PNNL-34399

Design Requirements and Hardware Specification for the Low-Cost, Interoperable, User-Centric, Supervisory Controller Kit for Small and Medium Size Commercial Buildings

May 2023

Carolyn Goodman, Srinivas Katipamula, and Robert G Lutes, Pacific Northwest National Laboratory
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Prepared for the U.S. Department of Energy
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Pacific Northwest National Laboratory
Richland, Washington 99354

Abstract

Commercial buildings are responsible for approximately 20 percent of the total United States energy consumption and greenhouse gas emissions. Over 85 percent of these buildings lack building automation systems to manage the various building systems they have. Many of these buildings are small (< 50,000 square feet), underserved, and use rooftop units (RTUs) for heating, ventilation, and air-conditioning needs. Because these buildings lack proper control systems, they have several operational deficiencies that lead to excess energy consumption. Studies have shown that managing the RTU's heating and cooling setpoints, schedules, setbacks, and optimal start times can result in 20 to 25 percent reduction in electricity consumption in small and medium commercial buildings (SMBs). In addition, improving the demand flexibility of these buildings will result in additional cost savings for the building owner.

To address the needs of the SMBs, the Department of Energy's Building Technologies Office approved two projects: (1) development of an autonomous energy management software (AEMS) system, and (2) development and validation of a low-cost, user-centric, supervisory controller. The first project started in FY 2022 and is a Cooperative Research and Development Agreement (CRADA) with Pacific Northwest National Laboratory (PNNL) and Intellimation LLC. The primary goal of this CRADA project is to develop and validate an AEMS system that will continuously optimize SMB operations by minimizing energy consumption and cost while providing a solution for maximizing decarbonization benefits from electrification of these buildings. The work will leverage the vast experience of PNNL research and development staff who have over two decades of experience in developing and successfully transferring software technologies to the private sector. This solution will be jointly developed with Intellimation, a company that plans to use it to scale their building energy efficiency (EE) and grid services offering. Widespread deployment of the AEMS system will improve the EE and demand flexibility of the building commercial building stock. It should also support cities and states in meeting their climate change mitigation goals.

The second project will design, develop, test, and validate a low-cost, interoperable, user-centric, retrofit supervisory controller kit (SC-SMB) that can be used to continuously optimize energy consumption and deliver demand flexibility of SMBs, including all-electric buildings, and provide a means for maximizing decarbonization benefits. This document describes the various hardware elements that will be part of the SC-SMB system, how the features will be integrated, and cost targets for the features. The initial reference design of the SC-SMB system is planned for September 2023. The final release is planned for December 2025. Section 2.0 of the report documents the relevant building types that the SC-SMB system is suitable for. 3.0 documents the various components and features of the SC-SMB system. Features to make deployment easy and scalable are described in Section 4.0. Testing and validation of the SC-SMB system is described in Section 5.0. The planned next steps are described in Section 6.0, and references are listed in Section 7.0.

Acknowledgments

The authors acknowledge the Building Technologies Office of the Department of Energy's Office of Energy Efficiency and Renewable Energy for supporting the research and development effort. The authors also acknowledge the valuable guidance from Dr. Brian Walker, the Technology Development Manager at the Building Technologies Office. The authors also acknowledge Ronald Underhill for peer-review comments, and Catherine L Himes for editing the report.

Acronyms and Abbreviations

API	application programing interface
AEMS	autonomous energy management system
BACnet	building automation and control network
BAS	building automation system
BTO	Building Technologies Office
CTA	Consumer Technology Association
DER	distributed energy resource
DOE	Department of Energy
EE	energy efficiency
GHG	greenhouse gas
GS	grid service
HP	heat pump
HVAC	heating, ventilation, and air-conditioning
I/O	input/output
IoT	Internet-of-Things
MPC	model predictive control
ORNL	Oak Ridge National Laboratory
PNNL	Pacific Northwest National Laboratory
PV	photovoltaic
ROM	reduced-order model
RTU	rooftop unit
SC-SMB	retrofit supervisory control kit
SMB	small and medium commercial buildings
TCP/IP	transmission control protocol/internet protocol
WSN	wireless sensor network

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1.0 Introduction

Commercial buildings are responsible for approximately 20 percent of the total United States energy consumption and greenhouse gas (GHG) emissions. Over 85 percent of these buildings lack building automation systems (BASs) (EIA 2018). Many of these buildings are small (< 50,000 square feet), underserved, and use rooftop units (RTUs) for heating, ventilation, and air-conditioning (HVAC) needs. Because these buildings lack proper control systems, they have several operational deficiencies that lead to excess energy consumption. Reducing the excess energy consumption associated with these buildings will result in energy and cost savings to the building owner, as well as significant GHG emission reductions. 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 percent (Katipamula et al. 2012). A detailed national simulation study showed that with proper energy management, the energy savings can be between 10 and 45 percent of energy consumption, based on building type and location (Fernandez et al. 2018). In addition, improving the demand flexibility of these buildings will result in further cost savings for the building owner.

In 2021, the Department of Energy's (DOE's) Building Technologies Office (BTO) approved a project to address the needs of small and medium commercial buildings (SMBs). The project is led by Pacific Northwest National Laboratory (PNNL) with Intellimation LLC as the cooperative research and development agreement partner. The primary goal of the project is to develop and validate an autonomous energy management software (AEMS) system that will continuously optimize small commercial building operations by minimizing energy consumption and cost, providing a solution for maximizing decarbonization benefits from electrification of buildings. This solution will be jointly developed with Intellimation, a company that plans to use it to scale their building energy efficiency (EE) offering. Widespread deployment of the AEMS system will improve the EE and demand flexibility of the building commercial building stock. It should also support cities and states in meeting their climate change mitigation goals.

In FY 2022, BTO also approved another project focused on SMBs. This second project will design, develop, test, and validate a low-cost, interoperable, user-centric, retrofit supervisory controller kit (SC-SMB) that can be used to continuously optimize energy consumption and deliver demand flexibility of SMBs, including all-electric buildings, and provide a means for maximizing decarbonization benefits. While the first project is software focused, the second project involves developing a reference hardware design. This document describes the various hardware elements that will be part of the SC-SMB system, how the features will be integrated, and the cost targets for the features. The initial reference design of the SC-SMB system is planned for September 2023. The final release is planned for December of 2025.

1.1 State of Small and Medium Commercial Building Operations

Many SMBs do not have a dedicated building operator or an energy manager; therefore, the HVAC equipment tends to be serviced only when occupants complain or when the equipment completely fails. Even buildings with periodic maintenance contracts have several operational problems that go undetected. These problems result from improper control or incorrect commissioning, which leads to inefficient operation, increased energy use, and reduced equipment life. Many small buildings use rudimentary controls that are mostly manual, with limited scheduling capability and no monitoring or failure management. Currently, HVAC/RTU systems are generally operated as follows:

- Systems are controlled by programmable thermostats with a hardwired remote outdoor-air temperature sensor. If the thermostat has advanced capabilities and if they are programmed correctly, they can have seven-day scheduling, along with the ability to select different occupied heating and cooling setpoints and unoccupied heating and cooling setpoints. However, the dead band (difference) between the occupied heating and cooling setpoints is typically not configurable. The dead band could be as small as 1 °F, which leads to excess energy consumption.
- There is no capability for holiday scheduling.
- Some thermostats support rudimentary optimal start sequencing. However, these sequences have many shortcomings. This includes having a hard time predicting the optimal start time on Monday mornings in buildings with weekend setbacks or Tuesday mornings with 3-day holiday setbacks.
- Most thermostats cannot be networked, although some are capable of networking.
- There are no remote diagnostic, alarming, or trending capabilities.
- When an RTU uses setbacks and start-up schedules in the thermostat, they are generally set too early (between 3 a.m. and 5 a.m. for an 8 a.m. occupancy) and the RTUs are generally shut off too late (between 7 p.m. and 9 p.m., when occupancy ends at 5 p.m.). This is done as a “just in case” action in anticipation of severe weather because these thermostats cannot be remotely controlled and there is no operator in the building to make changes as needed. In some buildings, the RTUs may be running all day long without schedules or with schedules that were bypassed/overridden during the last severe weather event and never released.
- RTUs may be scheduled to run on weekends for four to eight hours—another “just in case” action in anticipation of severe weather.

Therefore, many of these buildings operate inefficiently and consume excess energy. Although use of BASs could reduce or eliminate the excess energy consumption, there are several reasons why these buildings do not deploy BASs:

- Lack of awareness of benefits.
- Lack of affordable BAS hardware solutions.
- Sometimes, the owner is not the tenant and has no incentive to invest in a BAS (Katipamula et al. 2012). Buildings without BASs may have limited ability to monitor or trend the data necessary for detecting system degradation or for performing supervisory controls.
- Even if these buildings have programable thermostats, many studies, including the Environmental Protection Agency’s Energy Star® Program, have concluded that there is no evidence that these thermostats are being used properly to save energy (Malinick et al. 2012).

Significant advances have been made in residential connected thermostats with the advent of Google Nest®, Ecobee®, and others. While some of these thermostats are suitable for use in small commercial buildings, there is no evidence that their use is widespread. Even if these connected thermostats are deployed in commercial buildings, there is very little evidence that their operations (setpoints, dead bands, schedules, and optimal start) are being managed properly. In addition, there is no evidence that HVAC system operations across the building can be optimized without some application that coordinates these systems.

1.2 State of Building–Grid Integration

As noted in the previous section, many small buildings lack BASs. Even if they include programmable thermostats for managing RTUs, many of these thermostats are not networked; therefore, they cannot directly participate in demand response programs. Also, the RTU operation across the building is uncoordinated, making it difficult to manage building peak. Furthermore, there is no evidence that the peak load in the buildings is being managed. With the push to decarbonize the built environment, many RTUs with gas heating will soon be converted to heat pumps (HPs) with backup electric heating. During cold weather conditions, it is common for the electric backup heating system on all or most of the HPs for a building to turn on simultaneously, resulting in large peaks in building demand. Proper management of the backup heating systems through intelligent scheduling and thermostat setpoint controls can positively affect grid stability while increasing the benefit from gas to electric conversion.

