Commercial Building Sensors and Controls Systems – Barriers, Drivers, and Costs

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National Renewable Energy Laboratory

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The Joint Institute for Strategic Energy Analysis is operated by the Alliance for Sustainable Energy, LLC, on behalf of the U.S. Department of Energy's National Renewable Energy Laboratory, the University of Colorado-Boulder, the Colorado School of Mines, the Colorado State University, the Massachusetts Institute of Technology, and Stanford University.

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List of Acronyms

AHU	air handling unit
BAS	building automation system
DDC	direct digital control
DOE	U.S. Department of Energy
DX	direct expansion
ERV	energy recovery ventilation
GEB	grid-interactive efficient building
GSA	U.S. General Services Administration
HVAC	heating, ventilating, and air conditioning
IoT	Internet of Things
MA	mixed air
MUX	multiplexer
RTU	rooftop unit
VAV	variable air volume
VFD	variable frequency drive

Executive Summary

The National Renewable Energy Laboratory, under the Clean Energy Manufacturing Analysis Center, investigated the barriers and drivers for adopting commercial building sensors and controls systems to provide insight into how to encourage more widespread adoption. The project assessed sensors and controls system costs, including the breakdown of hardware and various labor costs associated with the installation of these systems. This report also discusses other cost implications including building size, geographic location, and project scope. Key objectives of this project and report include:

- Identifying the barriers and drivers for implementing sensors and controls systems in commercial buildings
- Characterizing the breakdown of costs for commercial building sensors and controls systems.

We used a mixed-method approach to address the key objectives and collected qualitative data from interviews with stakeholders and sensors and controls system experts. We gathered quantitative cost data from original sources including project invoices and estimates, RSMeans, available U.S. General Services Administration schedule cost information from various manufacturers, and other cost data provided by interviewees.

Table ES-1 lists key barriers identified by various stakeholders.

Table ES-1. Interviewee-Identified Barriers for Implementing Control Systems

Identified Barrier	Barrier Description
High Cost	There is a perception that the costs for building sensors and controls systems are too high. This includes installation costs, replacement costs, and operations and maintenance costs.
Difficulty in Quantifying Savings	It is difficult to quantify the full value of building controls, including energy cost savings associated with control system installation and nonenergy benefits such as operations savings.
Product Incompatibility	There is a need for an industry standard ontology for building control systems, enabling plug-and-play applications across vendors.
Inconsistent Terminology in Vendor Communication	Vendor communication to owners can be complicated and inconsistent. Owners and representatives may not have adequate background knowledge of these systems, leading to an inability to make the most appropriate decision.
Lack of Economies of Scale	There is limited cost advantage to scaling down control systems for smaller commercial buildings.
System Complexity	Systems are complex—they consist of numerous devices and controllers that require expertise to effectively and efficiently operate systems.
Lack of Expertise	Often personnel at individual facilities have limited training; have multiple roles, including control system operation; and may have to interface with multiple systems at various facilities.
Other Barriers	Other barriers include equipment complexities, split incentives and associated challenges, and cybersecurity considerations.

Table ES-2 lists key drivers identified by various stakeholders.

Table ES-2. Interviewee-Identified Drivers for Implementing Control Systems

Identified Barrier	Driver Description
Operational Benefits	Systems may fail to meet a building owner's investment criteria because of high first costs. In addition, there is a perception that the costs for building sensors and controls systems are too high. This includes installation costs, replacement costs, and operations and maintenance costs.
Insight Into Operations	These systems compile building data that allow building owners to objectively assess the building's status and make appropriate changes. The data allow operators to perform root cause analysis of problems, understand space utilization, and adjust operation to improve performance.
Remote Access to Data and Controls	Systems often provide remote access to building operation data, so the engineer doesn't need to be in the building to control the building.
Cost Savings	These systems can help optimize building performance, saving the owner money over time.
Energy Savings	Sensors and controls systems save energy and reduce peak loads.
Ease of Use	Sensors and controls systems can be straightforward to integrate and they make building operations simpler.

