and electric load thresholds. Submetered plug load data can be shared with tenants to inform them of their energy use and allow property managers to bill tenants accordingly.

Because plugged-in devices are not for base building use, but rather for occupant- or business-specific tasks, these devices are generally portable and brought into the building by tenants. As a result, plug load energy use is closely tied to occupant behavior. An effective controls strategy for plug loads should begin by identifying the loads most common to the space type (such as an office or medical clinic) and addressing the highest energy consumer among these loads first.

Smart buildings address plug loads strategically by controlling devices at the outlet. Automatically controlled receptacles, known as *smart plugs*, easily replace existing receptacles and communicate with a controller, such as a timer or occupancy switch. Plug load monitoring and management tools remotely turn off receptacles based on feedback from occupancy sensors located in tenant spaces. Advanced power strips (APS) resemble standard power strips but can cut the power to any individual plug or combination of plugs on the strip. The strip turns off devices when they are no longer being used, or completely shuts off the power delivered to the strip itself to eliminate phantom load draw. Several power control features are available for APS, including schedule timers, motion sensors, and remote switches.

Some APS work by load sensing. These strips have a dedicated master plug for a system's primary device, such as a desktop computer, with the remaining plugs available for peripheral workstation devices. The APS constantly senses for the presence of a power load on the master plug to detect when the primary device is on, off, or on standby. It then operates the peripheral device plugs according to the primary device's status.

Building operators can monitor and schedule plug loads remotely through web- or mobile-based applications, then program schedules into lighting and building management systems accordingly. In addition, they can use receptacle and circuit submetering to detect when devices are malfunctioning and identify unnecessary energy use.

APS Demonstration Projects

According to a GSA Green Proving Ground study, APS reduced energy consumption in workstations by 26% and in kitchens and printing rooms by 50%. The energy savings in the kitchens paid for the APS in just over eight months. Schedule-based APS were most effective for 24/7 plug loads, resulting in 48% energy savings (GSA 2012).

In a 2013 National Renewable Energy Laboratory (NREL) demonstration, researchers installed APS with schedule-based controls in an 18,800 sq. ft. office building in Hawaii. The researchers based APS schedules on data collected from room occupancy sensors. They installed Wi-Fi-enabled submeters at the electrical panel and at receptacles to measure the energy consumption of circuits and individual devices. The APS reduced plug load energy use by 28% and whole-building consumption by 8%. The researchers further found that the building used 5% less energy for cooling due to a reduction in heat load.

LIGHTING

Lighting controls are evolving beyond infrared motion sensing, manual dimming, and timer switches. Historically, such technologies have had mixed performance for various reasons, including poor design, improper set up or programming, performance degradation, or insufficient user uptake. Smart lighting controls aim to improve on these issues and increase positive user experience. By year-end 2014, 12% of US commercial buildings had advanced lighting controls, with the highest penetration (2.43%) in the education sector (Arnold 2016b). The current market penetration of lighting management controls in existing US commercial buildings is minimal: approximately 15% are occupancy type, 6% dimming, 4% lighting management systems, 3% demand response, and 2% daylighting (EIA 2016). Worldwide, smart lighting occupies approximately 600 million to 1 billion square feet of commercial space. Smart lighting installations, globally, are projected to grow from 46 million units in 2015 to 2.54 billion units in 2020 (Gartner 2015b).

Lighting in the US commercial sector is responsible for approximately 350 terawatt-hours (TWh) of energy use in all existing commercial buildings (Arnold 2016b). While LED retrofits can achieve 30% energy savings, implementing advanced lighting controls offers an additional 44% energy savings with a payback of less than five years (Frank et al. 2015). Fully integrated smart lighting systems could achieve up to 90% energy savings, which includes installing LED luminaires and connecting sensors and controls to a centralized management system with data analytics and learning capability (Gartner 2015b). Advanced lighting controls available on the market today could save approximately 100 TWh of energy if implemented in every existing US commercial building, representing savings of $10.4 billion annually (Arnold 2016b).

Smart lighting consists of networked LED and linear fluorescent luminaires with advanced sensing and controls capability. Advanced sensors can detect luminaire failure and send alerts through a lighting management system. Advanced controllability consists of dual-technology (infrared plus ultrasonic) occupancy sensing, vacancy sensing, daylight harvesting, continuous dimming, and task tuning. Independent of the luminaire type, advanced lighting controls in commercial building retrofits can achieve 45% energy savings. Of this 45%, half is achieved through occupancy sensing and daylight harvesting (BEEx 2015). Vacancy sensing is thought to be more effective than occupancy sensing as it relies on the occupant to manually turn on the lights, therefore giving the occupant the choice of leaving them off if desired. If turned on, the lights automatically turn off when no presence is detected for a specified amount of time.

Daylight harvesting controls use photosensors to measure indoor ambient light levels and reduce the amount of artificial lighting needed to meet design requirements. One study found that through daylighting, artificial lighting levels could be reduced by 40–80%, while maintaining occupant satisfaction (Jackson et al. 2015). Daylighting controls can operate single or multiple zones and can dim the lighting instantaneously through step changes that reduce light levels either by the percentage of max output or gradually over 1–30 minute increments.[4]

Some types of smart lighting solutions use luminaires that are manufactured with embedded wireless microcontrollers and sensors. This eliminates the need for standard wall-mounted controls and can reduce equipment, installation, and commissioning costs. For lighting retrofits, flexibility in installations is key to keeping costs down. The DesignLights Consortium's Commercial Advanced Lighting Controls project demonstrated that an integrated wireless lighting system costs 50% less than a lighting system with standard controls (Arnold 2016a).

Networked sensors installed throughout a building can monitor multiple locations and collect minute-by-minute room conditions. Smart lighting solutions with wireless sensors and controls can be centrally managed through a web-based lighting management platform. The lighting management platform can utilize real-time data to auto-configure and auto-commission its operations. Luminaires can be programmed to operate individually or in zones and respond to other networked devices such as window shading and daylighting sensors. Facility personnel and even occupants can also control their lights by interfacing with the dashboard through their personal computers, smartphones, or tablets. Voice-activated control is now an option in some smartphones and tablets.

Power over Ethernet (PoE) is also gaining momentum for advanced lighting applications in new and existing commercial buildings. Originally developed to support Internet-based telecommunications—such as Voice over Internet Protocol (VoIP)—as a replacement for legacy telephone networks, PoE serves as a communications network and electric circuit providing Internet access and low-voltage DC power to connect lighting devices.

[4] The Mass Save program provides an incentive to customers for installing step-dimming controls. Some demand response programs incentivize customers to use 30-minute continuous dimming controls during peak periods of electricity demand (DiLouie 2014).

Because LEDs operate at low DC voltages, they are ideal for PoE solutions, eliminating the need for AC-to-DC power conversion through a ballast or driver. PoE supplies a maximum 57v DC, much lower than the 120v or 277v AC for traditional wired lighting applications. PoE cables can be pulled through ceilings easily in any direction; multiple luminaires can be connected through an in-line network switch and Wi-Fi-controlled through a wireless hub. In a lighting retrofit, luminaires and controls are not restricted to existing wiring locations, allowing for flexible lighting designs and control configurations.

Smart lighting solutions accommodate sensors with multifunction capabilities to serve other building systems such as HVAC to enhance their operations. For example, a sensor can measure space temperatures, humidity, and CO_2 levels in occupied spaces and communicate this real-time information to the building management system. Also, data can be collated to identify occupancy patterns for better space use planning. The full capacity of this functionality has yet to be widely implemented, however, as most smart lighting installations today stop after networking the controls and sensors, leaving the sophisticated task of data analytics to building operators.

Time Warner Center and the New York Times Building

In 2012, an advanced lighting controls retrofit project took place on two floors in the Time Warner Center building in New York City. The retrofit retained the existing fluorescent light fixtures, but increased functionality through the addition of dimmable ballasts, carefully positioned wireless sensors, and a control system with a web-based user interface. This retrofit reduced lighting energy consumption by 56%, shaved peak demand from 70kW to 30kW, and had a three-year return on investment (BEEx 2014).