1.3 Improving Small and Medium Commercial Building Operations and Grid Interactivity

Given the current state of building operations, there are several technology and policy barriers that need to be overcome to increase the operating efficiency and grid interactivity of SMBs. Although overcoming policy barriers is critical, this research effort will only focus on some of the technology barriers, while other technology barriers will be addressed as part of the AEMS system project:

1. Development of software solutions that can be deployed on SMBs to improve operating efficiency and grid interactivity. This will be addressed by the AEMS system development project.
2. Because SMBs are first-cost sensitive, the first technology barrier would be to develop a solution that has a relatively low first-cost. This means minimal integration, engineering, and ongoing operational cost. In addition, the SC-SMB project will establish cost targets for the various hardware components (platform, connected thermostats, wireless sensors, etc.).
3. The technology deployment should result in significant benefits. Cost savings resulting from energy-efficient operations may be sufficient for many building owners; however, the ability to extract multiple benefit streams such as EE and grid services (GS) from the same technology will make widespread deployment easy and more desirable. Furthermore, the benefits must be clearly articulated to building owners and other stakeholders (utilities, cities, etc.). Both projects will address this need separately.
4. Because most SMBs do not have full-time building operators, the solution must be fully automated or autonomous while providing the ability for owners/occupants to intelligently override. The solution must also assure continuous optimization of building operations. This need will be addressed by both projects.
5. Initially, the focus will be to manage RTUs, domestic hot water heaters, and connected lighting to improve operational efficiency and grid interactivity. However, the hardware reference platform should be capable of extending these concepts to solar photovoltaic (PV) and energy storage systems.

Therefore, the primary goal of this joint project between PNNL, Oak Ridge National Laboratory (ORNL), and the project partners Edo and Intellimation is to design, develop, test, and validate a low-cost, interoperable, user-centric, retrofit supervisory controller kit that can host EE and GS applications to continuously optimize energy consumption, deliver demand flexibility of SMBs (including all-electric buildings), and provide a means for maximizing decarbonization benefits. The work will leverage the vast experience of PNNL and ORNL research and development staff who have over two decades of experience in developing and successfully transferring hardware and software technologies to the private sector. To monitor and control the end uses in a building, the SC-SMB system can be of two flavors: (1) all digital and (2) a combination of digital and analog. The all-digital version of the SC-SMB system will include the following design capabilities:

1. Eclipse VOLTTRON™ is the preferred host Internet-of-Things (IoT) platform. This platform supports monitoring and control of connected thermostats to manage RTUs, connected lighting, and connected hot water heaters. The platform will also support integration of other distributed energy resources (DERs) such as solar PV and battery. The preferred communication protocol is a Building Automation and Control network (BACnet)[1] or Modbus,[2] both of which are open and standard.
2. Intelligent placement of sensor infrastructure and autonomous provisioning as a part of the retrofit deployment. Prior knowledge of the observability locations of the sensors enables a robust supervisory controller formulation pre-designed based on the available sensor data.
3. Because most connected lighting devices and some connected thermostats still use proprietary communication protocols, the IoT platform should have the ability to communicate with these devices using standard application programming interfaces (APIs) provided by the manufacturer of these devices.
4. Several thermostats support standard BACnet and Modbus communication protocols. Therefore, the preferred approach is to replace all proprietary connected thermostats or non-connected thermostats with thermostats that support standard or defined (API) communications.
5. Most solar PV and battery system inverters support Modbus protocol or API access to the energy generation and state-of-charge information. The proposed solution will leverage the Eclipse VOLTTRON Driver framework to incorporate additional sources of data for optimization and control.
6. In some SMBs that have interval meters, it is possible to get direct access to the whole-building electricity consumption. In most buildings, integration of the electric meter with the IoT platform will require installation of a Watt-hour meter that supports BACnet or Modbus protocol.
7. All these connected devices will be integrated with the Eclipse VOLTTRON platform via transmission control protocol/internet protocol (TCP/IP) using standard wireless communication. If the devices are already connected to the internet, existing internet connections will be leveraged. If the devices are not connected to the internet, a private network will be set up to coordinate all connected devices.

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[1] BACnet is a communication protocol for building automation and control (BAC) networks (net) that use the ASHRAE, ANSI, and ISO 16484-5 standards protocol.

[2] Modbus is a data communications protocol originally published by Modicon (now Schneider Electric) in 1979 for use with its programmable logic controllers.

The all-digital SC-SMB system is the preferred option for existing buildings because of lower cost. However, for some existing buildings, an all-digital system may not be possible. Also, a combination digital and analog version may be suitable for new construction. We will thus create a reference design for a combination digital and analog version of SC-SMB that is capable of monitoring, controlling, and integrating all devices discussed in the all-digital version. This version will include an open-source input/output (I/O) controller (e.g., EasyIO®) that will be integrated with the IoT platform. The I/O controller will allow physical (wired) integration of devices that cannot be connected via internet.

Project objectives: The key objectives for achieving the project goal are to:

1. Develop a low-cost BAS reference design that is capable of monitoring and controlling building systems and includes the ability to host the AEMS system to increase operating efficiency and demand flexibility of the underserved SMB sector, leading to significant energy and cost savings for the building owners/occupants and reductions in GHG emissions benefiting the society.
2. Increase the rate-of-return of the control infrastructure by providing a means to simultaneously host EE and GS applications that would reduce energy cost to the owners and support increasing hosting capacity of renewables.
3. Support hosting applications that will allow multiple objectives, including reduced energy costs, improved occupant comfort, resilient operations during extreme weather events by managing building consumption, reduced emissions, and automated load shaping.
4. Create a retrofit supervisory controller kit (SC-SMB) that will be easy to deploy and configure (i.e., minimal integration, engineering, and ongoing operational costs).
5. At a minimum, the SC-SMB will manage RTUs, hot water heaters, and connected lighting and will be easily extensible to manage and optimize other DERs in the building (see Figure 1).
6. Develop a pathway for commercial deployment in buildings.

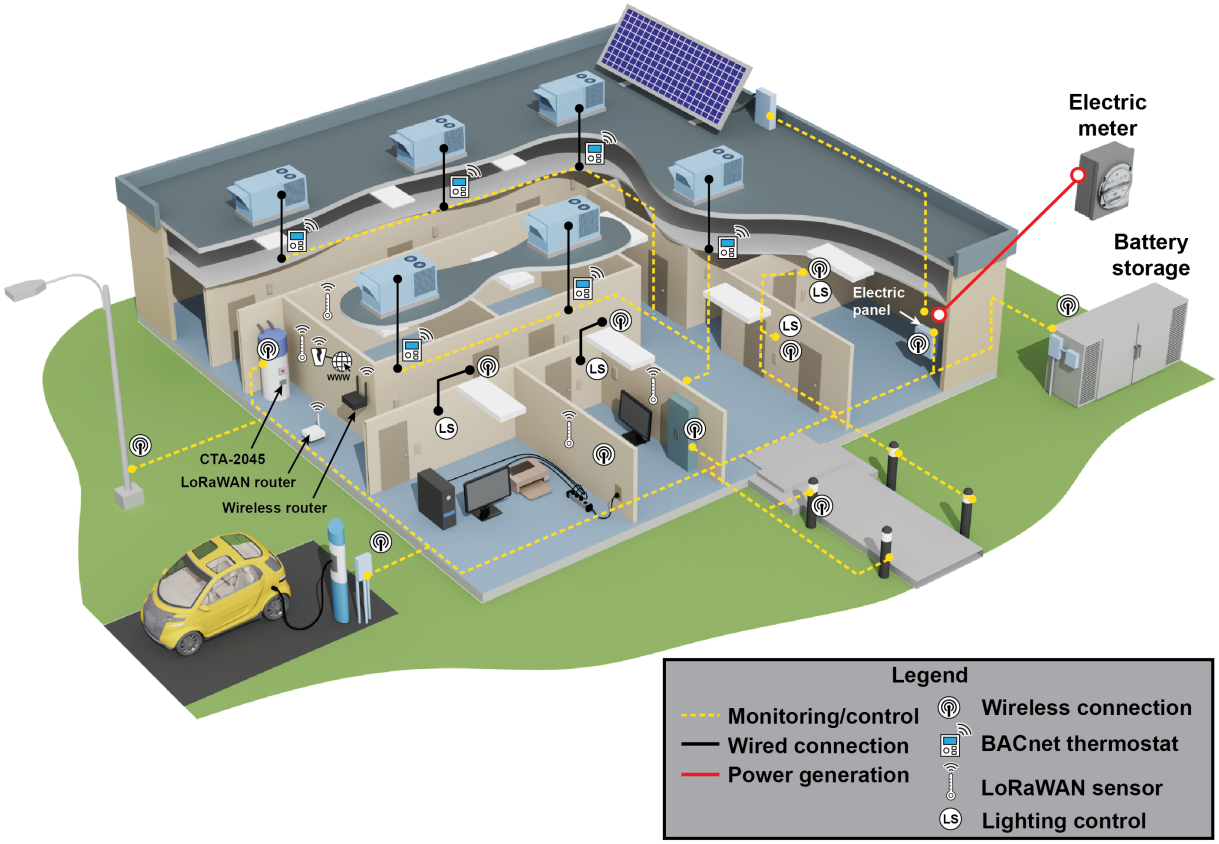

Figure 1: Potential deployment of SC-SMB system on an edge VOLTTRON device. Although the graphic shows several end uses, the initial focus of this project will be managing RTUs, hot water heaters, and connected lighting. (Illustration by Mike Perkins | PNNL)

1.4 Purpose and Scope

This document describes the requirements for the SC-SMB systems and the various components that are part of the reference design. It also details how the various features will be tested and validated, including field validation. The document also details what flexibility the users have and how they will be able to leverage those capabilities. The intent is to create an SC-SMB system that supports scalable deployment, requires minimal configuration, and is easy to maintain over its expected lifespan. The initial alpha release of the SC-SMB system reference design is planned for September 2023, and the beta release is planned for summer of 2024. The final release is planned for December 2025.