The costs for commercial building sensors and controls systems vary based on building size, heating, ventilating, and air-conditioning system type, and the number of control system points as well as other factors; geographic location, for example, influences labor rates. The cost breakdown for a number of common heating, ventilating, and air-conditioning system types in U.S. commercial buildings is summarized in the Figure ES-1.

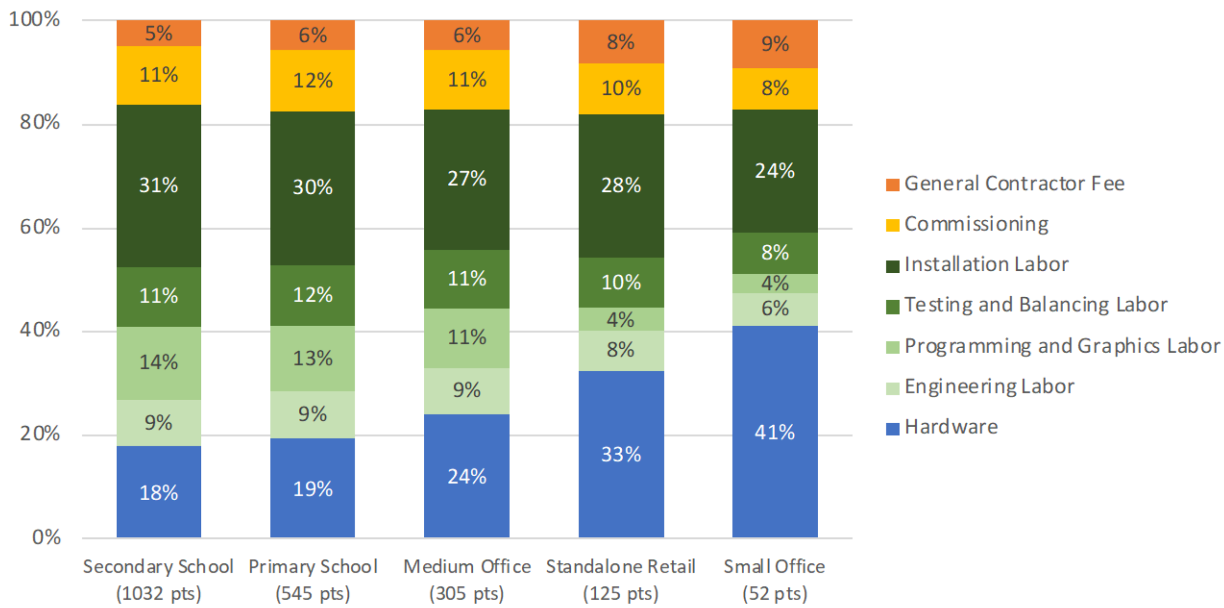

Figure ES-1. Cost breakdown comparison for complete control systems

Note: The number of system control points for each building is included in parentheses.

Key findings from our qualitative and quantitative analyses include:

- Most commercial building sensors and controls system costs come from labor.
- The complexity of these control systems is a significant barrier to adoption and can lead to specialized labor requirements and associated labor costs. A cost-reduction strategy might be to embed controllers at equipment similar to the way edge computing networks operate, which conceptually reduces the number of devices and controllers and the associated labor costs.
- Consistency and standardization across controls technologies to enhance system interoperability as well as increasing the approachability of these systems for users and facility operators may provide opportunities to increase the adoption of these systems, especially for buildings that have not historically implemented these technologies.

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1 Introduction

The U.S. Department of Energy (DOE) Building Technologies Office has significant energy savings goals for commercial buildings and has estimated that optimized performance using sensors and controls systems could lead to an aggregated 29% annual energy savings across all building types (Fernandez et al. 2017). In addition, commercial building sensors and controls systems enable grid-interactive efficient buildings (GEBs) to dispatch demand flexibility to provide grid services. GEBs can provide comfort for building occupants, sell services to the power grid, cut costs, and reduce carbon emissions (Neukomm, Nubbe, and Fares 2019). These control systems use data from sensors as input for programmed control sequences to direct functionality of a building's systems, such as heating, ventilating, and air conditioning (HVAC), lighting, and in some cases, plug and process loads. A popular example is the building automation system (BAS), a network of hardware, software, sensors, and controls that aids and automates the operation of the building's systems. The BAS most commonly controls HVAC systems, but other systems can be integrated into it.

