Development and Validation of a Low-Cost Building Automation System for Small- and Medium-Size Commercial Buildings

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ABSTRACT

There is overwhelming consensus among scientists that climate change mitigation requires significant reductions in greenhouse gas emissions. Because the building sector consumes over 27% of the energy worldwide, solutions will require significant reductions in building energy consumption. Studies have shown that commercial buildings in the U.S. consume as much as 30% more energy than they should. The operating efficiency of existing commercial buildings can be improved by properly controlling and managing their building systems. In small- and medium-size (<50,000 sf) commercial buildings (SMBs), lack of proper control infrastructure is the primary cause of the excess energy consumption. Many SMBs are historically underserved, and are capital starved. A low-cost building automation system (BAS) can help scale energy savings in this sector while addressing equity. In this paper, we describe development and validation of a low-cost BAS for SMBs using off-the-shelf components. We list the components and associated cost, including labor to install them. This system will be suitable for managing rooftop units, hot water heaters, connected lighting, solar, and storage in an all-electric SMB. The target cost of the BAS is between $0.6/sf and $1/sf with a payback of less than 3 years at an electricity price of $0.1/kWh. This paper also includes case studies that show savings of 20%-25% and demand flexibility of 10%-20% when such a solution is deployed in SMBs.

Introduction

There is overwhelming consensus among climate scientists that climate change mitigation requires significant reductions in greenhouse gas emissions (GHGs), and the overarching conclusion of the United Nations Environmental Panel is that “there is an urgent need for accelerated short-term action and enhanced longer-term national ambition, if the goals of the Paris Agreement are to remain achievable — and that practical and cost-effective options are available to make this possible” (UN 2017). Because the building sector consumes over 27% of the total primary energy worldwide, any solutions to mitigate climate change will require significant reductions in building energy consumption.

In 2018, the end-use (site) energy consumption of the U.S. commercial buildings was over 6.8 quads or 6.8×10^{15} Btu (EIA 2018), which represents almost 17% of the total U.S. primary energy consumption (EIA 2022). Although the U.S. population is about 4% of the world population, the commercial buildings in the U.S. account for almost 29% of the total world commercial building consumption. If we are to reduce the GHG emissions associated with buildings to mitigate climate change, we must significantly improve the energy efficiency (EE) of our commercial building stock. Traditionally, reductions in energy consumption in commercial buildings have been through improved building codes and higher manufacturing standards for the systems used in the buildings (Thornton et al. 2011; Halverson et al. 2014). Although this approach will reduce energy consumption, it only applies to new construction or major renovations and will not significantly impact existing commercial building consumption. We believe that the operating efficiency of the entire existing commercial building stock can be improved by properly controlling and managing the building systems.

Several studies have shown that commercial buildings in the U.S. consume as much as 30% more than they should (Brambley and Katipamula 2009; Claridge et al. 2000; Fernandez et al. 2012, 2014, 2017a, b; Katipamula et al. 2021). Lack of proper control infrastructure in SMBs and our inability to properly control and manage the building systems in large commercial buildings are the main causes of the excess energy consumption. Therefore, cities such as New York (NYC 2017) and Seattle (Seattle 2016) have adopted mandates that require commercial buildings to be "re-tuned" periodically. Seattle's mandate targets measures that would save significant energy with low or no implementation cost and simple paybacks of less than 3 years. The City of Philadelphia (Philadelphia 2019) adopted a mandate like Seattle's. A similar 2009 mandate by New York City includes requirements for documenting or implementing appropriate controls for 15 different building systems and training building operations and maintenance staff. Although these initiatives will significantly reduce energy and emissions, they are mostly focused on large commercial buildings (>50,000 sf).

In this paper, we focus on showing how to cost-effectively improve the operating efficiency of SMBs. First, we highlight why we should focus on SMBs. Then, we describe a low-cost building automation system (BAS) reference design suitable for SMBs that is built using off-the-shelf components, including cost estimates. Next, we describe the software system and the Internet of Things (IoT) platform used to deploy the low-cost controls, followed by documenting benefits of deploying central controls in SMBs and a section that estimates the potential energy and cost savings from widespread deployment of control systems in an SMB. We conclude the paper with the discussion section.

Why Focus on Small- and Medium-Size Commercial Buildings?

According to the latest Commercial Buildings Energy Consumption Survey (CBECS), there are over 5.9 million commercial buildings in the U.S. (EIA 2018). As shown in Table **1**, most commercial buildings (over 94%, representing almost 50% of the total floor space) are relatively small (<50,000 sf). These buildings consume about 45% of the total energy and are responsible for 49% of total expenditures associated with all commercial building energy consumption. Many of these SMBs use rooftop units (RTUs) for heating, cooling, and ventilation (EIA 2018).