Section 2.0 of the report documents the relevant building types that the SC-SMB system is suitable for. 3.0 documents the various components and features of the SC-SMB system. Features to make deployment easy and scalable are described in Section 4.0. Testing and validation of the SC-SMB system is described in Section 5.0. The planned next steps are described in Section 6.0, and references are listed in Section 7.0.

2.0 Relevant Building Types

The SC-SMB system is targeted at SMBs that predominately use RTUs to provide comfort heating and cooling. For this work, a small and medium building is defined as any building that is 50,000 square feet or less. As shown in Table 1, almost 87 percent of buildings covering 35 percent of floorspace in the United States are small or medium (EIA 2018). Almost 40 percent of the buildings covering 18 percent of all the floorspace in the United States have either a packaged RTU or an HP, and 57 percent of the buildings covering 24 percent of all the floorspace have a packaged RTU, an HP, a residential split system, or an electric air conditioner. These buildings consume over 3,375 trillion Btus of site energy and over 10,000 trillion Btus of source energy (EIA 2018).[1] Although the SC-SMB system can be used on any building being served by RTUs, after reviewing consumption patterns of the 20 different Commercial Buildings Energy Consumption Survey (CBECS)[2] building types (EIA 2018), we believe the following small and medium building 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. A vast majority of these buildings lack BASs.

Table 1: Distribution of Buildings in the United States with Relevant HVAC Systems (EIA 2018)

	All Buildings	SMBs (< 50,000 square feet)	SMBs with Packaged Unit or Heat Pump	SMBs with Packaged Unit, Heat Pump, Residential Split System, or Other Electric Air Conditioner
Number of Buildings	5,918,212	5,558,947	2,553,955	3,665,997
Total Floorspace (square feet)	96,527,825,711	48,032,820,197	26,304,775,358	34,338,637,046
Average Size (square feet)	16,310	8,640	10,299	9,367

As shown in Figure 2, 40 percent of the energy consumption in buildings with RTUs is from HVAC systems (EIA 2018). Controllable loads that include HVAC systems, water heating, lighting, and refrigeration account for almost 80 percent of the energy consumption. The initial focus of the SC-SMB system is to just manage the RTUs, hot water heaters, and connected lighting end uses in a building. However, the option to extend the SC-SMB system to manage other end uses (e.g., energy storage) in the future is possible. By limiting the scope, the SC-SMB system can be deployed in SMB—however, connected thermostats for RTUs and connected hot water control interfaces will be required.

With this minimal infrastructure upgrade, we can optimize the building operations for multiple objectives, including reduced energy costs, improved occupant comfort, and resilient operations during extreme weather events using intelligent load control (ILC) to manage demand for available resources, reduce emissions, and enable automated load shaping based on the preferences and choices of the building operator (Kim et al. 2020; Kim and Katipamula 2017; Kim et al. 2016).

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[1] Energy consumption data for 2018 CBECS have not yet been released but will be in the fall of 2022.

[2] Commercial Building Energy Consumption Survey.

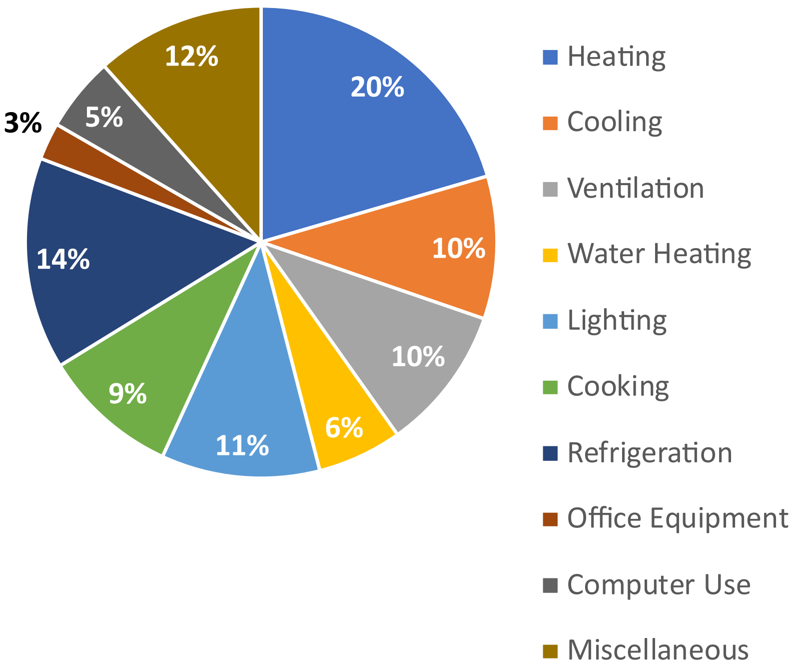

Figure 2: Disaggregation of energy end-use consumption of the small and medium commercial buildings that use RTUs (EIA 2018).

3.0 SC-SMB System Components and Features

As noted previously, managing setpoints and schedules can result in 20 to 25 percent reduction in whole-building energy consumption. In addition, better building–grid integration of SMBs can increase demand flexibility by 10 to 20 percent. The companion AEMS system developed to provide the EE and GS benefits will require hardware that is low-cost, interoperable, and easy to deploy. In this section, the supervisory controller kit features, hardware components, integration requirements, and communication capabilities are presented.

3.1 SC-SMB System Required Features

The SC-SMB kit must meet the following requirements:

1. **Monitor and Control Building Systems:** The platform must be able to integrate with a variety of sensors and controllers and provide reliable monitoring and control via widely used standard and open communication protocols (preferably BACnet or Modbus). The platform must have the ability to integrate with RTU thermostats, remote temperature sensors, hot water heaters, whole-building electricity meters, and end uses that can be controlled through manufacturer-provided APIs. Point names for BACnet/Modbus devices must support standard naming conventions with the ability to add meta data/information. Building systems that are integrated with the SC-SMB system will rely on manufacturer-provided onboard controls for their normal control operation, and the SC-SMB system will only generate supervisory control signals to manage the various building systems.
2. **Wireless Communication and Remote Access:** The host platform must be able to connect with the relevant building systems via TCP/IP using standard wireless communication. If the devices in a building are already connected to the internet, existing internet connections will be leveraged. If the devices are not connected to the internet, a private wireless network will be set up to coordinate all connected devices in the building. The system will also include a wireless connection (e.g., cellular) to communicate with external sources. This external wireless network must support remote management of the control platform.
3. **Fully Automated:** Most SMBs do not have full-time operators. Therefore, the solution will be fully automated and autonomous, with the ability for user override**.** Once configured, the platform will need minimal interaction with users.
4. **Digital and Analog Integration:** The platform must be able to integrate with digital and analog systems. One flavor of the kit will meet the integration needs of fully digital devices, and the second flavor will meet the integration needs of a combination of digital and analog devices. An open-source input/output (I/O) controller will provide the necessary conversion of analog points to digital for integration with the IoT platform. The all-digital platform will be the preferred deployment method.
5. **Off-the-Shelf Hardware Components:** To enable wide-scale adoption, the kit hardware components must be off-the-shelf and primarily open source or support open standards (e.g., BACnet or Modbus). Off-the-shelf hardware components allow for quicker procurement, setup, and troubleshooting than custom hardware. Examples of off-the-shelf platform hardware include Intel NUC©, Raspberry PI, or some equivalent.
6. **Low Cost:** The total cost of the hardware platform, excluding sensors or thermostats, must be between $200 and $400, preferably closer to $200. Target costs of the additional hardware for the combined analog/digital supervisory control system have not been defined,

though we expect that all off-the-shelf components will be available for a moderate cost (< $1,000).

3.2 SC-SMB System Hardware Components

The hardware can be split into three groups: (1) the supervisory controller or the platform, (2) the all-digital version, and (3) the digital and analog version. The supervisory controller is needed for both the integration versions. Different hardware components are needed for the all-digital integration version and the combination digital and analog version.

3.2.1 Supervisory Controller Hardware

The SC-SMB system will provide a means to integrate building systems and allow supervisory control algorithms to indirectly control (e.g., changing setpoints, etc.) the systems to either improve operating efficiency or to deliver GS. The supervisory controller is the primary hardware component and will integrate all building systems and host the EE and GS applications. The edge computing device cost will be limited to $200 to $400.

To execute the EE and GS algorithms, the supervisory controller must meet certain computing requirements. Off-the-shelf microprocessors or small-form-factor computers will be used for the supervisory controller. Some examples that meet our computing requirements are:

- Raspberry Pi 4 ($45–$75):
  - Quad-core Cortex-A72 at 1.8 GHz
  - 2–8 GB DDR4 RAM
  - Wi-Fi on board
  - Availability is very limited
- ROCKPro 64 ($60–$80):
  - Dual ARM Cortex-72 Quad-core and Cortex A53 Quad-core
  - 2–4 GB DDR4
  - eMMC option
  - Wi-Fi option
- Intel NUC ($200–$400):
  - Intel Celeron – Intel i3 processors
  - 8–16 GB RAM
  - Wi-Fi onboard
  - SSD storage
- Libre Computer Board ($45):
  - Quad-core Cortex-A53 at 1.5 Ghz
  - 2 GB DDR3 RAM
  - eMMC hard drive option
  - Wi-Fi adapter included

- Odroid N2+ ($85):
  - Quad-core Cortex-A73 up to 24 Ghz at 1.8 Ghz
  - Dual-core Cortex-A53 up to 2.0 Ghz at 1.9 Ghz
  - eMMC hard drive option
  - Onboard RTC backup battery
  - 4 GB DDR4 RAM
  - +$9 for additional Wi-Fi adapter.