Completed in 2007, the New York Times Building was an early adopter of advanced lighting controls. The building's lighting design integrated window shading and used dimmable lighting, task-level tuning, and daylight harvesting. A one-year post-occupancy study found that the building achieved 43% lighting savings and 24% overall energy savings, while providing high levels of lighting quality and comfort (BEEx 2015).

WINDOW SHADING

About one-third of commercial building HVAC energy use is due to heat gains and losses from windows (Lee et al. 2013). The California Energy Commission estimates that approximately 40% of the cooling requirement for a typical building in California is due to solar heat gain through windows (DeBusk 2012).

Window attachments, as simple as manual shades, have proven to be a low-cost measure for reducing solar heat gain and glare. However field studies have shown that manually operated shades, once lowered to reduce glare, often remain lowered regardless of changes in exterior light levels, sacrificing daylighting opportunities. Motorized window shades, controlled by manual switches or analog timers, and tinted glass and films are decades-old technologies designed to absorb the whole spectrum of sunlight, thereby reducing the solar heat entering buildings and diminishing visible light to reduce glare. Older window shading technologies did not incorporate daylighting features.

Automatically controlled shading systems go a step further, responding to changes in outdoor and indoor temperature conditions over the course of a day without relying on human input. Solar-adaptive shades work in the same way in response to the position of the sun. These smart shades rely on sensors that measure indoor and outdoor ambient temperatures or the sun's position and radiation, automatically adjusting their height to manage the amount of light and heat entering the building. These devices can be integrated with lighting and building management systems for centralized control. When added to a lighting retrofit project to maximize daylighting, smart shades offer an additional 10% energy savings in lighting energy use (BEEx 2015).

Advanced window glass and films can save even more energy, and passive glass technologies (such as low-E glass) are readily available. Traditional glass has bronze or gray tinting. Advances in tinting now achieve a wider color spectrum, permitting visible light to pass through to the interior of the building while reducing solar heat gain. Recent developments in window films, such as dual reflective, solar control, and daylight redirecting films, can be applied to existing untinted windows to achieve the shading benefit of tinted glass. These simple, moderately priced advances in technology commonly accompany daylighting designs in commercial building retrofits, and have the added benefit of reducing solar heat gain and glare. A window film retrofit study on buildings in California found an average return on investment (ROI) of 39% for films applied to single-pane windows and 25% for double-pane window applications (ConSol 2012).

Passive glass technologies are also trending in the smart buildings market. However they lack network controls and the ability to integrate with other building systems. Two types of passive window systems worth mentioning are photochromic and thermochromic, which autonomously adjust their tint according to light and temperature, respectively. Photochromic glass transmits varying levels of light into the building according to changes in sunlight. Thermochromic glass varies according to ambient outdoor temperature swings, permitting or preventing the entry of solar heat into the building. One thermochromic smart window, the RavenWindow 2.0, came to market in 2012; it claims 30% energy savings and an ROI of three to five years (RavenWindow 2016).

Active, or electrochromic, smart glass is electrically controlled. Known by various names including active, switchable, and e-charged glass, it helps control daylighting and solar heat transfer. Window tinting is driven by a low voltage charge in response to solar intensity and ambient temperature. Changes in voltage alter the sunlight-reflecting and absorbing properties of the glass. E-charged self-adhesive films are also commercially available. The e-charged glass and films change from opaque to clear, or dim along a grayscale in between, depending on the electrical charge received. These glass and films are becoming increasingly popular in tenant space buildouts for interior partition walls because they allow daylight to penetrate the space when clear and provide privacy when opaque.

The penetration of electrochromic glass is modestly growing due to the market availability of larger sizes and volumes, more aesthetic options, wireless power and control capability for retrofit applications, and enhanced daylight management features (Sanders 2015). An example of electrochromic glass on the market is SageGlass, which claims 20% savings in operational costs and a 25% decrease in HVAC system sizing, resulting in 10% system cost savings and a 25% reduction in peak demand (SageGlass 2016).

Currently, the largest barrier to smart window deployment is upfront costs. Material and labor costs are approximately $40/sq. ft. for thermochromic and $61/sq. ft. for electrochromic, compared to $24/sq. ft. for low-E (Lee 2013). Although window shading systems can be a large investment, they are the most effective means of integrating daylight, reducing glare and solar heat gain, and maximizing occupant comfort (BEEx 2015).

Smart Window Demonstration Project

GSA conducted a pilot study on electrochromic and thermochromic windows in 2012 through its Green Proving Ground program. The one-year study took place in an existing 9,500 sq. ft. office building in Denver. The building's windows were retrofitted with 14 thermochromic windows and eight electrochromic windows with interior and exterior temperature sensors. The study showed that thermochromic and electrochromic windows reduced solar heat gain by 58% and 46%, respectively, over a baseline low-E double-pane window, resulting in a 10% and 9% reduction in annual HVAC cooling and electricity use, respectively (GSA 2014).

ENERGY MANAGEMENT AND INFORMATION SYSTEMS

Energy management and information systems (EMIS) represent a wide range of hardware and software used to manage energy use in commercial buildings. The term *EMIS* is often used interchangeably with other terms, including building automation systems (BAS), building management systems (BMS), energy management systems (EMS), energy management and control systems (EMCS), and direct digital control (DDC) systems (Katipamula et al. 2012). In keeping with Lawrence Berkeley National Laboratory's Technology Classification Framework guidelines, here we distinguish between traditional BAS, which provide building equipment controls; energy information systems (EIS), which provide data analytics; and automated system optimization (ASO), which provides automated controls based on data analytics (Granderson 2013).

BAS have steadily evolved over the past few decades, starting with the use of compressed air (pneumatic) control systems in the 1950s and shifting to digital (electronic) controls in the 1980s. BAS broke new ground with the implementation of open communication protocols in the 1990s and then again with wireless communication technology in the 2000s (Control Solutions 2015).[5]

A whole-building interconnected BAS centralizes controls to manage building operations. It allows a building operator to adjust certain HVAC settings (such as temperature, pressure, and schedule) and lighting schedules from a centralized location rather than manually adjusting settings at the unit. Additionally, a typical BAS provides the ability to program

[5] Communication protocols are similar to languages: Building automation equipment that uses proprietary protocols is unable to speak with equipment from other vendors. However, when such equipment uses open protocols (e.g., BACnet and LonWorks), it can communicate with a range of equipment from different vendors, greatly increasing options for building automation (Giarrusso 2015).

basic control sequences. For example, an operator could use the BAS to configure chiller staging so that a smaller, less energy-intensive chiller could be used to meet low loads and a larger, more energy-intensive chiller could be used only when the load exceeds the smaller chiller's capacity (NREL 2011).

Historically, the cost of installing a BAS, which ranges from $1.50 to $7/sq. ft., justified their use primarily in large buildings (FPL 2016). This is evidenced by the fact that more than 70% of large commercial buildings (those bigger than 100,000 square feet) contain a BAS, while less than 13% of small- and medium-sized buildings have one. However interest in BAS for these smaller buildings is clearly increasing, as less than 5% had one in 2003 (EIA 2016).

Because installing a robust BAS is often not cost effective in small- and medium-sized buildings, these building owners may consider less expensive smart controls options. Programmable thermostats, which control individual HVAC systems, and occupancy sensors, which control lighting, represent the most cost-effective smart controls for small and medium buildings. A master controller connecting the thermostats and sensors allows the building operator to perform basic control measures, such as adjusting equipment schedules and temperature set points from a centralized location (Katipamula et al. 2012).

However, since many small and medium buildings have at most only part-time onsite engineering staff to adjust schedules and set temperature set points, installing a centralized controller still may not be the optimal control method for some buildings. Lawrence Berkeley National Laboratory suggests using the increasingly popular EIS strategy of cloud- or network-based remote monitoring (Granderson, Lin, and Piette 2013). Using EIS, remote engineering staff or a third-party organization installs sensors to monitor HVAC, lighting, and/or end-use loads. Because building data are stored in the cloud, engineers can monitor building operations from virtually anywhere with an Internet connection. Remote engineers can also optimize equipment controls, detect and resolve faults remotely, and even dispatch service to the site if needed (Katipamula et al. 2012).