Small commercial buildings are diverse, and over 80% of these buildings lack BASs (EIA 2018). Some end-uses (e.g., RTUs) in these buildings are controlled by dedicated thermostats. However, if the building has multiple thermostats, they generally are not coordinated, the set points may not be "optimal," for comfort and the schedules configured in each thermostat are often not synchronized with each other or the overall building occupancy patterns. In most cases, even if the buildings have programmable thermostats, they are unlikely to be programmed correctly (Malinick et al. 2012). In addition, other major end-uses, like interior and exterior lighting and exhaust fans, are not generally controlled in an automated way. Therefore, significant energy is wasted in these buildings (Katipamula et al. 2012). Although the low-cost control system would benefit any SMB served by RTUs, after reviewing consumption patterns of the 20 different CBECS building types (EIA 2018), we believe the following SMB types will benefit the most: small office; education; retail, including strip mall, enclosed malls, and retail other than malls; outpatient; and religious worship and services. Energy consumption associated with the heating, ventilation, and air conditioning (HVAC) end-use is nearly 40% of the building's total energy use in those with RTUs. In total, controllable loads including HVAC systems, water heating, lighting, and refrigeration account for almost 80% of total energy consumption of these buildings (EIA 2018).

Table 1. U.S. Commercial building characteristics (EIA 2018).

	All buildings	All buildings < 50,000 sf	
Number of buildings	5,918,211	5,558,948	94%*
Total area [million square feet]	96,527	48,033	50%
Total energy consumption [trillion Btu]	6,789	3,055	45%
Total expenditures [million $]	141,278	68,558	49%

*Value in parentheses is percent of total commercial building stock.

While there are several reasons why these SMBs lack proper control infrastructure, the primary reason is cost. The cost includes the first cost of material and labor for installation and subsequent on-going maintenance costs. A second reason is lack of awareness of the potential benefits from installing central controls or a BASs, which is a major impediment for widespread deployment of these systems in SMBs. For many buildings, energy cost reductions from operational improvement may not justify the addition of proper controls. However, if the same control infrastructure is leveraged to provide additional services beyond improving EE, the owners/tenants of these buildings may find it more compelling. Many SMBs can provide grid services (GSs) because they have end-uses that are demand flexible to support the grid with increased penetration of distributed generation, much of which is from variable renewable generation. The third reason is the split-incentive; many SMB owners may not be occupants in these buildings, so they lack an incentive to invest in proper control infrastructure. This paper provides solutions to the first two challenges, while the third challenge is being addressed by many states and cities who are mandating discloser ordinance and periodic retro-commissioning of the buildings. With awareness of potential savings, low-cost BAS solutions, and mandates, the owners will eventually change their attitude and invest in building controls.

Low-Cost BAS Reference Design for SMBs

The high cost associated with the deployment of building controls and third-party monitoring and diagnostic tools has been recognized as one of the major challenges that prevent the large-scale adoption of these applications in SMBs. Monitored data from case studies have shown that lack of proper energy management in these buildings results in excess energy use between 20% and 25% (Katipamula et al. 2012). A detailed national simulation study showed that with proper energy management, the energy savings can be between 10% and 45% of energy consumption, based on building type and location (Fernandez et al. 2017a). Energy management features include managing the RTU heating and cooling set points, schedules, setbacks, and optimal start. Studies have also shown that improving demand flexibility of these buildings will yield additional cost savings for the building owner. Therefore, as part of a project funded by the Building Technologies Office of U.S. Department of Energy, we created a reference design for a low-cost control system for SMBs that would overcome some of the challenges. This design includes (1) a list of low-cost, interoperable, off-the-shelf hardware components; (2) fully validated EE and GS applications to realize operational efficiency and demand flexibility in SMBs; and (3) a fully validated, easy-to-deploy process to lower deployment and ongoing operational costs. The low-cost supervisory controller for SMBs (SC-SMB) includes a set of hardware and software to realize the EE and GSs. In this section, the reference hardware design and necessary software system are described.

Reference Building

The SC-SMB reference design is described using a 10,000-sf reference office building with six RTUs, a hot water (HW) heater with an ANSI/CTA-2045 (ANSI/CTA-2045 2021) controller, connected lighting, battery storage, electric vehicle charging, and solar photovoltaics, as shown in Figure 1. The low-cost control system will also integrate a whole-building electricity meter, which is required if the building is providing GSs.