3.2.2 SC-SMB System All-Digital Integration Hardware

The all-digital supervisory control system is the preferred option for existing buildings because of the lower cost. Integrating building systems via wireless communications is significantly cheaper and less time intensive because integration primarily relies on configuration of the communication protocol rather than wiring. Standard communication protocols, such as BACnet and Modbus, will be leveraged to lower the cost of deployment and increase interoperability. The hardware components required for the all-digital integration platform include connected thermostats to integrate RTUs and HPs, a CTA-2045 (ANSI/CTA-2045 2021; Consumer Technology Association) controller interface to integrate connected hot water heaters, wireless temperature sensors (~$10 each) that support LoRaWAN® protocol (LoRaWAN 2023), a LoRaWAN gateway that aggregates the sensors and converts LoRaWAN protocol to BACnet (~$100), a wireless router (< $100) to create a private wireless network to integrate all building systems that need to be monitored and controlled, and a cellular modem (< $150) for external internet connection. The all-digital version assumes that building system components can communicate with the platform wirelessly via a standard and open communication protocol. The connected thermostats, CTA-2045 control interface, wireless sensors and gateway and API-based controls are discussed in more detail in the following sections.

3.2.3 SC-SMB System Digital-Analog Integration Hardware

In some existing buildings, an all-digital system may not be possible. Therefore, the host platform must support a combination of the digital and analog version of the supervisory controller. This requires integration of an open-source or low-cost I/O controller with the SC-SMB platform. All hardware listed in the previous all-digital version of the supervisory control is also required for the combined analog and digital control system. The I/O controller will allow physical (wired) integration of devices that cannot be connected via the internet or other standard wireless communication protocols. The preferred I/O controller is the open-source EasyIO® controller or equivalent (Figure 3). The I/O controller must be able to communicate with the supervisory controller wirelessly and support standard communication protocol (preferably BACnet/IP) to communicate with the building systems. The I/O controller must have the analog and digital inputs and outputs necessary to control and monitor building systems that are not capable of communicating with the supervisory controller wirelessly. Although we currently do not have a price target for the digital-analog integration device, we expect that it will cost between $1,000 and $2,000. Because the all-digital version will be sufficient for most existing buildings, the primary focus of this project is to support the all-digital version.

Figure 3: An open-source I/O device.

3.3 SC-SMB System Monitoring and Control Features

The supervisory controller will act as the hub for all monitoring and control decisions for the building. The AEMS system will optimize RTU setpoints, schedules, setbacks, and optimal start. The AEMS system will also optimize the hot water heaters’ load for GS. The SC-SMB kit will be extensible in the future to manage and optimize other DERs in the building, such as energy storage devices, electric vehicles, and solar. Monitoring and control requirements vary by end-use, and preliminary points are outlined in Table 2. Monitoring features may vary depending on what points are locally monitored by the manufacturer-provided onboard controls for the building system. Control points are primarily setpoints rather than direct control of the building system. Distributed control is more resilient to supervisory controller downtime because the local onboard control strategy is maintained.

A user interface being developed as part of the AEMS system project will display all relevant information and allow users to easily modify setpoints and schedules. Monitoring capabilities will include graphics of the RTU and hot water heater that display current operations, trending of BAS points for troubleshooting, and alarms with adjustable thresholds.

If communications to the supervisory controller are lost, each field device will be configured to default to onboard setpoints. The user interface will also display communications status with all field devices. If communications are 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.

Table 2. Monitoring and Control Points by Building System

Building End-Use	Monitoring Points	Control Points
RTU controlled via thermostat	• Occupancy status • Zone temperature • Outdoor-air temperature • Mixed-air temperature • Discharge-air temperature • Auxiliary sensors • Fan status • Heating/cooling status	• Occupancy command • Occupied heating and cooling setpoints • Unoccupied heating and cooling setpoints • Economizer setpoint • Heating and cooling stage enable
Remote temperature sensors	• Zone temperature • Zone humidity	N/A
Hot water heater	• Tank temperature • Heating element/compressor status	Tank temperature setpoint
Lighting	• Occupancy status • Light sensors	On/off lighting control and dimming level
Solar PV	• Output • Solar irradiation • Power factor	Active power setpoint
Battery Energy Storage Systems	• State of charge • State of health • Output	• Charge/discharge control • Power output setpoint
Whole-building electricity meter	• Energy consumption • Demand • Power factor	N/A

3.3.1 Support and Integration of Connected Thermostats

The preliminary integration focus of this project is the management and control of RTUs and HPs. The mechanism of RTU control is through connected thermostats. The selection criteria for connected thermostats that align with the monitoring and control needs of this project are:

1. Wireless read/write integration via BACnet/IP over Wi-Fi.
2. Complete heat pump control, which includes compressor, reversing valve, auxiliary heat, and fan control.
3. Economizer control via floating point or open/close damper control based on outdoor-air temperature.
4. An onboard temperature sensor resolution of 0.2 °F or less to provide effective monitoring of zone temperature for setpoint adjustments.
5. The thermostat must be programable via the BACnet protocol. Thermostat configuration can be done either via the SC-SMB platform or on the thermostat keypad.

Most RTU thermostats have the capability to integrate outdoor air, zone air, and discharge air or mixed-air temperatures. The thermostat’s onboard control strategy controls the fan when the zone calls for heating or cooling, or the fan can run continuously (during occupied mode) to ensure ventilation requirements are met. Heating mode is initiated when the zone temperature is less than the heating thermostat setpoint minus a dead band. Similarly, cooling mode is initiated when the zone temperature is greater than the cooling thermostat setpoint plus a dead band. Heating or cooling are typically shut off when the zone temperature has met the thermostat setpoint (see Figure 4 for an example of the onboard RTU thermostat heating and cooling control strategy). Most thermostats use hysteresis control for heating and cooling, but some incorporate a proportional-integral-derivative control algorithm to minimize overshoot of the heating and cooling setpoints. Economizer control or free-cooling initiates when the outdoor-air temperature is less than the economizer enable setpoint.

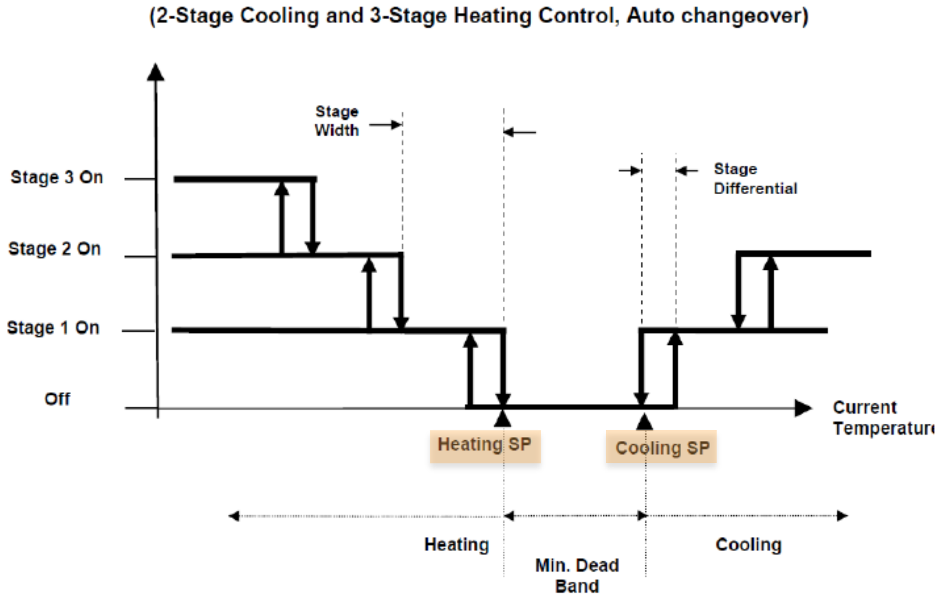

Figure 4. Example RTU thermostat control strategy with 2-stage cooling and 3-stage heating. (Source: BACstat Wireless Heat Pump Thermostat User Manual[1]).

BACnet-enabled thermostats provide read/write integration of a remote source for analog values within the thermostat controller. All setpoints and adjustable control points are stored as analog values within the local controller. Because RTUs vary across buildings, modifying the heating and cooling setpoints will be the primary method of control modifications from the supervisory controller. Modifying the heating and cooling setpoints from the supervisory controller enables scheduling and load-shedding capabilities. If the connected thermostat has internal scheduling capabilities, scheduling setpoints will be integrated with the supervisory controller. The supervisory controller will either directly set the occupied or unoccupied mode, or the supervisory controller will set the occupied time and unoccupied time. Modifying the RTU thermostat schedule and setpoints is the primary mechanism for implementing optimal start capabilities. The thermostat heating and cooling setpoints will be modified to switch on heating or cooling at the latest possible start time to meet the occupied thermostat setpoints. Although some RTU thermostats include optimal start capabilities, the supervisory controller will integrate optimal start with GS features—therefore, the supervisory controller optimal start algorithm is the preferred option.

Additional control integration includes economizer control via the economizer enable setpoint. The economizer control sequences of most RTU thermostats enable the economizer when the

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[1] BASstat Wireless Heat Pump Thermostat User Manual. In Wireless BACnet Communicating Thermostat for 2-stage Heat Pump Operation: Contemporary Controls.

outdoor-air temperature is less than the economizer enable setpoint. The economizer enable setpoint and the economizer supply air temperature setpoint will be modified by the supervisory controller to increase economizer operations and reduce mechanical cooling needs.