Remote Monitoring at Bank of America

Remote monitoring turned out to be Bank of America's best method to successfully manage energy consumption in its smaller facilities. The organization had previously implemented sophisticated energy control systems in larger buildings, yet struggled to effectively monitor energy consumption and diagnose equipment issues in its smaller branch buildings.

Implementing the Intelligent Command & Control Center (iC^3) system allowed Bank of America to network more than half of its branches throughout the country, and remotely monitor both lighting and HVAC. Technicians in the iC^3 in Charlotte, North Carolina, can now instantly adjust HVAC temperature set points or shut off exterior lighting in, say, a Phoenix, Arizona branch.

In total, the remote-monitoring upgrade is estimated to save 2 million kWh in the 98 locations in Duke Energy's service area alone. When energy savings are extrapolated to Bank of America's more than 3,000 branches, it results in *tens of millions* of kWh savings (Realcomm 2009).

When EIS's analytics are combined with BAS automation, the result is ASO. What differentiates ASO from traditional automation systems is that the ASO moves beyond simply responding to changes in certain conditions (such as weather). Instead, it uses hardware and software to gather and analyze data to make strategic decisions about how to control the building systems in advance of an external condition (e.g., atmospheric, economic, behavioral). In other words, a BAS reacts to external conditions, whereas an ASO is capable of anticipating them.

A simple example—of each system responding to temperature change—highlights the difference between a regular BAS and an ASO. A typical BAS may receive and interpret temperature data from duct, indoor, and outdoor temperature sensors. The BAS adjusts the HVAC operation by reacting *to* these readings, providing more or less conditioned air to zones that are outside the programmed temperature range. If the outside air temperature suddenly becomes much hotter, a simple BAS must work at full capacity to cool the building. However ASO has the ability to adjust the system operation in advance, based on predicted weather conditions. This might include predictively precooling a building at night in preparation for a hot day (Barnard 2016), saving the building owner money by avoiding operating during peak demand times.

Stanford's Automated System Optimization Controls

In 2009, Stanford initiated the Stanford Energy System Innovations (SESI) project with the goal of becoming a leader in sustainability by implementing a series of projects that used efficient, clean, and renewable energy technologies. In addition to becoming a showcase for innovative heat recovery and thermal energy storage techniques, SESI represents one of the best examples of a campus ASO.

Developed jointly with Johnson Controls, Stanford's ASO, called the *Enterprise Optimization Solution*, uses more than 1,220 variables to predict and optimize controls to essentially run the plant on autopilot. The system uses the variables—such as building occupancy, weather, energy prices, and system conditions—to develop predictive models of hourly campus heating and cooling requirements seven days in advance (Stanford 2017). Stanford's ASO can even use these variables to optimize the amount of heat recovery from chillers and the dispatch of hot and chilled water storage. The Enterprise Optimization Solution is projected to save the university $420 million over the next 35 years (C. Nesler, VP, Global Energy and Sustainability, Johnson Controls, pers. comm., January 8, 2017).

HUMAN OPERATION

Even the most advanced smart building analytics and technologies can be rendered useless without effective human operation. Humans determine which types of alerts and reports will be the most useful to receive from analytics software; they interpret data displayed through smart building interfaces to create schedules, set points, and operational strategies or sequences; and they act on information to correct faults and reduce energy consumption. Equipping these users with the right data and tools to effectively use the extensive building data available is every bit as important as installing smart hardware and software in buildings.

Data Display and Prioritization

Building users are more likely to respond to data when data are presented in a meaningful way. *Meaningful data* is a metric that varies based on several factors, including the type of building, occupant, and owner. For instance, a basic display on the building operator's computer should include important information for building operation, such as hourly energy consumption, energy costs, and equipment faults. Alternatively, consider the type of data that would be most effective to display for building occupants. User-friendly dashboards and mobile apps designed for occupant use have been shown to trigger small but effective energy-saving behavior changes (Vaidyanathan et al. 2013). In this particular case, effective metrics might include greenhouse gas emissions, an ENERGY STAR score, and a simple comparison of current energy use versus a baseline or target.

Northshore School District

The case of the Northshore School District, which is comprised of 33 schools and three administrative facilities in Snohomish County, Washington, highlights the importance of two of the most critical features of a data analytics platform: an easy-to-use dashboard and prioritized alerts. Although the school district had a real-time energy monitoring system, its dashboard was difficult to navigate and it could not produce customized reports.

After extensive research, the team ended up using two different software packages to develop a custom platform. Visually, the new software platform's designers created the dashboard to display metrics that mattered most to the intended audience (e.g., technicians, facility managers, and financial analysts). For example, the metrics included the number of dollars saved by a project, instead of just kWh saved. The new design included easy-to-understand graphics and visualizations that let building operators quickly spot energy savings opportunities. The system also reduced the number of incorrect alerts (e.g., false positives) and provided useful information, such as that the building was wasting energy during unoccupied hours (NEEC 2016).

While presenting data in a meaningful way maximizes the user's ability to interpret the information, correctly prioritizing smart building alerts minimizes the risk of the data set becoming overwhelming. Especially when first installed, smart building systems often provide too much information, resulting in user paralysis due to data overload—and thus no action to actually improve building operations. The most effective smart building software includes algorithms to prioritize the alerts by whatever metrics the building owner and operator consider the most important. Some experts think that the optimal number of alerts at one time is three to five (A. Buglaeva, director of business development, Aquicore, pers. comm., June 1, 2016).

Modern technology gives individuals the ability to determine not only which information to receive, but also how they wish to receive it. Large buildings owners may wish to receive large reports and summaries of potential energy-saving options. Small building owners may not have the time or personnel to dissect a large energy report, and may be interested in learning only the top three low- to no-cost changes they can make to reduce building energy consumption. In addition, within the past decade, technology users have grown accustomed to receiving notifications through tablets, laptops, and cell phones. With so many potential interruptions and distractions available, the challenge for the smart building industry moving forward will likely be to find ways to limit notifications to only those that are the most meaningful for each particular user.

HVAC and Human Resources

Some of the smartest building data analytics incorporate information from disparate systems. A major technology organization's sustainability strategist offered the following scenario, in which a smart building system uses the HVAC and human resources (HR) databases together to help prioritize alerts. In this example, it is the middle of a hot summer, and the building engineer receives an alert that a building's HVAC units have failed in three offices: one in a software developer's office, one in a salesperson's office, and a third in the CEO's office.

An algorithm in the smart building system compares the alerts to the HR database. It automatically prioritizes fixing the HVAC unit in the CEO's office first, since it recognizes this person as the highest-ranking member of the company. The algorithm places the software developer as the second priority, since she or he is more likely to be working in the office and is more likely to overheat due to high computer usage. The third priority is the salesperson, who has a 50% probability of being out of office on travel; also, the salesperson's office will be slower to overheat as relatively little computing power is used to carry out his/her work. By the time the building engineers receives these alerts, they know the exact order in which to repair the HVAC units.

Monitoring-Based Commissioning and Evaluation, Measurement, and Verification

Smart building technologies can help speed the transition from traditional commissioning and retrocommissioning to ongoing MBCx.[6] Traditional retrocommissioning has been shown to save energy, but it loses effectiveness over time as a building's occupancy and use continues to change. Energy efficiency benefits from a retrocommissioning job may decline by as much as 35% after four years (Bourassa, Piette, and Motegi 2004). In addition, retrocommissioning projects can take as long as 18–24 months to implement from the initial screening to follow-up verification (York et al. 2013).

Alternatively, smart building equipment lets building operators perform MBCx continuously in real-time, rather than every few years. With contemporary MBCx, building operators can evaluate historical trend data, identify where building occupancy and usage patterns have changed, and adjust system operations to minimize energy consumption.

[6] Building commissioning tests new building systems and equipment (e.g., HVAC, lighting, and water heating) to ensure the building operates as it was originally intended. Retrocommissioning uses similar methods on existing buildings to address changes to building occupancy and use (LBL 2016). MBCx analyzes trend data to monitor and commission building systems and equipment in real-time.