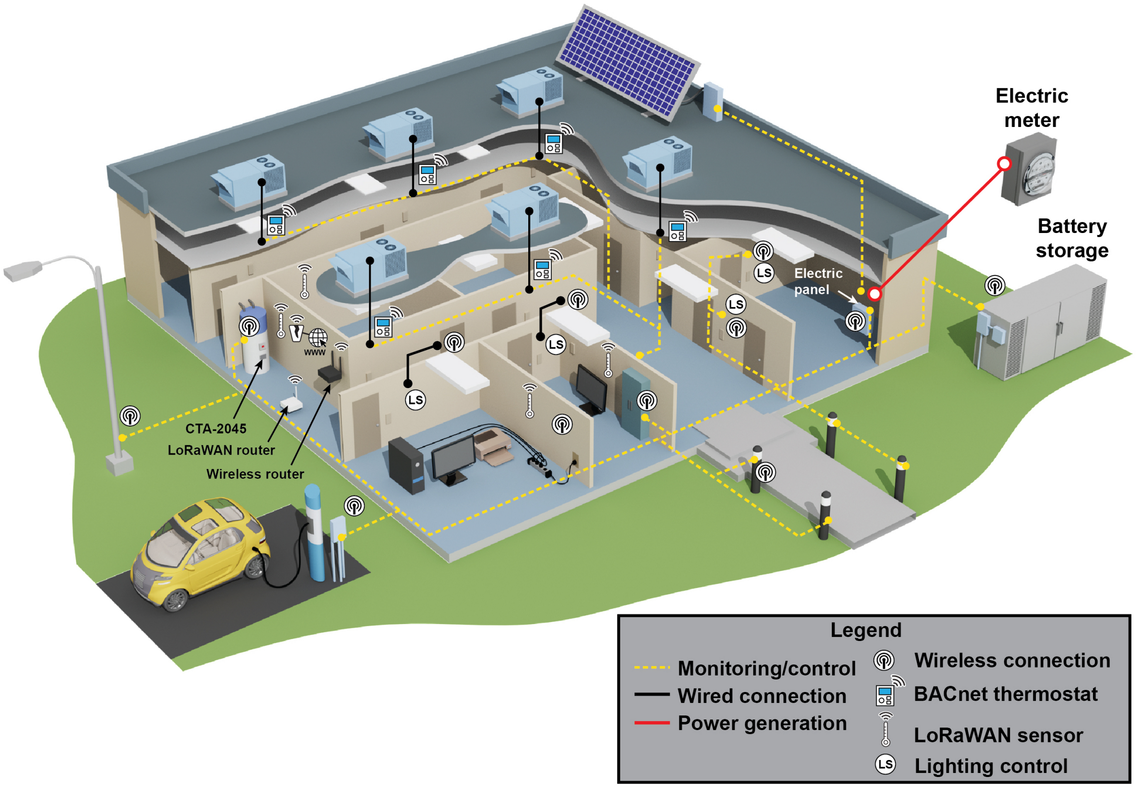

Figure **1**. Potential deployment of the SC-SMB system on an edge Eclipse VOLTTRON™ device. (Illustration by Mike Perkins | PNNL.)

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Reference SC-SMB System

Initially, the low-cost control system will control RTUs, HW heaters, and connected lighting. BACnet-WiFi (BACnet 2016) based connected thermostats to manage/control RTUs and the CTA-2045 interface for HW heaters with CTA-2045 controller are used. Most CTA-2045 interfaces (e.g., SkyCentrics, eRadio) and connected lighting products use proprietary communication and require a vendor-provided application programing interface (API) to manage the device. The SC-SMB system can be easily extended to manage other end-uses (e.g. energy storage).

Most RTU thermostats can only monitor the temperature of one or two spaces, while an RTU serves several spaces with varying comfort needs. To improve comfort, the SC-SMB system will include wireless temperature sensors in all spaces. Figure 2 shows an example floorplan where the RTU thermostat is in one space with an additional wireless temperature sensor in each of the spaces served by the RTUs. Because the RTU thermostats do not allow this many temperature inputs, wireless LoRaWAN® (LoRaWAN 2023) temperature sensors will be integrated into the supervisory controller via the LoRaWAN aggregator, which also supports BACnet/IP. The supervisory controller will average the temperature sensors across all spaces served by the RTU to control more effectively.