Most RTU thermostats generally include the capability to monitor the temperature of one or two zones. The thermostat includes an onboard temperature sensor, and many support a second wired temperature sensor input. The thermostat may include averaging capabilities of the two temperature inputs. Multi-zone RTUs may serve spaces with varying heating and cooling requirements. Figure 5 shows an example floorplan where the RTU thermostat is in one space, and an additional wireless temperature sensor is in each of the spaces served by the various RTUs. Because the RTU thermostats do not allow this many temperature inputs, wireless LoRaWAN temperature sensors will be integrated to the supervisory controller via the LoRaWAN aggregator that also supports BACnet/IP. The supervisory controller will average the temperature sensors across all spaces served by the RTU to control more effectively.

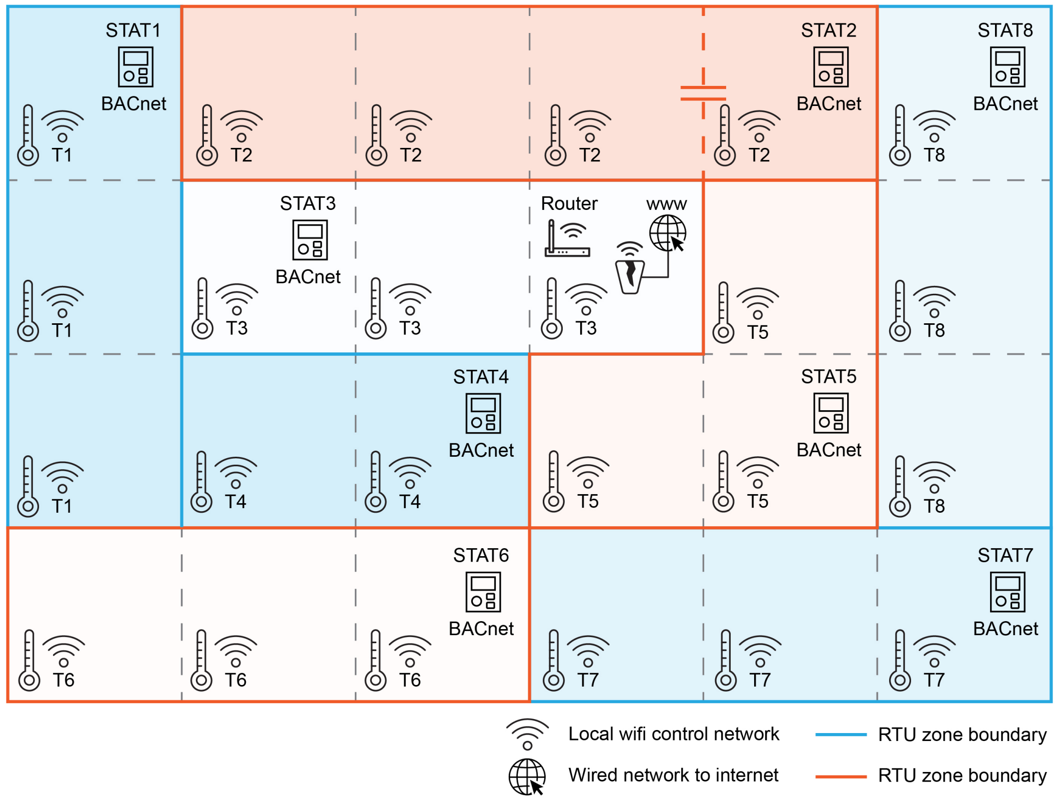

Figure 5. Example floorplan served by multiple RTUs. Although typically only the thermostat zone temperature is used to control the RTU, the SC-SMB system will average temperature measures from all spaces served by the RTU and use that to control the RTU.

3.3.2 Wireless Sensors Requirement and Supported Protocol

Adequate sensing devices are indispensable to optimal building control. However, temperature sensing in the SMBs is limited and can lead to comfort issues in some spaces. Although multiple spaces may be served by a single RTU, the thermostat (i.e., the temperature sensor) controlling the RTU to heat or cool is in only one of these spaces. Therefore, the space that has the thermostat with an onboard temperature sensor dictates the comfort needs of all other spaces served by that RTU. In practice, the location of the temperature sensor is determined by the importance of the spaces being served (e.g., office area versus the corridor), the total thermal load (e.g., spaces that have the largest floor areas), or the representative of the worst condition (e.g., spaces that are farthest from the RTU system). However, none of those methods for the location of the temperature sensor can handle all the operational requirements, such as EE and thermal comfort. In addition, because the location of the temperature sensor is fixed once thermostat location is determined, this single-sensor-setting cannot capture the variation in the building operations, e.g., changes in the thermal load during the day.

Multiple temperature sensors can be integrated to control an RTU (as shown in Figure 5). In such cases, one or more additional temperature sensors can be assigned to spaces served by the RTU. Then, the existing control sequence of the RTU can be enhanced to better trade off different operational requirements and/or capture the varying operating conditions. For example, the control input, i.e., the temperature of a single space, can be replaced by the average value of the multiple space temperatures to better represent the overall thermal condition of the spaces served by the RTU. Alternatively, the highest space temperature can be used to capture the changes in the thermal load over time so that the thermal comfort level can always be maintained. Multiple-sensor-setting can potentially enable new building controls that can further push the limit of energy savings. For instance, using multiple-sensor-setting, spaces that are unoccupied can be ignored when making decisions about how the RTU should be operated. In addition, one can implement dedicated thermal comfort settings for each space to harvest the diversity in thermal comfort preferences to avoid over-cooling or over-heating.

To ensure large-scale deployment of multiple-sensor-setting in SMB, the following requirements shall be considered:

- Minimize the cost of additional sensors (< $10). With the increased number of temperature sensors, the cost of multiple-sensor-setting is expected to be higher if conventional temperature sensors are employed. Therefore, low-cost wireless sensors must be used.
- Installation and maintenance costs for these wireless sensors must be minimized. The installation of multiple-sensor-setting includes the labor for locating sensors in different spaces and for setting up communication between sensors and supervisory control platforms. The maintenance of multiple-sensor-setting includes the costs for calibrating sensor measurement and replacing or charging the batteries that power the sensors. The costs for installation and maintenance are generally proportional to the number of the sensors. The key to reducing those costs includes (1) reducing the human involvement with some level of automation, and (2) eliminating customized settings by leveraging well-accepted standards.

Wireless sensor networks (WSNs) are promising for supporting large-scale deployment of multiple-sensor-setting in SMB. In this context, WSN refers to the “Energy-Harvesting, Self-Calibrating Wireless Sensors” developed by ORNL with funding from DOE BTO. This WSN has the following unique features:

- Low-cost (≤ $10/node) and multi-modal (both temperature and humidity)
- Long operational lifetime (replacement of batteries ≥ 10 years, time between charging ≥ 72 hours)
- Accurate measurement with self-calibration capability

- Ready to integrate with SC-SMB using the LoRaWAN to BACnet Gateway.

These features provide an adequate solution to meet the requirements in Section 3.1. Specifically, the capital cost of WSN is expected to be close to that of single-sensor-setting with conventional temperature sensors (~$100/node). The long operational lifetime and self-calibration capability can significantly reduce human efforts needed for maintaining multiple-sensor-setting. In addition, by leveraging the standard protocol LoRaWAN, a local communication server—namely “LoRaServer”—has been established to provide scalable and safe data acquisition. The LoRaServer can not only manage the local communication network but also serves as a hub to facilitate the integration of the WSN with the larger building automation network.

3.3.3 Support and Integration of Connected Hot Water Heaters

Many hot water heater vendors provide communications that are compliant with the ANSI/CTA-20450A (ANSI/CTA 2021) communication interface standard (or equivalent) and the ANSI/CTA-20450A application layer requirements, which is also commonly rereferred to as EcoPort or CTA-2045. For hot water heaters that already include a CTA-2045 controller, all that is needed is an interface that connects to the CTA-2045 and provides connectivity to the external internet network. Some of these interface devices connect to the manufacturer’s portals, some provide a local TCP/IP wireless connectivity, while some act as a BACnet gateway. For devices that only talk to the manufacturer’s portal, the only way to control the hot water heater, is by using the manufacturer’s API; therefore, it is not the preferred option. The preferred option is to have the ability to locally control the hot water heater. The other two options listed above will meet our requirements. Although the cost of these interface devices has not been established yet, we anticipate the cost to be less than $300.

The CTA-2045 modules enable network communications with appliances to support GS. The BACnet protocol is supported by the CTA-2045-B interface as a pass-through protocol that allows for easy integration with the supervisory controller’s communication interface. The monitoring and control features of the CTA-2045 controller are outlined below:

- Modification of the tank temperature setpoint to indirectly control when the heating element turns on and off.
- The supervisory controller’s algorithm will learn usage patterns and adjust the setpoint accordingly to reduce energy consumption and provide GS.
- Implement an occupancy schedule to allow for a night setback on the tank temperature setpoint.
- Monitor the tank temperature and display on the user interface.

Vendor support for communication via BACnet or BACnet Wi-Fi supported devices is limited. Another option for communication with CTA-2045 devices is direct communication with the devices on Wi-Fi using the vendor-supplied API. This would require the vendor to provide the API specifications and additional development to integrate this API into the VOLTTRON driver framework.

3.3.4 Whole-Building Electricity Meter Integration

To provide GS, real-time access to the whole-building electricity consumption data is essential. Whole-building electricity meters measure the incoming three-phase current and voltage to determine the electricity consumption of the building. 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, third-party access to the electricity consumption data in real-time is restricted by most utilities 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. Although the preferred meter has not been selected yet, the meter and Wi-Fi interface shown in Figure 6 could be used to meet the project needs. The cost for these devices is expected to be around $1,000 with $500 to $1,000 to install them (labor). 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.