Monitoring-Based Commissioning in a Chicago Office

Although Citigroup Center Chicago was efficient enough to earn both a LEED EB certification and ENERGY STAR rating, the engineering staff still had not uncovered every opportunity to improve its HVAC controls. As part of its ongoing HVAC optimization program, Sieben Energy Associates decided to implement SkySpark analytics software to help perform MBCx.

Using five-minute interval data, SkySpark highlighted a number of HVAC operational anomalies. Sieben used this information to develop a set of energy-reduction measures such as an HVAC optimal start control sequence that reduced HVAC demand during morning startup. By implementing seven measures identified through the MBCx software, the building saved nearly 2 million kWh in energy, equating to $112,000.

In addition to long-term energy-savings measures, the software also helped the team identify dozens of faults that they corrected in real time before the faults resulted in extensive energy losses. Commonwealth Edison provided both front-end and outcome-based utility incentives to help ensure the project's cost-effectiveness (SkyFoundry 2016).

When building operators commission a building on an ongoing basis, they avoid traditional retrocommissioning's efficiency losses over time. Smart building systems can improve on MBCx's effectiveness by using fully automated, continuous correction tools. Instead of alerting building operators to make changes, smart algorithms can identify and automatically make the appropriate adjustments without burdening the building operator. Although automated ongoing commissioning is still an emerging field, as the smart building and IoT industries grow, it will likely become much more prominent.

The ability to review historical trend data can also greatly enhance the accuracy of a building's evaluation, measurement, and verification (EM&V) program. EM&V quantifies the energy consumption of individual equipment or energy efficiency measures through the EMIS, BAS, or EIS. Typically, in commercial buildings, EM&V can be completed using only whole-building energy use data. Because whole-building data encompasses energy consumption from every piece of equipment in the building, quantifying the energy savings from a specific piece of equipment or energy efficiency measure is particularly difficult. By including data analytics and additional sensors, smart building systems can provide a much more granular data set that can help building operators use EM&V more precisely. The resulting EM&V data can be used to verify a project's energy savings, justify future energy efficiency projects, and even help utilities quantify the impact of energy efficiency programs.

Trained Interdisciplinary Teams

The better a building operations team understands smart building technology, the greater the chance it will embrace that technology. Teams need training in network management, data analysis, and smart technology. After installing smart building equipment, the smart building experts should perform consistent follow-ups (preferably onsite) to ensure that the team understands how to maximize the benefits of the smart building system. Similarly, to ensure the effectiveness of remote control and monitoring, remote services personnel must receive the appropriate training in building science, advanced control and algorithms, data analytics, and networking.

Because smart buildings weave together traditional building operation with innovative technology, it only makes sense that a strong smart building team contains experts from different disciplines. Successful smart building teams often contain both building operators and information technology (IT) specialists.

Developing an Energy Management Taskforce at McGill University

McGill University in Montreal developed a taskforce consisting of energy managers, HVAC operators, control technicians, building operators, and unit directors to help carry out its ambitious energy management plan. In 2010, the university installed nearly 400 meters to monitor the energy consumption of 67 of the largest energy-consuming buildings on campus, measuring electricity, steam, condensate, chilled water, hot water, and natural gas consumption.

The task force meets regularly to review nonconforming events (such as unusual energy spikes) and to push forward campus-wide energy efficiency programs. In addition, the task force selected Pulse Energy to develop a public dashboard to display building energy use.

Installing the meters and developing the dashboard cost McGill roughly $2.4 million. With $75,000 in efficiency rebates and an estimated $400,000 in energy savings per year, the project was projected for a 5.7-year simple payback (McGill University 2013). More information about the dashboard is available at https://my.pulseenergy.com/mcgill/dashboard#/overview.

CONNECTED DISTRIBUTED GENERATION AND POWER

Distributed energy resources (DER) are small-scale power generation sources that generate electricity at or near the point of use (e.g., a commercial office building or a university campus). DER involve distributed generation technologies—such as combustion turbines, fuel cells, and solar photovoltaic (PV)—that produce power independent of the utility grid. They can thus operate either as standalone systems in parallel to the electric power grid or as grid-connected systems. Where regulation permits, grid-connected systems can sell power to the grid.

DER also involves distributed power, most commonly in the form of energy storage. Onsite energy storage systems discharge electricity to a building during periods of reduced (or no) distributed generation. Rechargeable lead-acid and lithium-ion batteries support the most common storage systems in the commercial market. Energy storage enables building owners to reduce peak demand charges and electricity costs for grid-supplied power. Grid electricity can charge storage systems in the middle of the night, when energy prices are lowest. The storage systems can then discharge electricity for building use during the day, when prices are highest. Power-monitoring software is used to switch automatically and continuously between the grid and the storage system to curb the building's peak energy use. A portion of the energy storage market uses a storage-as-a-service model, where energy storage companies own a building's storage hardware and monitoring software, and the building owner pays for the management and delivery of stored energy through a service subscription.

A common DER for commercial and industrial facilities is combined heat and power (CHP), or cogeneration, which uses waste heat from power generation to supplement building HVAC and water heating. According to a 2016 DOE technical study, commercial buildings represent the strongest potential growth market for CHP in the United States (DOE 2016a). CHP is currently installed in more than 2,500 existing commercial buildings, representing only 14% of existing CHP capacity.

Another commercially available DER is solar PV, with grid-connected systems having the most traction. Upfront costs for most solar PV systems have significantly declined in recent years, with PV module costs down 75% since 2009 (IRENA 2015). Onsite solar PV systems can be ground- or pole-mounted, installed on rooftops, or directly integrated into the building enclosure. Building-integrated PV modules comprise part of the building envelope, such as the exterior cladding or window and skylight glass.

A major challenge with grid-connected PV systems is that they can cause grid stability issues by feeding excess power into the grid when demand for grid power is low. If uncontrolled and unmanaged, this excess power enters the grid intermittently and can overload the grid network, potentially leading to failure.

Smart functionality is now being added to DER via smart inverters that allow control through two-way communication between the DER and the utility. The smart inverter can thus direct a PV system's excess power to the grid or to an energy storage system. Also, when the building needs power, the smart inverter can signal the grid to supply it. Smart inverters can be programmed to ride through power lags or disturbances that could otherwise lead to grid outages (Unger 2016).

Smart inverter hardware is almost identical to that of standard inverters; the difference lies in its advanced controllability and data collection capabilities. Smart inverters are software-controlled, permitting continuous communication between the DER and the grid. They collect voltage and frequency data for grid-connected DER and upload the data to a cloud-based platform, giving utilities a deeper view into over- and under-voltage conditions across their distribution system.

Enphase

An Enphase Energy study compared a solar PV system with storage to one without and showed a 14% reduction in overall building energy demand for the system with storage. The study also showed that, when a smart inverter was added, the PV system with storage saw an additional 12% energy savings (Berdner 2015).

Some utilities have begun integrating smart inverters into their customers' grid-connected solar PV systems. In early 2015, the Hawaiian Electric Co. rolled out a smart inverter program for connecting customer-owned PV systems to the grid, thereby releasing its previously placed hold on grid connection for approximately 4,000 customers (St. John 2015). California plans a 2017 regulation, under CA Rule 21, requiring smart inverters for new installations. PG&E and the Arizona Public Service are also looking into smart inverter rollout programs (Edge, York, and Enbar 2015). ComEd's Next Generation Energy Plan proposes a smart inverter rebate of $500/kW of generation for commercial and industrial customers. It plans to test smart inverters in a microgrid pilot project in Chicago (Unger 2016).

Nonenergy Benefits of Smart Buildings and Barriers to Their Adoption

BENEFITS

If smart technologies are to proliferate in the market, the building industry must better understand smart buildings' value proposition and begin to shift the building operator culture.