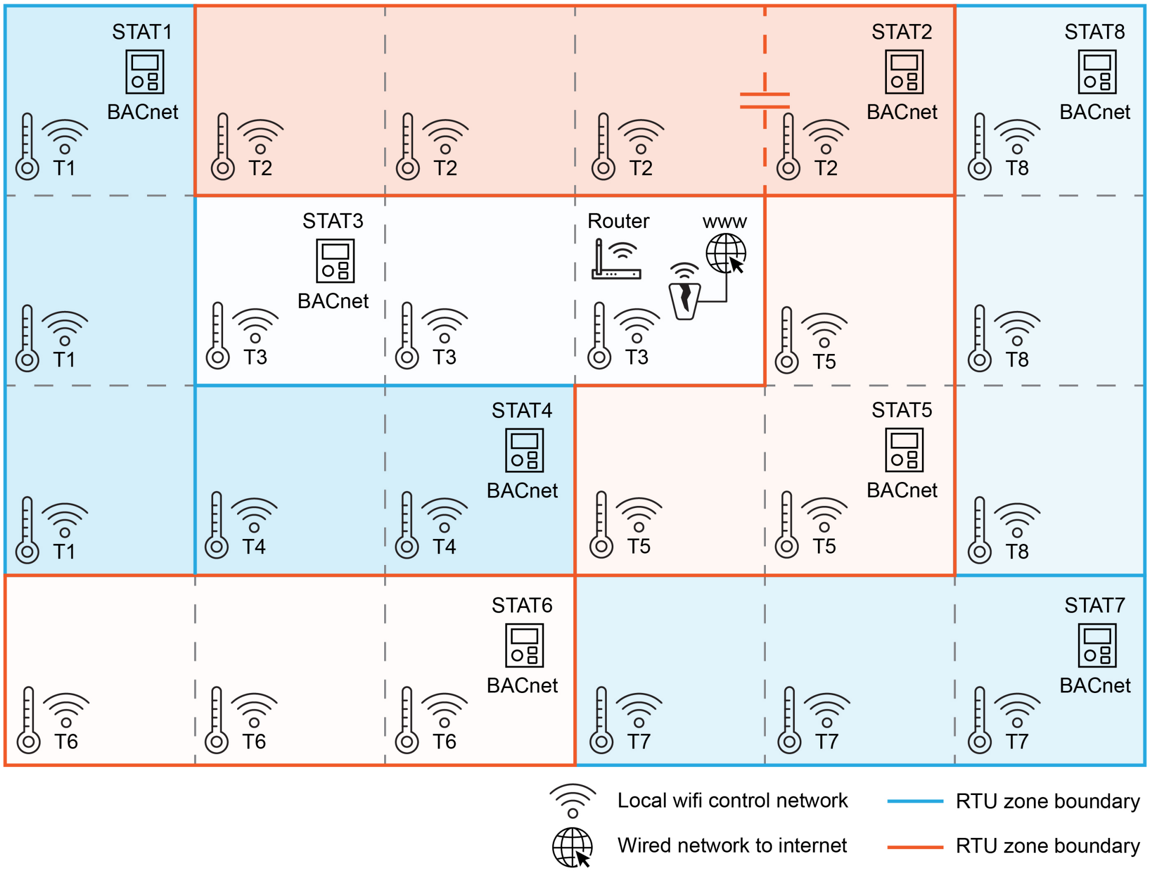

Figure **2**. Example floorplan served by multiple RTUs. Although typically only the thermostat zone temperature is used to control the RTU, the SC-SMB system will average temperature measurements from all spaces served by the RTU and use that to control the RTU.

The SC-SMB reference system consists of the supervisory controller or the platform, and hardware components. The SC-SMB system will provide a means to integrate building systems and allow supervisory control algorithms to indirectly control (changing set points, etc.) the systems either to improve operating efficiency or to deliver GS. The supervisory controller is the primary hardware component or an edge computing device (e.g. Intel NUC®) that will integrate all building systems and host the EE and GS applications. To execute the EE and GS algorithms, the supervisory controller must meet certain computing requirements.

Integrating building systems via wireless communications is significantly less costly and less time intensive because integration primarily relies on configuration of the communication protocol rather than wiring. Standard communication protocols, such as BACnet and LoRaWAN, are used to decrease deployment cost and increase interoperability. A wireless router is used to create a private wireless network to integrate all building systems that need to be monitored and controlled, and a cellular modem is used for external internet connection. Before setting up a local wireless network, it is essential to plan the coverage for the network, access device requirements and network security. Although network security is critical, it is not covered in the paper.

To provide GS, real-time access to the data on whole-building electricity consumption is essential. Whole-building electricity meters measure the incoming three-phase current and voltage to determine the building's electricity consumption. Many existing SMBs could have a utility-installed automated meter. These meters typically record electricity consumption at a high resolution (15-minute or hourly). However, most utilities restrict third-party access to the electricity consumption data in real-time because these meters are installed for billing purposes. Therefore, in most cases, an independent whole-building meter will have to be installed and integrated with the SC-SMB platform. The preferred meter will wirelessly integrate with the SC-SMB platform using either BACnet or Modbus protocol. Integration of the whole-building meter with the SC-SMB system will allow the platform to monitor the consumption at any frequency; however, the preferred monitoring frequency is 1 minute.

Table 2 lists the hardware components, their cost, and the cost to integrate each with the SC-SMB system. After reviewing over two dozen BACnet Wi-Fi thermostats and testing six in the lab, we selected two, with one thermostat priced around $100 (Temco) and another at $450 (Schneider). Although both thermostats provide all the features we need, the Temco thermostat must be programmed while the Schneider is fully programmed. The total hardware cost for supporting just the EE measures is $2,160 with Temco and $4,200 with Schneider, and the total labor for installing the hardware is $3,350. The same infrastructure can provide GS as well. For GSs, we will also need a whole building electric meter and CTA-2045 interface; therefore, the total hardware cost to provide GSs is $1,500 and the installation cost is $1,950. The total hardware, deployment, and engineering cost to integrate these components into a working SC-SMB system in the field that would provide both EE and GSs is $8,960 with Temco and $11,000 with Schneider.

Table 2. List of hardware components and cost to deploy and integrate them in the field.

DER/Meter	Controller/Interface	Number	Cost	Notes	Deployment and engineering cost
IoT edge device	Intel NUC - Intel Celeron – Intel i3 processors; 8–16 GB RAM; SSD; Wi-Fi onboard	1	< $400		Preparing edge devices – 1 to 2 hours (at $150/hr), configuration of router and wireless thermostats – 4 to 6 hours (at $150/hr), and configuration of cellular modem – 1 to 2 hours (at $150/hr). Total: $1,500
Wireless router	Generic (e.g., TP-Link AX 5400)	1	< $200		
	TP-Link AX1800 WiFi 6 Extender Internet Booster	2	<$150		
Cellular modem	Verizon, AT&T, or T-Mobile, etc.	1	$150	External internet communications	
RTU	Temco Controls (Tstat10-W); Each BACnet Wi-Fi is $110	6	$660		Replacing existing thermostats with wireless thermostats – 1 hour each (at $150/hr). Total: $900
	Schneider Electric SE8650U0B00	6	$2700*		
Wireless temperature sensors	ORNL-LoRaWAN Sensor; assuming each RTU is serving six office spaces, so will require five additional sensors at < $10 each	30	$300		Installation and commissioning wireless sensors – 8 hours (at $100/hr). Total: $800
LoRaWAN-BACnet gateway	Generic; this gateway will aggregate the 30 wireless temperature sensors and present them as BACnet Wi-Fi devices to the IoT platform	1	$300		Installation and commission – 1 hour (at $150/hr). Total: $150
Hot water heater	Assuming the water heater already has a CTA-2045 controller	1	$200		Configuration of adding a CTA-2045 interface – 2 to 3 hours (at $150/hr). Total: $450
Connected lighting	Assuming that the control interface for the connected lighting fixtures is via vendor-provided API	NA	NA		Configuration of lighting fixtures – 4 hours (at $150/hr). Total: $600
Whole-building electricity meter	Shark Power meter Modbus Wi-Fi Current transformers	1	$1,100 <$200		Installation of power meter – 4 hours (at $150/hr); configuration of BACnet gateway – 2 hours (at $150/hr). Total: $900
Total			$3,660/5,700*		$5,300