(a) (b)

Figure 6: (a) BACnet-based three-phase whole-building electricity power meter and (b) BACnet wireless communication module that integrates with the power meter shown in (a).

3.4 Communication Capabilities

Eclipse VOLTTRON™ will be the preferred supervisory controller interface with all remote controllers, sensors, and meters. VOLTTRON enables the supervisory controller to communicate across a variety of communication protocols with minimal upfront configuration. VOLTTRON supports several pre-built programs called "services" to facilitate communications and control of various devices and connection to external sources. The primary means of communication between algorithms and devices is through the VOLTTRON message bus. The control algorithm will read and write messages to the message bus. The service agents will then distribute the information to the connected devices. The primary VOLTTRON services that will be used are listed below. Each of these services have already been developed and require minimal configuration.

- **BACnet Proxy Agent**: This agent manages a single virtual BACnet device that communicates with BACnet devices on the BACnet network. A BACnet Proxy Agent is required for each BACnet network.
- **Modbus Driver**: This agent supports Modbus TCP/IP. A device configuration file is added for each Modbus device along with a registry configuration file that configures each Modbus point.
- **MQTT Plugin**: A Python-based MQTT plugin was developed for the RabbitMQ-based VOLTTRON. The plugin coordinates all messaging between VOLTTRON and the MQTT broker. The MQTT broker will be hosted on the supervisory controller.
- **OpenADR Agent**: This agent enables the building to participate in demand response events from utilities and to be informed of changes to the time-of-use pricing during peak periods.
- **WeatherDotGov Agent**: This agent queries weather data from the National Oceanic and Atmospheric Administration to improve predictive control algorithms. The control kit can use the current weather queried with this agent in place of or as a backup to local outdoor-air temperature and humidity sensors.
- **Historian Agents**: Agents write data to and query data from databases. This enables the control algorithm to use historical time series data and provides trending capabilities for the supervisory controller decisions. Historian agents currently support several open-source databases, including SQLite, MySQL, MongoDB, Timescale, etc.

VOLTTRON will be responsible for communications and monitoring with all field devices. A communication loss alarm will be triggered if communications are interrupted between VOLTTRON and a field device after a time delay. The host platform will be remotely accessible via a virtual private network for device addition, configuration, and troubleshooting.

4.0 Features to Make Deployment Easy and Scalable

The high cost associated with the deployment of advanced 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. The primary reason for the high cost of advanced controls deployment is that the process tends to be manual, as shown in Figure 7. The first step, *Migration*, migrates the control sequence from the development environment (e.g., MATLAB) to the deployment environment (e.g., JCI Metasys). the second step, *Configuration*, configures the control sequence in terms of the control structure and data mapping based on the system topology. The last step, *Tuning*, determines the values of the parameters of supervisory controllers (namely control parameters), e.g., the interval for updating thermostat settings, based on the responses of the controlled building system to the change of control parameters. Due to the lack of tools for automation, usually all three steps must be executed manually, leading to an expansive and error-prone control deployment process.

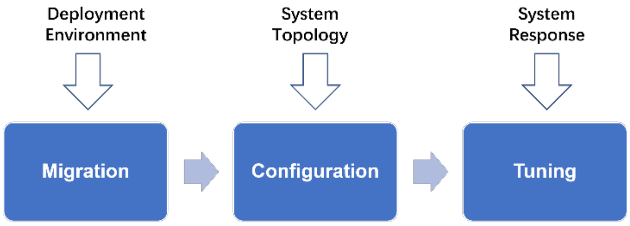

Figure 7: A typical process for building control deployment.

Because of the manual-driven process, the deployment of advanced building control deployment tends to be realized with ad hoc solutions. Those ad hoc solutions, however, may not be ideal when it comes to large-scale deployment, as each building system must be considered individually. In addition, ad hoc solutions discourage the development of innovative methods for building design and operation. For example, one can potentially achieve better energy performance by simultaneously optimizing both the design parameters (e.g., nominal cooling capacity) and the control parameters, compared to the conventional method that determines the design parameters and the control parameters sequentially. However, without a standard building deployment process, it is difficult to quantify the cost associated with various building controls.

To support the large-scale deployment of the platform, Eclipse VOLTTRON, and supervisory control sequences, we will develop the following features to streamline the building control deployment process:

- **Software-container-based deployment environment:** This feature aims to simplify *Migration*. Specifically, software containers will be employed to encapsulate the complexity of setting up the deployment environment. APIs will also be developed to facilitate the seamless integration of control sequences into the deployment environment.
- **Standard naming convention and semantic tagging:** This feature is designed for *Configuration*. Indeed, applying standard naming conventions and semantic tagging to building data points can reduce or even eliminate the involvement of human efforts in data mapping, which is a key aspect of *Configuration.*

- **Online model identification as a service**: This feature is related to *Tuning.* Specifically, we will develop and implement functions to identify the parameters of reduced-order models (ROMs) based on building data. Those ROMs are commonly used as parts of supervisory control sequences. Those functions will then be provided as services of the deployment environment to reduce duplicated efforts when tuning those control sequences.

The following subsections will highlight the requirements for each feature and discuss the demonstration of those features with model prediction controls (MPC).

4.1 Software-Container-Based Deployment Environment

As mentioned in Section **Error! Reference source not found.**, VOLTTRON will be employed to establish the communication between supervisory controllers and various building devices. In this case, VOLTTRON effectively serves as a deployment environment for supervisory controllers. To facilitate the usage of VOLTTRON, we will develop a set of configurable scripts that can set up instances of VOLTTRON, install/configure VOLTTRON agents, establish communication between VOLTTRON instances/agents, and so on. As illustrated in Figure 8, those scripts can take the descriptions of control architecture as inputs to automatically generate a customized setup in software containers that meet the requirements for deploying a specific supervisory controller. This supervisory controller can then communicate with the customized setup via APIs to update the control actions and query building data.

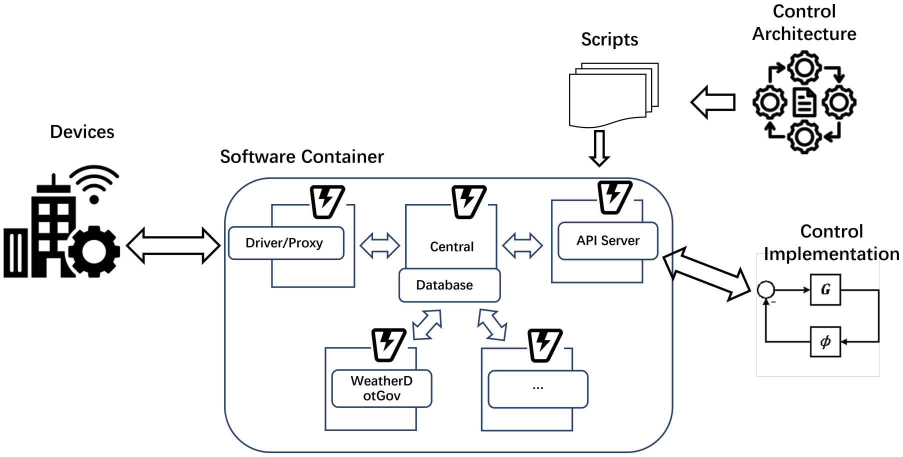

Figure 8: Software-container-based deployment environment.

4.2 Point Naming Convention and Metadata Creation

To address the issues noted in the previous section, it is necessary to introduce standardization and automation into the deployment process. Specifically, the following requirements will be implemented to enable scalable deployment of schedule manager, setpoint manager, optimal start manager, ILC, and MPC applications:

- **Standard name**: All points used for controls and other analytics will use standard names. The use of a standard naming convention will automate data mapping. It can also provide machine-readable information regarding the system topology, which is the key to streamlining the *Configuration* step.

- **Semantic tagging**: All data points will also include metadata (e.g., units, what the point represents, limits, etc.)

When developing semantic tagging, we consider building data points from two sources: (1) structured data that follows well-documented naming conventions, and (2) unstructured data whose naming conventions are unknown or are not well documented. The structured data is usually from API provided by manufacturers of building devices, while the unstructured data is from building management systems (e.g., thermostats).

As shown in Figure 9, because the naming convention has been provided by API specifications for the structured data, there is no need to extract information from the data points. However, validation is still needed based on prescribed rules before converting its naming convention to a standard one. For the unstructured data, the semantic tagging process is like that for the structured data, except an additional process is used to identify the data point based on the name of data points and/or their data patterns, in which manual efforts may be necessary.

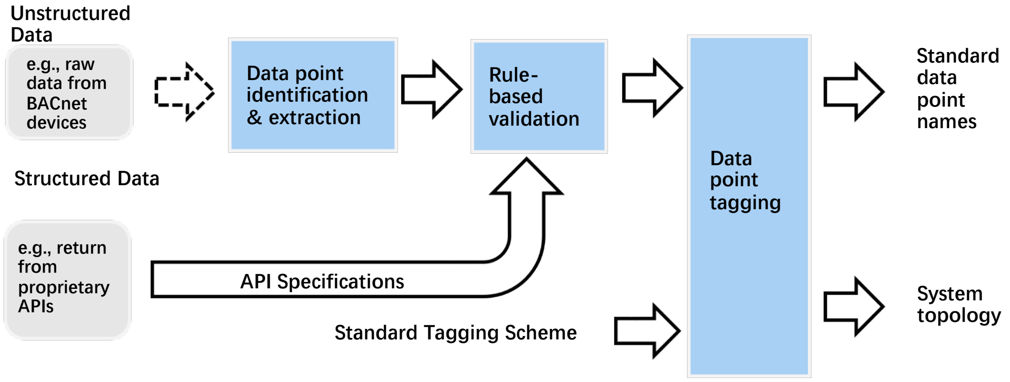

Figure 9: Semantic tagging process.