Although nearly 60% of commercial buildings larger than 50,000 ft^2 report having a BAS to control HVAC systems, only 13% of small to medium buildings (smaller than 50,000 ft^2) in the United States have adopted them (CBECS 2018). Because small commercial buildings represent more than 90% of the building stock, Commercial Buildings Energy Consumptions Survey (CBECS) data suggest that fewer than 20% of commercial buildings in the United States use BAS systems at all. Even fewer report integration of lighting controls into the BAS. Figure 1 summarizes the adoption rates from the most recent CBECS survey (CBECS 2018) for BAS control of HVAC, lighting, and internet-based smart thermostats.

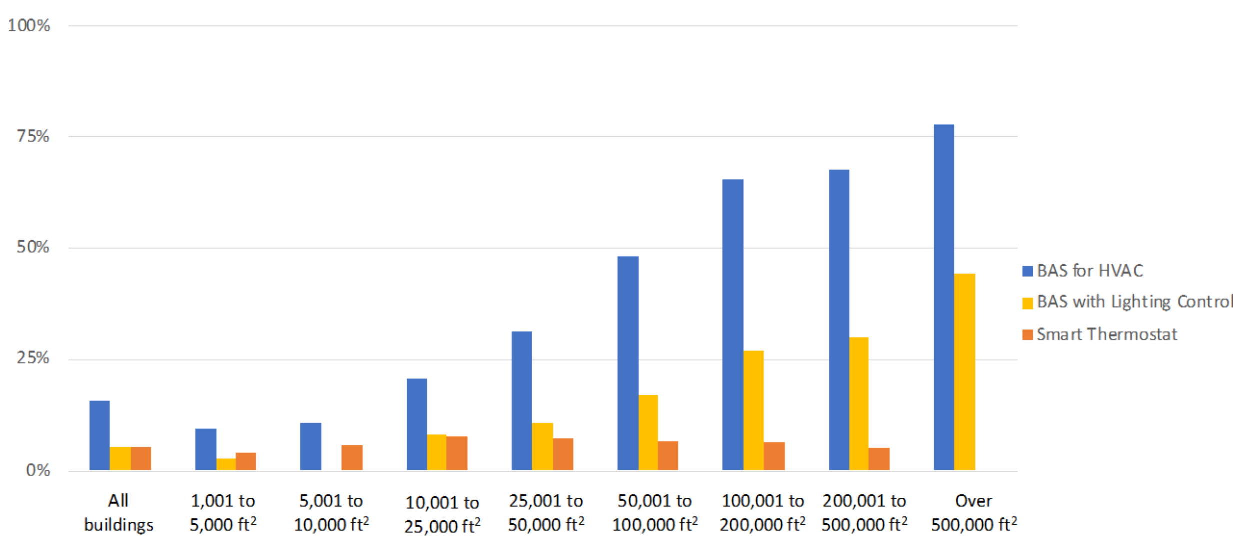

Figure 1. Summary of reported use of control systems in commercial buildings (CBECS 2018)

Radhakrishnan and others (Radhakrishnan et al. 2020) documented a number of barriers related to the adoption of controls including:

- Perception of prohibitive installation and maintenance costs

- Building owner's uncertainty about the cost-benefit trade-off
- Relatively large capital expenditure
- Lack of interoperability that holds consumers to one technology and therefore its pricing.

Although these barriers have multiple facets, there is a clear need to understand how costs for systems impact adoption. In addition, there is a need to clarify the additional non-cost barriers and drivers in order to accelerate the adoption and effectiveness of commercial building control systems, leading to realized energy savings, increased grid interactivity, and accelerated decarbonization of the U.S. electric grid.

This report documents the barriers and drivers for adopting HVAC control systems and provides insights into how to encourage BAS uptake. It summarizes BAS hardware and labor costs as a function of building size, geographic location, and project scope. The findings are based on mixed-method research, discussed in subsequent sections.