*If we use Schneider thermostat as an alternate option to Temco thermostat

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Autonomous Energy Management Software System

With minimal infrastructure upgrades, we can optimize the building operations for multiple objectives, including reduced energy costs and improved occupant comfort, and enable automated load shaping based on the preferences and choices of the building operator. The supervisory controller will act as the hub for all monitoring and control decisions for the building. The Autonomous Energy Management Software (AEMS) system was developed and tested in the laboratory to deliver both EE and GSs.

It will initially support RTUs, HW heaters, and connected lighting, and can be extended in the future to manage electric vehicles, solar inverters, and energy storage devices. The AEMS system user interface will display all relevant information and allow users to easily modify set points and schedules. Monitoring capabilities will include graphics of the RTU and HW heater that display current operations, trending of points for troubleshooting, and alarms with adjustable thresholds. The AEMS system will constantly monitor the thermostats and correct any local set points and schedules overrides with the values entered using the web interface.

If communication to the supervisory controller is lost, each field device will be configured to default to onboard set points. The user interface will also display communication status with all field devices. If communication is lost, an alarm will be triggered on the user interface, and points originating from the field device that is no longer communicating will be shaded to indicate they are no longer displaying updated information. The AEMS system's EE features will optimize RTU set points, schedules, setbacks, and optimal start.

- **Manage Set Points**: The AEMS system can be set to a "desired" occupied period set point for each RTU and to automatically create desired dead-band values (i.e., the difference between heating and cooling set points), which are typically 4°F, and enforce the local heating and cooling set points. If the desired occupied period set point is 72°F and dead band is 4°F, the occupied heating and cooling set points will be 70°F and 74°F, respectively.
- **Manage Setbacks**: The AEMS system allows for configuration of night and unoccupied period setbacks. For heat pumps (HPs) with electric backup, the best (lowest cost) solution may be to run the RTU without a setback. The AEMS system recommends conditions under which the users should not use setbacks or automatically disable unoccupied heating set points during cold winter mornings to avoid creating significant peak electricity demand.
- **Manage Schedules**: The AEMS system allows setting weekday, weekend, and holiday schedules. The user can set schedules for each day of the week, pick holidays from a list, create schedules, or create custom holidays and add schedules. The AMES system also allows for creation of temporary schedules to override normal schedules for special events.
- **Optimal Start**: The AEMS system supports optimal start sequences that adapt to both indoor and outdoor conditions. The optimal start sequences work on individual RTUs and coordinate start times of other RTUs in the building.

For GSs, the AEMS system controls RTUs, HW heaters, and connected lighting. RTUs and HW heaters are controlled by changing the temperature set points of these devices. The control decisions are made using the Intelligent Load Control (ILC) algorithm (Kim et al. 2016, 2020; Kim and Katipamula 2017), which is integrated into the AEMS system. Because SMBs use over 20% of electricity generated in the United States and because RTUs, HW heaters, and connected lighting end-use loads are demand flexible, they can be managed to mitigate some of the imbalance in supply and demand caused by variable distributed renewable generation. Control of these loads has been shown to provide demand relief in response to grid needs. These loads can also be managed to limit electricity demand when a demand charge is a significant fraction of the total energy cost or when a building must maintain a certain level of demand in response to changes in the price of electricity over time. The ILC application can help manage building loads while also mitigating service-level excursions (e.g., occupant thermal and visual comfort, minimizing equipment ON/OFF cycling) by dynamically prioritizing available loads for curtailment using both quantitative (deviation of zone conditions from set point) and qualitative rules (type of zone). ILC leverages several services from the VOLTTRON platform and coordinates with external signals (including markets) to make local device control decisions. For more details on ILC and its use, refer to Kim et al. (2016, 2020) and Kim and Katipamula (2017).

Eclipse VOLTTRON Internet-of-Things Platform

VOLTTRON is an open-source distributed control and sensing platform that is designed for integrating buildings with the power grid (Figure 3). VOLTTRON connects devices, agents/applications in the platform, agents in the Cloud, and signals from the power grid. VOLTTRON provides an environment for agent execution and serves as a single point of contact for interfacing with devices (building HVAC systems, building electrical systems, power meters, etc.), external resources, and platform services such as data archival and retrieval. VOLTTRON applications are referred to as agents since VOLTTRON provides an agent-based programming paradigm to ease application development and minimize the lines of code that need to be written by domain experts such as buildings engineers. VOLTTRON provides a collection of utilities that simplifies agent development. VOLTTRON is used as an SC-SMB deployment platform to run the AEMS system and manage RTUs, HW heaters, and connected lighting.