4.3 Online Model Identification as a Service

It is common to employ ROMs that represent the building system dynamics based on streaming building data in supervisory controllers. For example, the optimal start algorithm uses ROMs to estimate the optimal start time for RTUs so that the zones are at the desired temperatures at occupancy time. Therefore, determining the model coefficients of ROMs is the major objective of the Configuration step when deploying predictive control methods.

The online model for Identification contains a set of scripts for *Input Processing*, *Regression*, *Model Assessment*, and *Output Generation*, as shown in Figure 10. *Input Processing* handles two types of inputs: *Model Type* and *Streaming Building Data*. *Model Type* allows control developers to define the type of ROM, while *Streaming Building Data* is the building data with standard data point names. Based on the *Model Type, Input Processing* identifies the mathematical formula of the corresponding ROM. *Input Processing* then converts the *Streaming Building Data* into independent and dependent data. *Regression* then conducts regression based on independent and dependent data and the mathematical formula to obtain the model coefficients. With those model coefficients and the mathematical formula, the *Model Assessment* assesses the prediction accuracy of the ROM. Finally, *Output Generation* generates the *Model Configuration*, which contains both the mathematical formula and the model coefficients that are ready to be integrated into the control implementation.

The online model for Identification will be implemented as a VOLTTRON agent (namely, the *Model Identification Agent*) to provide a Model Identification “service” to other agents. In this case, other agents can send a message, which contains the *Model Type*, to the *Model Identification Agent* to trigger the action of performing regression. The resulting *Model Configuration* will be used as parameters for other agents.

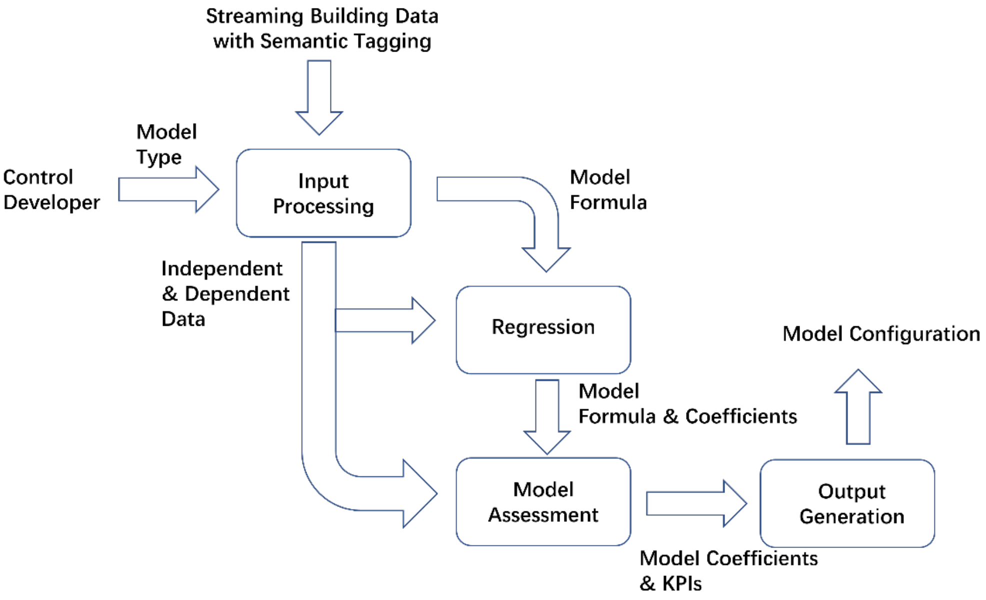

Figure 10: Online model identification process.

4.4 Plug-and-Play Model Predictive Control

The plug-and-play MPC is an example of how the proposed features can be used to streamline the process of deploying supervisory controllers. It will minimize the human involvement in deploying MPCs in a small or medium-sized commercial building. Specifically, we will develop (1) *MPC templates* that contain a generic mathematic formulation of MPC for building systems and configurable options for constraint-handling methods and commonly used optimization algorithms and (2) a mechanism (namely *self-optimization*) that can optimize the parameters of MPC, such as prediction horizon lengths, based on the responses of the controlled building system/devices to the control actions from MPCs.

As shown in **Error! Reference source not found.**:

- ***Migration:*** The MPC implementation is developed with the MPC templates by considering the given operating objectives of the building operators. The deployment of the MPC implementation is then realized with the software-container-based deployment environment.
- ***Configuration:*** The configuration of the MPC implementation is automated based on the system information provided by the standard point names and semantic tagging. Specifically, the mapping between variables in the MPC implementation (e.g., decision variables) and the building data points will be established based on predefined naming conventions. In addition, the mathematical formulation for estimating the objective functions and/or constraints will also be modified to accommodate the system topology.

- ***Tuning:*** By coupling online model identification and self-optimization, closed-loop tests investigate how sensitive the control performance is to changes in the control parameters, including but not limited to types of ROMs and prediction horizon length. Based on the results of the closed-loop test, Tuning then identifies a set of optimal values for the control parameters.

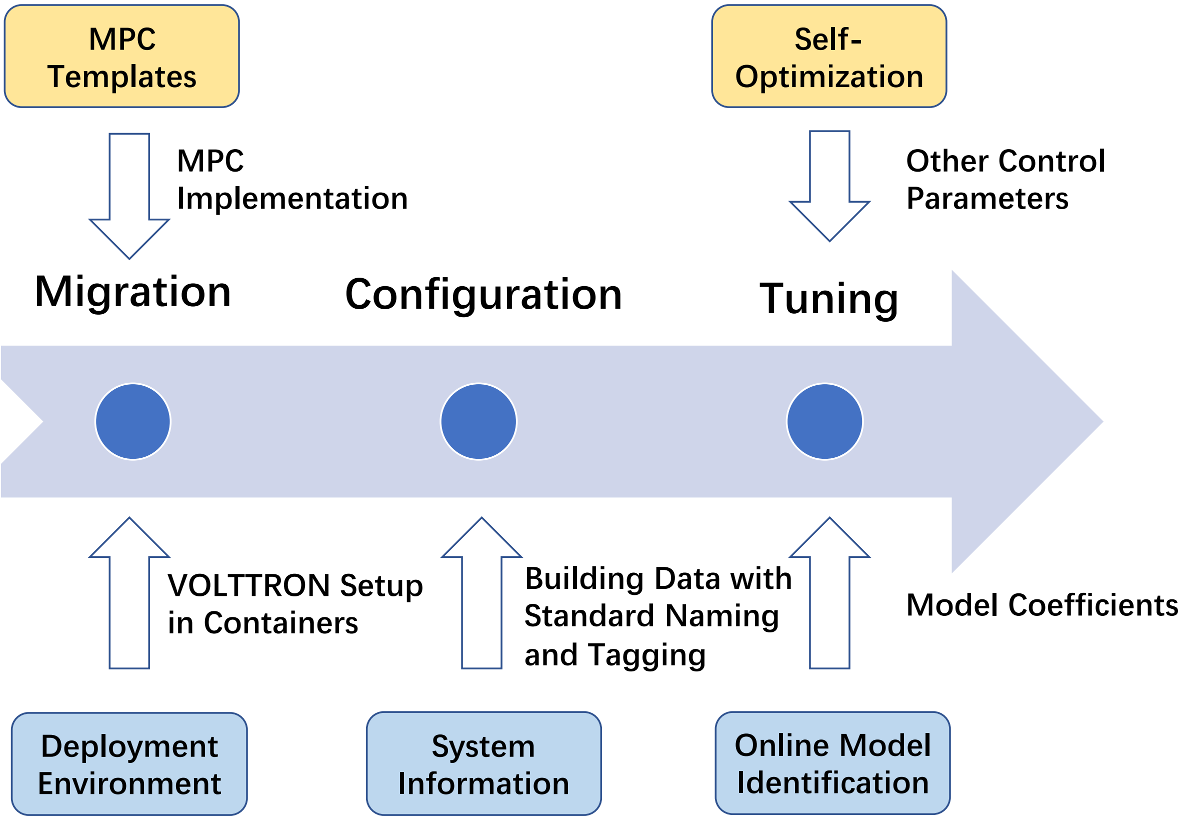

Figure 11: Plug-and-play MPC deployment.

In summary, the plug-and-play MPC provides a self-deployable MPC solution for small or medium-sized commercial buildings and requires nothing but the operating objectives from the building operators. The plug-and-play MPC will also generate a standard document for the deployed MPC that contains:

- Mathematical formulations of the optimization problem
- A table that contains values of all control parameters
- Assessment of the prediction accuracy of the ROM
- Estimation of the MPC control performances in terms of energy savings and enhancing thermal comfort compared to the baseline control.

The standard document expects to help smooth the learning curve for using MPC in real practice.

5.0 Testing and Validation

Testing and validation of the SC-SMB system will be done in two phases: (1) SC-SMB testing in a laboratory environment, and (2) testing and validation in real buildings in the field.

Two types of laboratory testing will be conducted. First, testing the SC-SMB system in a laboratory environment involves integrating with real thermostats, but not real RTUs. The laboratory testing will also include testing the hot water heater controller. Because of the various communication protocols required and the variety of devices to be connected, the laboratory environment ensures the supervisory controller can reliably communicate with the networked devices and validates the plug-and-play capabilities of the controller.

The second type of laboratory test will involve testing the SC-SMB system with connected thermostats in a real building on either the ORNL or PNNL campus. The details of this test have not been finalized yet.

The final testing and validation will be in real buildings with the preferred thermostats connected to RTUs. If the field test site includes a hot water heater and connected lighting, those devices will also be tested. The final testing will make sure the application can communicate with the thermostats and that the RTUs are being controlled according to the control application hosted on the supervisory controller. Remote management of the SC-SMB system will be validated as well.