The research in this report is guided by the following questions:

- What is the breakdown of costs for commercial building sensors and controls systems?
- What are the barriers to implementing sensors and controls systems in commercial buildings?
- What are the drivers for implementing sensors and controls systems in commercial buildings?

1.1 Background

To aid in summarizing the otherwise complex landscape of commercial building sensors and controls systems, particularly for integrated HVAC system control, this paper conceptualizes these systems as comprising five layers: field devices, field controllers, automation controllers, automation software, and analytics, where lower-level layers are needed to support the higher ones. Legacy control systems based on pneumatic technologies still exist; however, this work focuses on electronic or digital control systems. Figure 2 depicts this conceptualization.

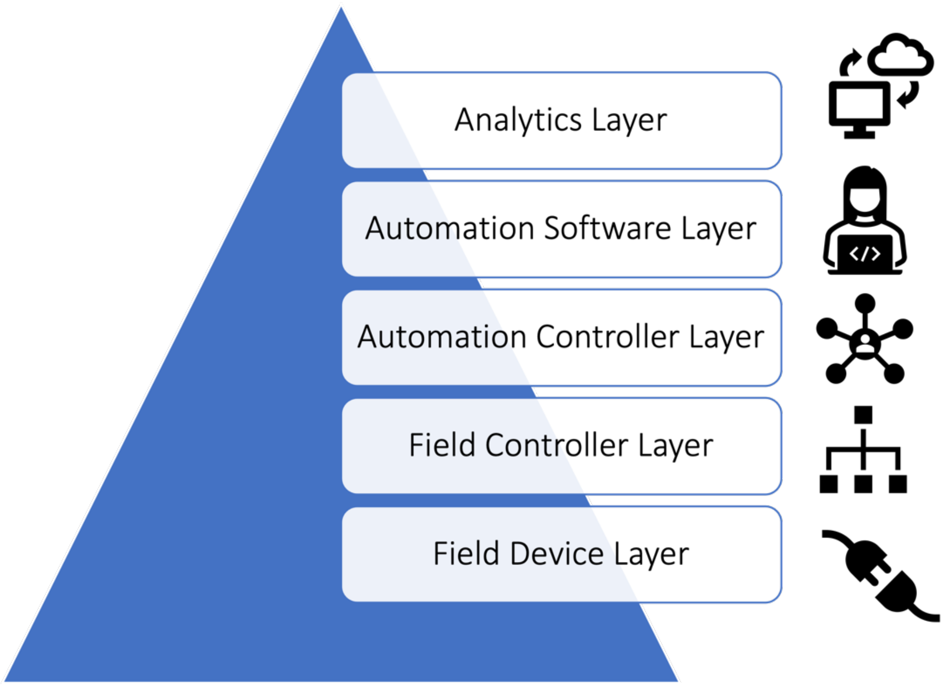

Figure 2. Summary of conceptualized building automation system control layers

The **field device** layer is the lowest level. Field devices include all types of sensors such as temperature and humidity as well as damper actuators, valves with associated actuators, variable speed drives, power meters, switches, and more. These devices send input data to, and receive actionable commands from, field controllers.

The **field controller** layer contains direct digital controls (DDCs) that are usually deployed close to the field devices and have multiple input and output channels. Field controllers use onboard logic to directly control and respond to field devices. In addition to controlling field devices, these controllers also communicate with the automation layer controllers using standard communication protocols for commercial building controls including BACnet,[1] Lon,[2] or Modbus.[3] These communication protocols are also standard for many applications and equipment.

The **automation controller** layer provides supervisory-level control of various networks that include many field devices and field controllers over various automation communication protocols, including BACnet, Modbus, and Lon. Some of the automation controllers used in the industry include Desigo PXC controllers[4] (Siemens), AS-P[5] (Schneider), and Metasys NAE[6]

[1] http://www.bacnet.org
[2] http://www.echelon.com
[3] https://modbus.org
[4] https://new.siemens.com/global/en/products/buildings/automation/desigo/automation-controls/desigo-pxc.html
[5] https://www.se.com/id/en/product/SXWASPXXX10001/smartx-controller-as-p/
[6] https://www.johnsoncontrols.com/building-automation-and-controls/building-management/building-automation-systems-bas/network-automation-engines

(Johnson Controls). Most automation controllers have expansion input/output modules to accommodate more input and output ports depending on system size and complexity.