Benefits of Installing an SC-SMB System in a Building

Significant reductions in energy consumption and cost savings are possible from operating SMBs properly. SMBs can also provide GSs to further reduce their energy cost burden. To quantify the potential savings, a central control solution, like the one described in the previous section, was deployed in three identical 20,000-sf office buildings in Eastern Washington. The deployment included an upgrade from a standalone thermostat control design to a centralized control design. This case study discusses the reasons for upgrading the controls, the energy performance of one of the three buildings (Building 4) before/after the controls upgrade, and the impacts to building occupants before and after the controls upgrade. It will also highlight installation details, including the “before” and “after” energy patterns of Building 4, the efforts to improve EE (consumption, demand, and overall energy costs), and how the same control infrastructure was used for GS to further reduce energy costs.

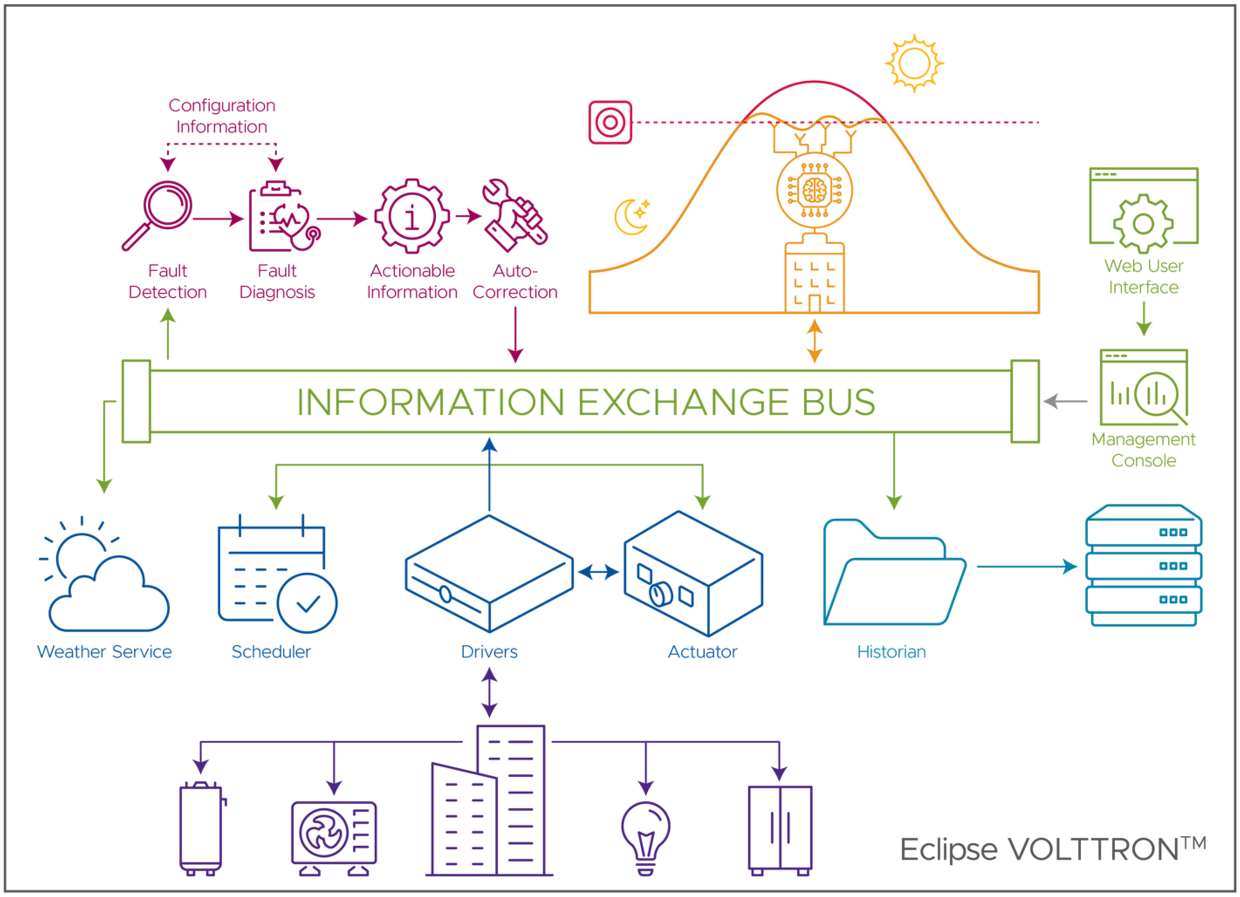


Figure **3**. Schematic of the VOLTTRON platform.

Building Description and Before and After Operations

The office buildings in the case study were built in the late 1970s, and each has a similar footprint. The major building characteristics for Building 4 include:

- 20,530 sf, single story on concrete slab (designed for 80 and 90 occupants).
- 36 perimeter offices, 44 interior offices, 3 conference rooms, 1 lunchroom, 1 lobby, 4 bathrooms, 2 LAN rooms, and 1 mechanical/electrical room.
- The window/wall ratio is approximately 17% and the wall perimeter is 680 linear feet.
- 11 RTUs (10 HPs and one air-conditioner; HPs include electric backup heating).

Table **3** compares the operations of the RTUs before and after the controls upgrade.