For all connected devices, the following steps should be taken during testing:

1. Interrupt communications with the connected device/equipment. Confirm that the supervisory controller identifies the communication loss and that an appropriate alert is displayed on the front-end.
2. Review historical database and confirm that values of interest were logged correctly. Verify that trending capabilities of historical data display correctly on the supervisory controller's front-end. Confirm that communication loss is included in the trend data so that data from the respective devices during the communication loss period are not included in optimization algorithms.

Finally, the testing should also demonstrate that the supervisory controller is able to host the EE and GS applications.

5.1 RTU-Connected Thermostat

The SC-SMB system will wirelessly integrate with RTU-connected thermostats over BACnet/IP. The steps to configure and validate communications for the RTU-connected thermostat are outlined below.

1. Use the VOLTTRON BACnet auto-configuration script to automatically generate the driver configuration files for VOLTTRON. The script creates a device configuration file and a point mapping (registry) configuration file.
2. Edit the automatically generated registry configuration file point names. Standardized names will be used to ease configuration and integration with the SC-SMB supervisory controller.
3. Launch the BACnetProxy agent configured to use the local Wi-Fi network. Launch the PlatformDriver agent using the configurations from steps 1 and 2. These agents will scrape

the thermostat data (room temperature, setpoints, system state, etc.) and publish the thermostat data on the message bus for the SC-SMB supervisor and facilitate the control of the thermostat by the SC-SMB.

4. For lab testing, change the temperature near the thermostat and modify setpoints locally on the thermostat. Verify that the new temperature and setpoints were communicated to the SC-SMB supervisory controller.
5. Write to the thermostat heating and cooling setpoint analog values. Confirm on the thermostat local user interface that the heating and cooling setpoints were successfully changed.
6. Write to the economizer enable setpoint and occupancy schedule analog values. Confirm on the thermostat local user interface that the heating and cooling economizer enable setpoint and the occupancy schedule analog values were successfully changed.
7. Write to the room-temperature analog value (may require configuration on the thermostat to accept a remote temperature sensor). Confirm on the thermostat screen that the room temperature was successfully changed.
8. Shut down the supervisory controller and validate that the RTU thermostat reverts to the onboard temperature sensor and maintains acceptable heating and cooling setpoints.
9. Integrate multiple thermostats by repeating steps 1 through 8 to confirm multi-device monitoring and control.

5.2 Remote Temperature Sensors

Remote wireless LoRaWAN temperature sensors will communicate with the SC-SMB system through the LoRaWAN aggregator/gateway. The test procedure is the same if the communication protocol has been correctly configured on the supervisory controller.

1. Configure the supervisory controller with the appropriate communication protocol for the remote temperature sensor being tested.
2. Start the applicable VOLTTRON agent and MQTT broker if needed.
3. Confirm that the supervisory controller received the current temperature. Because the temperature sensor does not have a local user interface, confirm that the temperature reading was received by the supervisory controller with a second temperature sensor. Verify that the supervisory controller receives updated temperature readings by moving the temperature sensor to a different environment.
4. Verify that the supervisory controller's averaging calculation between multiple temperature sensors is correct. The average can be weighted, favoring one thermostat over another (see Equation (1)). Verify that this calculated average was communicated to the RTU thermostat.
5. Integrate multiple temperature sensors by repeating steps 1 through 4 to confirm multi-device monitoring.

$$T_{avg} = w_1 T_1 + w_2 T_2 + w_3 T_3 \tag{1}$$

where T_{avg} = Average temperature
$T_{\#}$ = Temperature sensor value
$w_{\#}$ = Temperature sensor weighting (all weights add up to 1)

5.3 Hot Water Heater

Ideally, the SC-SMB system will integrate with the hot water heaters' CTA-2045 communication module using BACnet via Wi-Fi. Vendor CTA-2045 BACnet support is limited, so another approach is to directly communicate through Wi-Fi with the hot water heater via a REST-like API. The steps to configure and validate communications for the hot water heater via BACnet are outlined below.

1. Use the VOLTTRON BACnet auto-configuration script to automatically generate the driver configuration files for VOLTTRON. The script creates a device configuration file and a point mapping (registry) configuration file.
2. Edit the automatically generated registry configuration file point names. Standardized names will be used to ease configuration and integration with the SC-SMB supervisory controller.
3. Start the BACnet agents and confirm that the supervisory controller is receiving data from the hot water heater (tank temperature, setpoint, system state, etc.). If the agents are already running, then the configurations generated in steps 1 and 2 need to be loaded into the configuration store[1] for the PlatformDriver.
4. To test device connectivity, change the hot water heater tank temperature and modify the tank setpoint locally. Verify that the new temperature and setpoints were communicated to the supervisory controller.
5. Write to the water heater's tank temperature setpoint analog value. Confirm on the water heater's local user interface that the tank setpoint was successfully changed.
6. Shut down the supervisory controller and validate that the water heater maintains an acceptable tank temperature setpoint.

Direct communication with the device via a vendor-supplied API will depend on the vendor specifications.

5.4 API-Based Devices

The SC-SMB system will integrate with API-based devices using VOLTTRON agents. An example of such an agent is the Ecobee agent, which was previously developed for VOLTTRON.

1. Configure the Ecobee agent and start it. Confirm that the supervisory controller is receiving data from the thermostat (room temperature, setpoints, system state, etc.). For lab testing, change the temperature near the thermostat and modify setpoints locally on the thermostat. Verify that the new temperature and setpoints were communicated to the supervisory controller.
2. Write to the thermostat heating and cooling setpoints via the API. Confirm on the thermostat local user interface that the heating and cooling setpoints were successfully changed.
3. Shut down the supervisory controller and validate that the Ecobee thermostat maintains acceptable heating and cooling setpoints.

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[1] https://volttron.readthedocs.io/en/main/platform-features/config-store/commandline-interface.html

5.5 Whole-Building Electricity Meter

Whole-building electricity meters will be integrated with BACnet/IP over Wi-Fi using the SC-SMB kit. The configuration and testing steps are outlined below.

1. Use the VOLTTRON BACnet auto-configuration script to automatically generate the driver configuration files for VOLTTRON. The script creates a device configuration file and a point mapping (registry) configuration file.
2. Edit the automatically generated registry configuration file point names. Standardized names will be used to ease configuration and integration with the SC-SMB supervisory controller.
3. Start the BACnet agents and confirm that the supervisory controller is receiving data from the electricity meter. If the agents are already running, then the configurations generated in steps 1 and 2 need to be loaded into the configuration store for the PlatformDriver.
4. Confirm that the supervisory controller is receiving data from the electricity meter (energy, demand, power factor) at required intervals.

5.6 Plug-and-Play Capabilities

One of the most important features of the SC-SMB kit is its plug-and-play capabilities. Configuring an additional device must be straightforward and not interfere with the monitoring or controls of the existing set of connected devices. To enable plug-and-play capabilities, the following features are essential:

- Use of a standard naming convention for device data and control points on connected thermostats and other connected devices (e.g., water heaters, wireless sensors).
- Standard suite of control applications for connected devices. For example, all connected thermostats will support integration of the scheduling manager, optimal start, and setpoint control manager applications within the SC-SMB.

Users can interact with the SC-SMB through the SC-SMB web interface. Here, the plug-and-play capabilities of the SC-SMB will allow users to quickly integrate connected devices to the SC-SMB and configure those devices with minimal effort to optimize the building's performance and realize better comfort for occupants.

6.0 Next Steps

The next step is to procure the necessary connected thermostats and hot water heater interface and to set up a laboratory test environment for testing and validating the SC-SMB system reference design. After successful completion of the laboratory testing, select 3 to 5 field test sites for field testing and validation of the SC-SMB system.

7.0 References

ANSI/CTA-2045. 2021. Consumer Technology Association.

Energy Information Administration. 2018. “Commercial Buildings Energy Consumption Survey.” Accessed May 2021. https://www.eia.gov/consumption/commercial/data/2018/.

Fernandez, N., S. Katipamula, W. Wang, Y. Xie, and M. Zhao. 2018. “Energy Savings Potential from Improved Building Controls for the US Commercial Building Sector.” Energy Efficiency, 11(2):393 413. DOI: https://doi.org/10.1007/s12053-017-9569-5.

Katipamula S., R.M. Underhill, J.K. Goddard, D.J. Taasevigen, M.A. Piette, J. Granderson, and R.E. Brown, et al. 2012. “Small- and Medium-Sized Commercial Building Monitoring and Controls Needs: A Scoping Study.” PNNL-22169. Richland, WA: Pacific Northwest National Laboratory.

Kim W., S. Katipamula, and R.G. Lutes. 2020. "Application of Intelligent Load Control to Manage Building Loads to Support Rapid Growth of Distributed Renewable Generation." *Sustainable Cities and Society* 53. PNNL-SA-143847. doi:10.1016/j.scs.2019.101898.

Kim W., and S. Katipamula. 2017. "Development and Validation of an Intelligent Load Control Algorithm." *Energy and Buildings 135*. PNNL-SA-116744. doi:10.1016/j.enbuild.2016.11.040.

Kim W., S. Katipamula, R.G. Lutes, and R.M. Underhill. 2016. “Behind the Meter Grid Services: Intelligent Load Control.” PNNL-26034. Richland, WA: Pacific Northwest National Laboratory. Behind the Meter Grid Services: Intelligent Load Control.

LoRaWAN. 2023. LoRa Alliance. https://lora-alliance.org/about-lorawan/.

Malinick, T., N. Wilairat, J. Holmes and L. Perry. 2012. “Destined to Disappoint: Programmable Thermostat Savings are Only as Good as the Assumptions about Their Operating Characteristics.” ACEEE Summer Study on Energy Efficiency in Buildings.

Pacific Northwest
National Laboratory

902 Battelle Boulevard
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Richland, WA 99354

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