The **automation software** layer includes applications, workstations, and data servers providing the platform for BAS data services such as storage, processing, and securing. Different control companies have custom and often proprietary application software for BAS including Metasys[7] (Johnson Controls), StruxureWare[8] (Schneider), Desigo (Siemens),[9] and Apogee[10] (Siemens). This layer is typically how users can interact with the larger system.

The **analytics layer** is the top layer of our conceptualized control system architecture. The analytics layer includes software that analyzes the data collected by the automation layers to provide the user with actionable insight about the building's operation. Two common types of analytics platforms are energy information systems, including those that provide visualizations of energy use, and platforms that provide automated fault detection and diagnosis, which are systems that use logic to identify whether building equipment is running properly (Kramer et al. 2020). There are a growing number of analytics companies, many with software that sits on top of most BASs, and there are also vertically integrated control companies that offer products for each layer of the architecture shown in Figure 2.

Other related work has focused on cost analysis of the analytics layer referenced in Figure 2 (Granderson and Lin 2016, Kramer et al. 2020). The cost analysis effort summarized in this report focuses on the layers beneath. An important output of this report is a breakdown of the cost contributions such as hardware, software, labor, installation, commissioning, calibration, and maintenance; it excludes any analytics software that would incur additional implementation costs.

Decarbonization and GEB uptake will require market transformation. Commercial building sensors and controls system technology will need to be affordable in order to appeal to all building types and sizes, and cost transparency is a path to understanding the opportunities that aid and catalyze this transformation. Transparency provides information to help building owners choose control systems and also helps DOE's Building Technologies Office allocate funding for research focused on reducing cost or other barriers.

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[7] https://www.johnsoncontrols.com/building-automation-and-controls/building-management/building-automation-systems-bas
[8] https://www.se.com/us/en/product-category/50100-building-management/
[9] https://new.siemens.com/global/en/products/buildings/automation/desigo.html
[10] https://new.siemens.com/us/en/products/buildingtechnologies/automation/apogee/controls.html

2 Methodology

We used a mixed-method approach to address the research goals. We collected qualitative data from interviews with sensors and controls systems experts. We gathered quantitative cost data from original sources including project invoices and estimates, the RSMeans (RSMeans 2021) costing database, available U.S. General Services Administration (GSA) schedule cost information from various manufacturers, and other cost data provided by interviewees.

We investigated multiple other sources of information. We conducted a literature search, which yielded eight journal papers, one handbook, and one survey. However, none of these sources provided the comprehensive cost data required. We reviewed various electronic technical resource manuals, but found that they too had limited cost data, and the data were typically specified for a single sensor or controller unique to a single piece of building equipment (e.g., boiler temperature reset).

We planned and launched a revised campaign that marketed the benefits of participation to three expert types: building owners, controls contractors, and controls vendors. Participants were recruited through email and social media (LinkedIn).

The outreach effort was successful in generating a response and produced both qualitative and quantitative data. Section 2.1 further describes our approach for qualitative data collection and analysis. As described in Section 2.2, we secured whole building cost totals from the portfolios of two interviewees as well as an expense form for one building and a statement of value for another. We used the cost data provided by the interviewees and the quantitative cost-related data in RSMeans and the GSA schedules for the quantitative analysis. We further describe the data collection and analysis methodologies from these RSMeans and GSA schedules in Section 2.2.

2.1 Qualitative Methods

Our qualitative methods included interviewing experts and using qualitative research methods to analyze the data. In this subsection, we describe these methods.

2.1.1 Interviews

Our qualitative data came from interviews with sensors and controls experts. We framed our interview questions from our overarching research questions. Different sets of questions were written for each category of industry expert (building owners, controls contractors, and vendors).