Table 3. Operation of RTUs before and after controls upgrade for Building 4

Before	After
Thermostats programmed but easily changed by occupants	Thermostat hardwired to central controller
NA	Wireless sensors (4 to 6 per RTU) added to improve comfort (averaged sensor values)
No holiday scheduling	Eight holiday schedules added
No optimal start	No optimal start, but when the outdoor air temperature falls below 25°F, the RTUs run 24x7
No networking or central monitoring	Can be centrally monitored
Schedules set to start too early (3 to 5 a.m. start) and too late (7 to 9 p.m. stop)	Schedules tightened (staggered start times and 6 p.m. stop times) Monday through Friday
Weekend scheduling configured for 4 to 8 hours (just in case)	No weekend operation
Some lighting controls with time clocks	No change
Exhaust fans run 24/7	No change
No ability to monitor, trend, or perform diagnostics from a central location	Remote diagnostic and data trending added

In addition to the changes listed in Table **3**, the following operational changes were made:

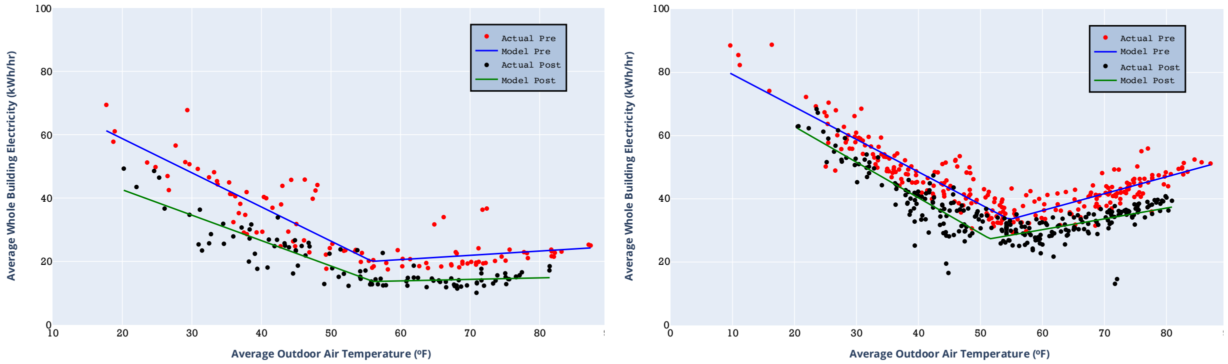
- Created a "master" set point for each RTU that automatically creates the desired dead band (typically 4°F) and tells the thermostat what the local heating and cooling set points should be.
- Automatic low-temperature override of the RTU to occupied mode; when the outdoor air temperature falls below 25°F, the RTUs run continuously. This helps eliminate operator overrides that occur when RTUs do not adequately recover office space temperatures on cold winter mornings.
- RTUs serving perimeter zones activate first to attempt to limit the peak electricity consumption, especially on cold winter mornings.
- Automatic night low and high limits maintain spaces no lower than 64°F and no higher than 82°F.
- Added a whole building electricity (WBE) meter and integrated it with the central controller.

Cost of Controls Upgrade

The total installed cost of the controls upgrades (hardware and labor) is $20K: 1) thermostats ($250 each x 10 thermostats) = $3K; 2) wireless sensors ($50 each x 60 sensors) = $3K; 3) wireless sensor integrator with repeater (1) = $1K; 4) network infrastructure (switch, network controller, network integration, cabling) = $6K; and 5) labor (design/engineering, install new thermostats, network infrastructure) = $7K.

Energy and Cost Savings and Comfort Improvement in Building 4 from Central Controls

Empirical models were developed for weekdays and weekends using 12 months of data on historical WBE consumption, or pre-controls upgrade data. Models were also developed using 12 months of post-controls upgrade WBE consumption data. Figure 4 compares the daily WBE consumption for the pre- and post-controls upgrade periods. The symbols present the actual pre- and post-controls WBE consumption and green and blue lines present the pre and post models, respectively. Energy and cost savings from the control upgrade for Building 4 are summarized in Table 4. The actual savings were computed by comparing estimated baseline consumption for the post-controls upgrade period and the actual measured consumption during the same period. The normalized savings are modeled savings that are computed by comparing the estimated baseline consumption using typical metrological year (TMY) weather data and estimated post-controls consumption using a post-control empirical model with TMY data.



(a) Weekends (b) Weekdays

Figure **4**. Comparison of daily pre- and post-controls upgrade to whole building electricity consumption in Building 4: (a) weekends and (b) weekdays.

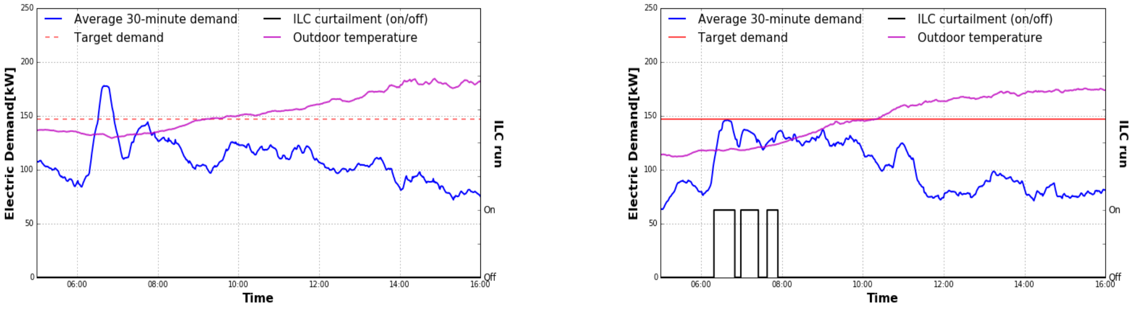
Table 4. Electricity consumption and cost savings for Building 4 from controls upgrade.