The intent of this report is to identify how smart buildings can save energy. However, many building owners retrofit smart measures into their buildings for nonenergy reasons. The 2016 Energy Efficiency Indicator Survey queried more than 1,200 facility management executives on key drivers for investing in energy efficiency in their buildings. Two-thirds indicated that increasing their company brand reputation and attracting new tenants were substantial investment drivers (Johnson Controls 2016). Business owners are also realizing the benefits that energy efficiency investments have on employee wellness and productivity. One study found that a 2% improvement in employee productivity equates to saving $6 per square foot in operating costs (JLL 2014).

Smart buildings add value to leasing and sales, and business owners are beginning to realize it. As consumer awareness of energy efficiency continues to grow and building energy performance data become increasingly available, potential renters and buyers can make better decisions about leasing or buying buildings based on energy efficiency and corresponding energy costs. Owners of smart buildings can also satisfy rising tenant expectations for flexible workspaces and autonomous control. This growing demand from tenants for energy-efficient and flexible workspaces can in turn lead to greater market adoption of smart building technologies.

Smart buildings have other benefits as well. Devices that operate over wireless Internet networks can be easier to install and do not disrupt existing building finishes. Aside from managing primary energy-consuming systems, smart buildings also incorporate management of the building's security, access, and safety systems. Building owners can use smart measures both to increase their buildings' remote controllability and to compare performance across their portfolio. Further, some smart buildings generate power onsite through distributed generation systems and participate in demand response events to reduce the building's peak energy use and assist in stabilizing the power grid.

BARRIERS TO ADOPTION

Building owners and operators are slow to adopt smart technologies for several reasons. Some are simply not aware of them. Those who are aware of them may never have used them and may view them as too complex. Once they start using these technologies, they may be unprepared to manage the new equipment and software, and they may find the learning curve too steep. Most operators have little to no experience analyzing large amounts of building performance data, and they (and the building owners) may not like realizing that they have been operating their buildings inefficiently for years. A commitment from manufacturers and trade associations to provide training could provide for greater understanding and awareness of the technologies.

Another barrier to smart building prevalence is the long replacement cycle for building infrastructure. It is all too common for building systems to undergo upgrades only at the point of failure. In many cases, this occurs later than the system's expected useful life, but the upfront purchase costs of some smart building technologies discourage more timely upgrades. Further, lack of funding is the leading barrier to greater investment in building improvements in the United States. Only half as many small organizations as large organizations report having capital set aside for making energy improvements (Johnson Controls 2016). Similarly, a lack of tax incentives also proves a barrier to investment. Without incentives, many building owners will require more evidence that smart buildings are worth the high costs, especially in underrepresented applications such as small- and medium-sized buildings and class B commercial real estate.

Another barrier to smart building proliferation is the lack of seamless interoperability between connected devices. Although open communications protocols (e.g., BACnet and Lonworks) allow some products from different manufacturers to communicate, no single standard protocol exists that lets all smart equipment and devices communicate. Efforts to address these interconnectivity issues are beginning to emerge, including those of the Open Connectivity Foundation (OCF), which helps manage IoT standards and certifications; and Project Haystack, which is developing a common list of naming conventions (i.e., tags) for smart equipment to ensure that all equipment speaks the same language.

Microsoft's Smart Campus

Microsoft's 88 Acres project has become one of the most well-publicized examples of a large-scale smart building implementation. The company was uniquely positioned to create one of the smartest office campuses in the United States at its 500-acre headquarters in Redmond, Washington. Like most corporate campuses, the Redmond campus was built in phases, which resulted in buildings that contained sensors, HVAC equipment, and BAS from different eras and different manufacturers. As might be expected, each piece of equipment essentially spoke its own language; the challenge was to find a way for all equipment to communicate so that a central system could manage it.

To develop its headquarters into a smart campus, Microsoft experts hired real-time automation software firm ICONICS to create a naming convention for each installed device, storing it in a library so that they could easily connect any additional equipment of the same type. As more equipment began communicating, the team began to receive more data points. Microsoft building engineers used the data to improve operations—from staging building startup based on usage patterns to resolving previously undetectable simultaneous HVAC heating and cooling issues.

Microsoft eventually migrated its data to a cloud server, and it plans to develop its platform so that other functions—such as HVAC and data analytics—can use and enhance it. Microsoft estimates that it achieved as much as 10% energy savings from its smart building initiative, saving the company approximately $0.25 million each year (Warnick 2016).

Building owners are also growing increasingly concerned about cybersecurity, including the potential for widespread disablement and safety concerns for building occupants once a building's management system has been connected to the Internet. These concerns are justified; the number of security breaches has increased as buildings have become more interconnected. In late 2016, for example, IoT devices contributed to a major cyberattack, temporarily disabling services such as Twitter, Spotify, and PayPal (Peterson 2016). An analysis of the vulnerability of smart buildings by Frost and Sullivan (2015) stresses the importance of the IT and operational technology (OT) industries collaborating to develop and implement strategies to mitigate cybersecurity threats.

Energy Efficiency Potential and Energy-Savings Analysis

INDIVIDUAL TECHNOLOGIES

Through our analysis of reports and case studies and our interviews with field experts, we gathered enough data to attempt to quantify the typical costs and savings from implementing specific smart building technologies. Examples of newly constructed smart buildings were much more readily available than smart building retrofit projects. Table 1 shows the costs and energy-saving potential of smart HVAC technologies.

Table 1. Retail costs and savings estimates for smart HVAC technologies

Category	Technology	Components	Cost	Energy savings	Simple payback	Measure life
HVAC	Wired sensor	Energy, temperature, flow, pressure, humidity sensors	$50–100/ sensor + $1.60/linear foot wiring	Not applicable	Not applicable	15–30 years
HVAC	Wireless sensor	Energy, temperature, flow, pressure, humidity sensors	$150–300/ sensor	Not applicable	Not applicable	15–30 years
HVAC	Variable frequency drive	Variable frequency drive (pumps and motors)	$125–250/ hp	15–50% pump or motor energy	1–2 years	7–10 years
HVAC	Smart thermostat	Smart thermostat	$150–330/ thermostat	5–10% HVAC	3–5 years	10 years
HVAC & lighting	Hotel guest room occupancy controls	Door switches, occupancy sensors	$100–500/ guest room	12–24% HVAC, 16-22% lighting	2.5–3.0 years	10 years

Excludes installation costs. *Sources:* Wireless sensors costs: ACEEE analysis, Shoemaker 2015. Wired sensors costs: Kintner-Meyer et al. 2002). Smart thermostats costs: Grant and Keegan 2016. VFDs savings: ACEEE analysis, Hydraulic Institute, Europump, DOE 2004. Smart thermostat savings: DOE 2016b. Simple payback: ACEEE analysis. Life expectancy: ACEEE analysis, ASHRAE 2013. VFDs life expectancy: Delta Automation 2010. Smart thermostats life expectancy: Harder 2016. Hotel occupancy controls (all): CPUC 2011.

Advanced sensors and controls continue to decline in cost and are relatively easy to install in building retrofit projects. Low-cost sensors, controls, and retrofit BAS can reduce building energy consumption by 20–30% in small and medium commercial buildings, representing 0.3-0.4 quads in total energy savings (Roth et al. 2005).

Recent sensor technology advancements include smaller-sized sensors that are embeddable in the primary equipment they serve (e.g., light fixtures). This replaces the conventional standalone sensor that is mounted and wired separately. The wireless capability of advanced sensors and controls makes their installation and commissioning easier and quicker. As wireless sensor technology evolves further to include self-powered units, their deployment should become even more economical.

Tables 2 and 3 show retail costs and savings estimates for plug load, lighting, DER, and window shading technologies.