We validated the interview protocols through think-aloud interviews with two commercial building experts who were not a part of the research team. We improved the clarity of the questions based on the feedback. The finalized interview protocols are in Appendix B.

We conducted 21 interviews with a total of 28 experts. When multiple people were interviewed, they represented the same organization. Figure 3 shows the industry role of the party being interviewed.

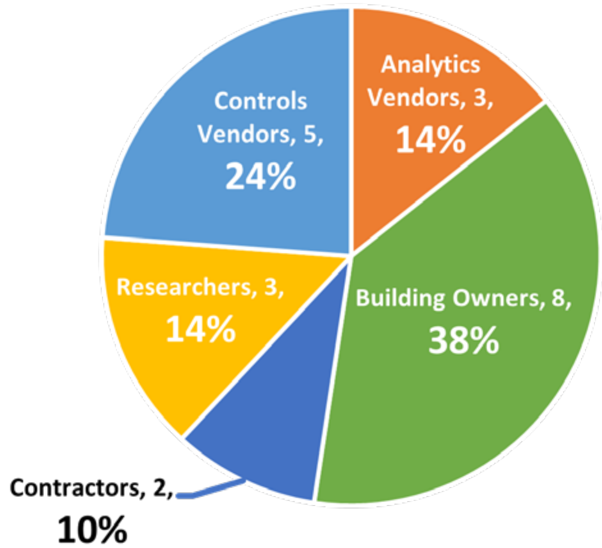

Figure 3. Breakdown of interviews by role in industry. There are 21 interviews total.

The experts represented five different industry roles:

- **Building owners** own and operate a building. They represented K–12 schools, higher education, retail, state government, and the federal government. Entities that work with building owners in their sensors and controls system purchase decisions are also included in this category. The eight building owner interviews included 13 individuals because two included three interviewees and one included two interviewees.
- **Contractors** are companies that provide building control engineering and are mostly independent from a hardware vendor. They represent two of the interviews.
- **Controls vendors** are manufacturers and sellers of BASs and commercial buildings controls or control system implementers. There were five control vendor interviews, and two included two interviewees each. The interviewees included senior leaders such as chief executive officers.
- **Analytics vendors** are companies that develop and sell analytics platforms such as energy information systems. These platforms are the analytics layer of Figure 2 and integrate on top of the automation software layer. There were three analytics vendor interviews and interviewees included company chief executive officers and other staff.
- **Researchers** are commercial building sensors and controls systems experts with deep understanding of building controls technology or the controls market. They do not represent an organization that is directly impacted by the sensors and controls industry. There are three researcher interviews.

We scheduled the interviews for 30 minutes. Many interviews lasted 30 minutes, but some lasted up to an hour. At least two National Renewable Energy Laboratory researchers were present during each interview. One had the role of lead interviewer and conducted the interview, asking follow-on questions as needed. The other members of the interview team took notes, with the goal of capturing as much of the interviewee’s statements as possible. If there were two notetakers, the notetakers took notes on separate documents and combined them afterwards. The notes consisted of direct quotes and summarizations of information. At the end of the data collection, there were 21 documents of interview data.

2.1.2 Analysis

We used grounded theory (Glaser and Strauss 1967) to analyze the interview data. We coded the interview data, interpreting it through the lens defined by our research questions. Our codes were often for one to two sentence portions of the interview data. During coding, trends began to emerge, and we grouped codes and the related data of the same topic into categories. Our analysis of each category included comparing and contrasting the codes and documenting the trends that became the results of this work. We validated our analyses by having multiple researchers evaluate the data.

2.2 Quantitative Methods

This section includes the description of the quantitative cost data. We used two industry standard resources—RSMeans and the GSA schedules and data library—to compile cost ranges specific to the various devices, controllers, and associated labor on the market today. In addition, project-specific cost data were collected through the interview process for a select set of example projects.

2.2.1 Data Sources

The sections below describe the data sources used for the quantitative analysis. It is important to point out that quantitative cost data collection focused on component and installation first costs and did not focus on acquiring cost data for annual BAS software subscriptions, licenses, or any maintenance contracts associated with these systems. We found that these ongoing costs vary widely by vendor and project, and we discuss the results in Section 5.