	Post 12 Months	Normalized (TMY)
Projected baseline and normalized baseline energy consumption (kWh/yr)	342,798	346,202
Projected baseline and normalized energy cost ($/yr) (@$0.06/kWh)	20,569	20,772
Actual post and normalized post energy consumption (kWh/yr)	273,174	275,541
Actual post and normalized post energy cost ($/yr)	16,390	16,532
Actual post and normalized energy savings (kWh/yr)	69,624	70,661
Actual post and normalized energy cost saving ($/yr)	4,179	4,240
Percent savings compared to baseline (%)	20.3	20.4

In addition to energy savings, there was significant improvement in occupant comfort. Previously, the RTU was controlled with the zone temperature from one space, although the RTU was serving multiple spaces. The new controls used an average of multiple space temperatures to control an RTU. This significantly improved comfort across all spaces served by the RTU.

Peak Load Reductions

Deploying central controls not only improves SMB operational efficiency, but also provides an opportunity to reduce demand charge. Most of SMBs with HPs will also have electric backup and might set back heating set points during unoccupied period. Often, when the building warm-up starts, backup electric heaters on these HPs will be engaged. This creates a significant (>100%) increase in peak power consumption. Figure 5 shows the 30-minute rolling average peak electricity demand in a 25,000-sf office building that is served by HPs with electric backup. When the RTUs start in the morning, the peak electric demand is 175 kW (Figure 5a), which is almost 50 kW higher than the rest of the day. By coordinating the operations of HPs and managing the peak using the ILC application, the peak was held under 150 kW (the next day). Although not shown in this figure, the zone service levels were still within the desired comfort levels when the peak load was being managed. Based on several tests like the one shown below, 20% of the winter peak electricity consumption can be eliminated without impacting the service levels, which will also reduce demand charges by 20%. By optimizing the setbacks, it is possible to reduce the peak even more; although it might result in additional energy consumption, the overall energy cost will be lower. Peaks during winter are significantly higher but for short durations (< 1 hour); peaks during summer afternoons are not as high as winter peaks, but they persist longer (up to 4 hours). The AEMS system will also be able to manage summer peaks and allow buildings to participate in utility demand response programs, creating additional revenue for the building owners/occupants.



(a) (b)

Figure **5**. 30-minute rolling average peak electric demand (in blue) in a 25,000-sf building with heat pumps with electric backup: (a) unmanaged peak and (b) managed peak; the purple line shows the outdoor air temperature.

Technical Potential of Energy Savings

The target market for the control solution is all SMBs, especially the eight building types that were previously identified. These buildings consume over 3,055 trillion Btu of site energy (Table 1). Therefore, on average, if the control solution results in a 20% reduction in energy consumption, the total technical potential for savings relevant to the target market is approximately 611 trillion Btu. The energy savings will eliminate corresponding GHG emissions associated with the built environment. In addition, by managing peak consumption, there is a potential of savings 20% of demand charges in SMBs.

Discussion

Mitigation of climate change requires significant reductions in GHGs from the built environment because it represents almost 40% of the total U.S. energy consumption. Small- and medium-size commercial buildings constitute 94% of the U.S. commercial building stock and 45% of total commercial building consumption. Most of these buildings lack proper control infrastructure and operate inefficiently. In this paper, we showed how we can remedy the current state by installing central controls and managing the building systems efficiently, resulting in WBE consumption reductions between 20% and 25% and reducing the peak electricity consumption by 10% to 20% without significantly impacting the service levels in the building. Many SMBs are historically underserved, and are capital starved. Although we did not propose direct solutions to alleviate this situation, developing a low-cost BAS can help these building owners lower their energy burden. The AMES system currently can manage RTUs, HW heaters and connected lighting, but it can be easily extended to manage storage (electric and thermal) systems and monitor solar generation.

Although there are several reasons for the current state of these buildings, the primary reason is lack of cost-effective central controls. Therefore, we created a reference design that centrally controls and manages RTUs, HW heaters, and connected lighting using off-the-shelf components and the open source IoT platform, VOLTTRON. The normalized (by area) cost to deploy the reference design in a 10,000-sf prototype office building with six RTUs with the low-cost thermostat option will be between $0.55/sf (EE) and $0.75/sf (EE + GS). With the higher cost thermostat, the cost will be between $0.9/sf (EE) and $1.1/sf (EE + GS). For most SMBs with a blended (kWh + demand charge) utility cost of $0.1/kWh, the simple payback will be less than 3 years. If the SMB provides GSs or reduces their peak electricity demand, the payback can be less than 3 years. The payback periods can be even shorter (< 2 years) in many regions of the country where the utility prices are significantly higher than $0.1/kWh with high demand charges and where there are utility incentives to install building controls.

In conclusion, widespread adoption of the proposed solution in SMBs can address many state and city goals for mitigating climate change while also lowering the energy cost to the customers. The technical potential energy savings could be 611 trillion Btu/year with a corresponding reduction in GHG emissions.

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