Table 2. Costs and savings estimates for plug load, lighting, and DER technologies

Category	Technology	Components	Cost	Energy savings	Simple payback	Measure life
Plug load	Smart plug	120v 220v	$100 each $200 each	50–60%	4–12 months	9 years
Plug load	Advanced power strip	Tier One types	$45–50 each	25–50%	8–18 months	10–20 years
Lighting	Advanced lighting controls	Occupancy/vacancy, daylighting, task tuning, lumen maintenance, dimming, daylighting	$2–4/sf	45%	3–6 years	10–20 years
Lighting	Web-based lighting mgmt system	Software and hardware	$1.15/sf	20–30% above controls savings	1–4 years	10–15 years
DER	Smart inverter	Smart inverter	$0.16/watt	12%	4–5 years	10 years

Excludes installation costs. *Sources:* Advanced lighting controls costs: Gilliland 2016, DLC 2016. Plug load energy savings: Boss 2016, GSA 2012. Advanced lighting controls and management systems savings: BEEx 2015. DER savings: Berdner 2015. Simple payback: ACEEE analysis. Life expectancy: ACEEE analysis, ASHRAE 2013. APS life expectancy: NEEP 2012, Huffstetler 2016. Smart inverter life expectancy: Chung et al. 2015b.

Table 3. Retail costs and savings estimates for window shading technologies

Category	Technology	Components	Cost	Energy savings	Simple payback	Measure life
Window shading	Automated shade system	Shades w/ automatic controls	$375 (motorized shades)	21–38%	4 years	10–20 years
Window shading	Switchable film	Self-adhered	$15–20/sf	32–43%	2–3 years	10 years
Window shading	Smart glass	Thermochromic Electrochromic	$40/sf $61/sf	20–30%	21 years 33 years	30 years 50 years

Excludes installation costs. *Sources:* Window shading costs: GSA 2014, Wagner 2016. Energy savings: Lutron 2014, InvisiShade 2016, SageGlass 2016, RavenWindow 2016. Simple payback: ACEEE analysis. Life expectancy: ACEEE analysis, ASHRAE 2013. Switchable film life expectancy: InvisiShade 2016.

We noted consistently high costs for certain technologies, which represent cost barriers. A smart window is an example. Passive and active smart windows cost approximately two to three times more than widely used low-E windows. Although smart glass has an estimated energy-saving potential of 40%, the payback time for this technology is long—up to 33 years.

Smart films and automated shades are a more economical solution for window shading; they are also more feasible for whole-building retrofits. Like plug load and lighting management solutions, these technologies could find a place in existing buildings through tenant buildouts. In buildings where tenants are the utility customers, they can take advantage of widget-based incentives for technologies exclusive to their space.

Table 4 shows costs and savings estimates for building automation systems.

Table 4. Retail costs and savings estimates for building automation systems

Category	Technology	Components	Cost	Energy savings	Simple payback	Measure life
Building automation	Traditional BAS	Sensors, controllers, automation software	$1.50–7.00/ sf	10–25% whole building	3–5 years	10–12 years
Analytics	Cloud-based EIS	Sensors, communication systems, web-based software	$0.01–0.77/ sf + service contract	5–10% whole building	1–2 years	Length of contract

Excludes installation costs. *Sources:* Traditional BAS costs: FPL 2016. EIS costs: Granderson, Lin, and Piette 2013. Energy savings: Gilliland 2016. Simple payback: ACEEE analysis. Life expectancy: ACEEE analysis, ASHRAE 2013. Traditional BAS life expectancy: Winkelman 2009, Tatum 2011.

Building automation is the most expensive technology in this space. As mentioned previously, the industry-accepted cost of a traditional BAS ranges from $1.50 to $7.00/sq. ft., with average whole-building energy savings ranging from 10% to 25%. Because wireless, cloud-based EIS require less hardware than a typical BAS, they are advertised as costing up to 30% less to install (Tracy 2016). However, a cloud-based BAS typically requires subscription service costs that also must be considered.

Because cloud-based energy monitoring and control systems are a relatively recent addition to the building controls market, reliable cost data were not readily available. As a result, in table 1, we distinguish between traditional BAS, which have well-documented costs, and a cloud-based monitoring system (without controls), which few researchers besides Lawrence Berkeley National Laboratory have studied. In reality, building owners face a wide variety of costs for BAS. If the building already contains a traditional BAS, adding cloud-based remote monitoring might entail only a small incremental cost. If the building has no control or monitoring systems, installing the required base of sensors and controls will entail higher costs.

In terms of energy savings, how do cloud-based monitoring and control systems stack up against conventional BAS? Cost savings for whole-building BAS range from 5% to 15% on the low end (Brambley et al. 2005) and 20% to 30% on the high end (Roth et al. 2005). While we have seen energy-savings claims as high as 30% from cloud-based EIS, preliminary results show that savings are closer to the low end of traditional BAS, averaging about 10% of whole-building energy savings (Gilliland 2016). However, when a cloud-based EIS is overlaid on an existing BAS, the benefits of combined analytics and controls can yield energy savings of 10–30%.

Limited information was available on the costs and savings of automated FDD systems and ASO, so we did not include them in table 1. However a Lawrence Berkeley National

Laboratory study estimated that costs for automated FDD and ASO were approximately the same—and were less than the cost of a traditional BAS. An FDD system is estimated at 2–11% of whole-building energy savings (LBNL 2015); no estimate was available for ASO, though we speculate that energy savings would be similar or higher.

The industry would benefit from further demonstrations measuring energy saved through EIS, ASO, and automated FDD in commercial building retrofit projects. Additionally, as companies offering cloud-based analytics continue to gather data and improve their services, we may begin to see additional energy savings. This is true for all of the technologies we examined. Further demonstrations will continue to show technology advancements and may find additional energy-saving potential for sector-specific applications.

WHOLE BUILDINGS

Based on DOE's *2015 Quadrennial Technology Review* (QTR), the average primary energy use intensity (EUI) of the current US commercial building stock (14.6 kWh/sq. ft.) could be reduced by 46%—to 6.7 kWh/sq. ft.—by using the best available cost-effective energy-efficient technologies on the market today (DOE 2015).

Further energy savings are possible by using ICT to integrate building equipment and systems. A building performs most efficiently when all of its components are controlled as part of an integrated system. Systems integration in a smart building can realize an annual savings of 2.37 kWh/sq. ft. compared to a building lacking energy-efficient systems. Another study shows that systems integration can account for 30–50% of whole-building energy savings (Frank et al. 2015). Even just a BAS and fluorescent lighting can result in 25% whole-building energy savings and 10% operational maintenance savings (Ruiz, Nesler, and Managan 2014).

As discussed earlier, the type of automation system implemented in a building largely depends on the building size. Generally, the higher energy costs of large buildings more easily justify BAS installation than the lower energy costs of smaller buildings. However, while a 50,000 sq. ft. office building's owners may not be able to justify the cost of installing a full-scale BAS, they might see the value in installing lighting controls, smart thermostats, or a remote HVAC monitoring system. HVAC and lighting represent, on average, 70% of a small or medium building's energy consumption; by our estimates, these technologies can save an average of 23% of total building energy consumption (see table 2).

Building Subsectors

We took our analysis a step further and estimated energy savings from smart building technologies in specific commercial subsectors. Table 5 shows the results, and Appendix A describes the calculation methodology.

Table 5. Commercial building subsector energy savings from smart building technologies

Building type	Floor area (sq. ft.)	Smart building technology	Average energy consumption (kWh/year)*	Percent savings	Average savings (kWh/year)
Education	100,000	Occupancy sensors Web-based lighting control management system	190,000	11%	20,900
Office	50,000	Lighting controls Remote HVAC control system	850,000	23%	200,000
Hotel	200,000	Guest room occupancy controls	4,200,000	6%	260,000
Laboratory	70,000	Air quality sensors Occupancy sensors Real-time ventilation controllers	980,000	40%	390,000
Hospital	120,000	Lighting controls + LED upgrade Data analytics software package	7,900,000	18%	1,400,000

* Includes both electricity and natural gas (converted to kWh) consumption

We conservatively estimate that individual guest room occupancy controls, which automatically shut off lighting and set back temperatures when guests leave their rooms, can save 6.2% of hotel energy costs. Based on the average energy consumption of a 200,000 sq. ft. hotel, this represents 260,400 kWh in energy savings per year.

Savings in laboratories are particularly remarkable. As described in the case study above, UC Irvine laboratories achieved 60% savings.

Central Vermont Medical Center

Next to food service, hospital buildings have the highest energy intensity of any other building type. For example, on average, a hospital uses nearly three times more energy per square foot than an office building (EIA 2016). Existing hospitals therefore represent a huge opportunity for energy savings; however, they pose greater challenges than most other building types due to heighted caution surrounding patient health and safety.

In response to rising energy costs, Central Vermont Medical Center initiated its Energy Savings Initiative (ESI) in 2010, becoming the first hospital in Vermont to develop an energy master plan. Soon after, it began implementing energy efficiency upgrades. The implementation team decided to include both integrated lighting controls and a SkySpark data analytics platform. The team used the software to implement energy-saving measures such as lowering airflow to unoccupied rooms, which reduced the number of air changes by 70%.

Of the more than $700,000 spent on energy efficiency upgrades, roughly $120,000 was spent upgrading air-side HVAC controls and $34,000 upgrading boiler controls. The hospital expected to save more than $100,000 from these upgrades, which, when coupled with more than $30,000 in Efficiency Vermont rebates, yielded close to a one-year simple payback for the two controls upgrades (CVMC 2014). In total, the hospital has reduced its energy consumption by 28%; in 2016, it earned the ENERGY STAR designation for the first time (CVMC 2016).

Building owners and managers have been more likely to embrace smart building technologies in office buildings and education facilities than in other types of commercial buildings. Microsoft, for example, can afford to retrofit its headquarters because it has substantial upfront capital and a small probability of moving locations; this means that, even if the upgrade does not pay itself off for 10 years, the company will still end up saving money. Barriers in other building types make them less likely to embrace smart building technologies. Hotels may be concerned about compromising occupant comfort by implementing smart HVAC controls. Hospitals are concerned primarily with patient safety, and may view smart building controls as a potential way of spreading pathogens through the air and thereby endangering patients. However our research shows that smart building retrofits can be installed in each of these building types and yield energy savings without compromising health or comfort.

Smart Building Programs

Energy efficiency program portfolios for commercial buildings can incorporate a range of programs to meet various customer needs, including the following:

- Prescriptive rebates for individual efficiency measures
- Custom incentives for more comprehensive or larger-scale retrofit projects
- Demand response and distributed generation programs

Smart buildings technologies and strategies offer new opportunities for enhancing building performance and increasing savings in each of these program types.

PRESCRIPTIVE REBATES

Energy efficiency programs most often offer cash incentives for implementing prescribed measures in existing buildings. These incentives pay part of the purchase cost of efficient equipment upgrades—most usually, lighting retrofits and equipment replacement.

Most smart technologies programs also use cash incentives. By offsetting a portion of the building owner's initial investment in smart technologies, these standard incentives can increase project cost effectiveness and shorten the payback time. Incentives in the early market for emerging technologies could lead to further deployment and market transformation.

Historically, prescriptive programs have not included enabling technologies such as sensors, meters, and controllers, because they do not directly save energy but rather help identify opportunities to do so. Recently, however, some programs have started including these technologies in their portfolios. Examples include coupling metering with refrigeration system improvements and automated FDD capability. Smart technologies commonly incentivized through prescriptive programs include advanced occupancy and vacancy sensors that work with lighting and HVAC controls, photosensors for daylight harvesting, smart power strips and smart plugs, and BMS. Programs may also include incentives for HVAC equipment such as high-efficiency air compressors, super-efficient chillers, and motor variable speed drives. In the smart window technologies market, incentives are offered for passive window shading such as films and screens.

National Grid's commercial building programs offer incentives for advanced lighting controls, high-efficiency air compressors, new BAS, and expanding existing BAS by adding more control points to integrate additional equipment into the system. For advanced lighting controls, the incentive amount is based on the control type, with up to $40 for occupancy and daylighting. A $75-per-sensor incentive is offered for hotel guest room occupancy sensors responsible for temperature setbacks when the room is unoccupied. Incentives from $100 to $200 are also available for 15–75 horsepower air compressors with load or variable speed controls.

The Eversource Mass Save custom retrofit program for large buildings provides incentives that cover up to 50% of the incremental cost of higher-efficiency equipment. For advanced lighting controls, the program offers $60 for remote occupancy sensors, $25 per fixture for daylight dimming sensors, and an additional $20 per fixture for step-dimming systems.

CUSTOM INCENTIVES

Custom incentive programs aim for systems-level efficiency improvements and savings. Performance-based programs, such as pay-for-performance and strategic energy management, target multiple building systems with one building-wide energy-saving goal. Incentives are paid based on verified kWh saved. This model encourages building owners and energy service companies to work together to achieve deeper savings through an energy efficiency measures package—which often includes an EMIS—customized to the individual building. Strategic energy management programs, common to industrial facilities, are gaining in popularity in the commercial sector and offer features beyond energy savings such as management support, occupant engagement, and facility staff training.

Austin Energy, for example, provides incentives for variable frequency drives (VFDs) ($400/kW saved) and other measures ($350/kW saved). For plug load occupancy sensors, the rebate is $25/unit. For retrofit projects, daylight harvesting lighting controls are $275/kW saved and occupancy sensors are $225/kW saved. To qualify for these incentives, the facility must have a smart meter installed and be in operation at least four consecutive hours between 2 p.m. and 8 p.m. during summer weekdays (unless it is a school).

PG&E provides incentives for much of Northern California. For retrocommissioning, incentives cover up to 50% of the cost, for savings of $0.08/kWh, $1.00/therm, and $100/kW peak demand. Eligibility requirements include buildings of at least 50,000 square feet and annual consumption of 1 gigawatt-hour (GWh) or 50,000 therms. VFDs are $140/unit of horsepower, and plug load occupancy sensors are $15 each.

NYSERDA's Commercial Implementation Assistance program, started in March 2016, provides cost-shared, financial support of up to 50% for targeted energy efficiency projects. These projects include clean energy or underutilized technologies and systems-based projects that capture deep savings through an array of energy efficiency measures. The NYSERDA Advanced Building Systems program also funds product research and development projects for emerging efficient building technologies, including those specific to smart buildings. Examples include advanced building automation, CHP, and behind-the-meter distributed generation and energy storage.

In June 2016, NYSERDA launched its Real Time Energy Management (RTEM) program to encourage smart technology implementation in existing buildings by requiring the use of sensor and meter data and data analytics to show real-time building performance. The program requires building owners to acquire an RTEM-qualified vendor for third-party monitoring of building data. Service providers are responsible for installing and managing ICT hardware and software, and program incentives are paid directly to them to offset project costs. Up to $155,000 is available for system installation and five-year service contracts through June 2018, with up to $115,000 available thereafter through June 2021.

Eversource provides incentives to existing small and large commercial buildings through its Smart Energy Solutions program. The program covers up to 50% of installation costs for qualifying measures.

ComEd's Smart Ideas Energy Efficiency program is a comprehensive retrofit program that provides cash incentives for the installation of smart technologies and advanced controls. Under the program, each project implements three to five energy efficiency measures, such as occupancy and daylighting controls for lighting as well as whole-building lighting management systems. The program also offers incentives for BMS, demand-controlled ventilation (driven by occupancy sensor data), advanced controls for RTUs, variable speed drives for motorized equipment, and high-efficiency air compressors.

National Grid's Custom Retrofit program focuses on peak demand reduction and energy savings during the highest cooling and heating periods of the year (June–August and

December–January, respectively). Any type and combination of technologies can be installed to achieve the peak load reduction. National Grid covers either up to 50% of the total installed costs of the new equipment or an amount that buys down the project's cost to a one-year payback.

Southern California Edison is piloting a small commercial retrocomissioning program that incentivizes BAS/EIS installations, paying half the incentive—up to 50% of the installed cost—up front and the other half after a year of M&V.

Baker Sports Complex at Davidson College

In 2010, the Davidson College (North Carolina) Baker Sports Complex participated in Duke Energy's SmartBuilding Advantage® program. An energy assessment of the building found that energy consumption was the same during events as it was during off-peak or unoccupied times. This was because the HVAC and lighting systems operated around the clock.

Despite the campus having an EMIS in place, it could not interface with the Baker Sports Complex due to outdated controls. Through the Duke program, the college received a $75,000 incentive to replace the building's pneumatic controls with digital ones and add a BAS. VFDs were installed on existing air handler units, along with new valves and damper actuators. The building was then able to participate in Duke Energy's demand response program. The program incentive covered approximately 22% of total project costs, helping the project pay for itself in 2.5 years. Continuous commissioning of the building demonstrates that 30% average annual energy savings are being maintained over pre-retrofit energy use (Duke Energy 2013).

DEMAND RESPONSE AND DISTRIBUTED GENERATION PROGRAMS

Some utility demand-side management programs rely on smart meters deployed across their customer base. Smart meter data gives customers access to their building's electricity use in real time and lets them participate in demand response events. Customers can identify demand response opportunities in their buildings to reduce electrical consumption during peak pricing periods.

For Massachusetts customers, National Grid offers net metering and distributed generation interconnection with its electric power grid. Worcester residents and business owners can participate in demand response through National Grid's Smart Energy Solutions program, receiving low off-peak rates or conservation credits for reducing energy use during peak demand periods. The program installed smart meters for every Worcester customer and offers no-cost energy technology toolkits. These toolkits are equipped with a smart plug, smart thermostat, a load control module for connecting high-wattage devices (e.g., water heaters, pool pumps, and room air conditioners), and a platform for monitoring energy use through the smart meter.

Demand response and other performance-based programs go through the EM&V process to determine their value and the effects of individual measures. Traditionally, EM&V compares post-retrofit energy use to a baseline level using utility bill data. Smart meters and cloud-based EMIS can provide continuous EM&V by providing energy data at frequent intervals, such as hourly or by the minute, and thus enable more accurate quantification of energy savings.

Recommendations

New energy efficiency programs that include smart technologies—especially comprehensive programs, as opposed to single-measure or single-system retrofits—could help increase smart buildings deployment. A commitment from manufacturers and trade associations to provide training could also provide for greater understanding and awareness of the technologies and help overcome building operators' lack of preparation to use them.

Prescriptive incentive programs should target small- and medium-sized commercial buildings to increase the uptake of smart technologies. This could benefit owners of single buildings who lack the upfront capital to make improvement investments, as well as tenants who want to reduce their energy bills by installing a single measure, such as a smart thermostat.

Programs can introduce smart technologies into an existing package of prescriptive rebates. Combining the energy savings of established measures (such as LED lighting retrofits) with that of newer technologies (such as daylighting sensors) could result in a cost-effective project. The program could define incentives for each individual measure, with an additional incentive for installing smart measures.

Another way to facilitate smart building techniques is to have incentives pay not only for hardware but also for ongoing third-party software services to monitor and suggest operational improvements to buildings. As noted above, the NYSERDA RTEM program can include up to five years of a service contract.

These approaches could help facilitate deployment of smart technologies that are experiencing a barrier to market entry due to cost or lack of awareness. To ensure the strategy's cost effectiveness, packages of smart measures could be incentivized through a performance-based program and by requiring commissioning. Incentives could cover upfront or first-year costs for remote monitoring and optimization. Cloud-based EMIS would be a natural fit where continuous commissioning is specified following a building retrofit. Also, larger organizations with small- and medium-size building portfolios (e.g., banks and retail store chains) could benefit from a performance-based program approach.

Although several subsectors—such as hospitals and hotels—represent considerable energy-saving opportunities, they have completed and documented relatively few demonstration projects. Likewise, while programs report higher savings when using smart technologies across a portfolio of buildings, few such programs have been taken to completion. We need more smart technology demonstration projects in these subsectors to understand their potential and document actual energy savings.

Program developers who want to proceed with a smart buildings project may require more information than is currently available. The Emerging Technologies Coordinating Council created by the major California utilities provides a forum for sharing results of applied smart technologies research. These and additional studies of smart technology applications are necessary to gain a better understanding of their benefits—especially relating to energy savings—and their limitations. Additional studies specific to individual market segments may help us understand which smart technologies are most cost effective in each commercial building type. ACEEE is planning a 2017 study that will focus on some of the market segments identified above.

The potential of smart commercial buildings is enormous, generating energy and cost savings, upgrading control of building processes, promoting occupant comfort and convenience, and enhancing building value. Program managers are beginning to realize these benefits as they take innovative approaches to integrating smart building technologies into existing and new program offerings. Each individual technology offers its own operational advantages, investment opportunities, and energy savings. Working together in an integrated system, they create something new and more powerful, a smart building that saves energy, operates impeccably, and inspires innovative, cost-effective energy efficiency programs.

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Appendix A. Methodology for Calculating Commercial Building Subsector Energy Savings

Education. To determine the energy savings from installing a lighting control system in a medium- to large-sized education building, we used the 2102 Commercial Buildings Energy Consumption Survey (CBECS) data, which showed that lighting represents approximately 16% of total building energy use in education buildings (EIA 2016). As table 1 shows, web-based lighting controls can save 70% of lighting energy; 70% lighting energy of 16% total building energy is equal to 11% total building energy savings, or nearly 21,000 kWh a year in a building that uses 190,000 kWh annually.

Office. We sought to identify savings from installing lighting controls and cloud-based remote HVAC monitoring and control in a small- to medium-sized office. For this example, we estimate 60% lighting energy savings with lighting controls from table 1, and estimate that lighting contributes to 21% of energy consumption in small buildings (Katipamula et al. 2012), which amounts to 13% building energy savings. Additionally, table 1 shows a 10% energy savings using cloud-based remote monitoring. We obtained average 50,000 sq. ft. office energy consumption of 850,000 kWh by analyzing CBECS 2012 data (EIA 2016); 23% of this value yields 200,000 kWh savings.

Hotel. Using a hotel energy-use breakdown from Green Lodging News, we estimated that lighting represents 12% of whole-building energy use and HVAC represents 46% (Smith 2012). Table 1 shows that hotel guest room controls can save 12–24% HVAC energy savings, so we conservatively estimated 14% savings. The table also shows 16–22% lighting savings from guest room controls. Hotels are typically a combination of guest rooms and common areas, so we discounted 25% of this energy consumption. After using CBECS data to estimate the annual energy use of a 200,000 sq. ft. hotel to be 4.2 million kWh/year, we calculated the total energy savings to be about 260,000 kWh/year.

Laboratory. From our UC Irvine case study, we identified Croul Hall as a representative laboratory for this table. Using the UC Strategic Energy Plan, we determined that Croul Hall saved 117,399 kWh/year after installing smart ventilation controls (Newcomb Anderson McCormick, Inc. 2008). From the case study, we determined that the smart lab retrofit saved 40% of all kWh (Brase 2013), which we calculated to be 290,000 kWh/year. We performed a similar calculation for therms of natural gas, finding that smart ventilation controls saved 9,443 therms/year. After converting to 276,747 kWh, we determined that annual natural gas consumption was 690,000 kWh/year. We combined electricity and natural gas usage to yield 980,000 kWh of energy consumption per year. At a savings rate of 40%, the retrofit saved 390,000 kWh/year.

Hospital. For the hospital example, we used the available data from the Central Vermont Medical Center (CVMC) smart retrofit case study as our basis. The 2014 Energy Action Plan provided key insights for this calculation. From the sheet, we acquired the kWh savings from smart HVAC and lighting systems controls. The team upgraded lighting controls (18,175 kWh savings), and SkySpark software allowed the team to optimize HVAC end-use (200,000 kWh savings), chilled water plant operation (18,175 kWh savings), and HVAC air-side controls (521,731 kWh savings), which combined for a total of nearly 760,000 kWh per year of energy saved. In addition, these projects saved 13,804 gallons of fuel oil, which is equivalent to 606,000 kWh, yielding a total of 1.4 million kWh of energy saved per year. To determine the hospital's total energy consumption, we used the Energy Action Plan guideline of 231 kBtu/sq. ft. (CVMC 2014). CVMC is 120,000 square feet. We multiplied this value by 231 kBtu and converted to kWh to estimate that the hospital uses 7.9 million kWh/year.