2.2.1.1 RSMeans

RSMeans is an industry standard construction cost estimating data set (RSMeans 2021). The data set includes more than 90,000 line-item costs associated with construction projects across all building systems, including sensors and controls. We aggregated cost information in similar categories (sensors, digital input and output alarms, controller multiplexer [MUX] panel, DDC controller, and front end) to quantitatively understand the range of costs, including minimum, maximum, and average values. Cost information in RSMeans for each line item relating to digital control systems of commercial building HVAC systems included a combined material and labor cost. Therefore, other industry sources were required to ultimately understand cost stacks related to building sensors and controls systems. Table A-1 in Appendix A summarizes HVAC-related sensors and controls costs obtained from RSMeans.

2.2.1.2 U.S. General Services Administration Schedules

GSA Advantage (GSA 2021) is a website owned by GSA. It hosts, among other negotiated construction contracts, hardware costs for various BAS equipment. GSA, representing the federal government, negotiates prices with vendors. Many major sensors and controls vendors have provided their pricing, including Siemens, Johnson Controls, Honeywell, and Trane. The hardware costs were used in conjunction with the RSMeans combined hardware and installation costs to develop a cost breakdown discussed in Section 4. We compiled cost information from three vendors that represent most of the market share for sensors and controls systems with integrated HVAC control within the commercial building sector: Siemens, Johnson Controls, and Honeywell. Table A-2 in Appendix A summarizes the combined hardware-related costs collected from these vendors.

2.2.1.3 Project-Specific Cost Data

From the interviews, we collected project installation cost data for 18 buildings, including office buildings, elementary schools, and secondary schools. In all cases, the data included project size in square feet, total project cost, and building type. The number of system control points was also provided for 7 projects. We acquired detailed cost breakdowns for two of the secondary school projects and included project costs for project management, engineering, commissioning, programming, graphics, testing and balancing, installation, and the general contractor fee. Section 4.1 provides detailed definitions for these cost categories.

It is important to note that the project costs we acquired from interviews represented renovation projects where the scope encompassed some sort of upgrade or replacement of an existing control system. The details and implications of various project scope categories on project costs are discussed in Section 4. No data were acquired summarizing the costs of a complete system, such as a new construction project. We hypothesize that complete system costs can be difficult to extract from project cost information because multiple trades and subcontractors are often involved in the installation of a control system with integrated HVAC control, and these various trades and subcontractors are not necessarily required to itemize costs of the components and labor for all aspects of the control system in isolation.

2.2.2 Data Analysis

2.2.2.1 Complete System Costs for Prototypical Reference Buildings

We developed a methodology to create a complete control system installation cost breakdown to compare with project-specific data. The methodology we developed is discussed here.

The approach used RSMeans and GSA Schedule cost data to estimate the total project cost and cost breakdown for a complete BAS system for an example set of prototypical commercial buildings. The prototypical buildings were generated from the DOE Prototype Commercial Buildings Models (prototype models) from the DOE Building Energy Codes Program (BECP 2021), which serve as the basis of detailed EnergyPlus building energy models. The prototype models provide common HVAC system configurations for various building types. The basic methodology is summarized as follows and is shown graphically in Figure 4:

- First, we developed a comprehensive control point list based on the HVAC system configurations in the prototype models
- Then we used the RSMeans and GSA Schedule cost data to calculate the system costs and cost breakdown for a complete BAS for HVAC system control.

Figure 4. Workflow for development of cost stack from U.S. Department of Energy (DOE) prototype building energy model

We modified the prototypical building models for the purpose of generating a comprehensive control point list. The prototypical models do not necessarily reference exact equipment counts or take into consideration equipment redundancies and other considerations found in real buildings as these are not necessary to perform energy simulations. Table 1 summarizes the prototype building models selected for this study and shows they represent a range of building sizes and predominant HVAC system types found in commercial buildings. More detailed descriptions of these buildings and HVAC systems can be found in Appendix C.

Table 1. Prototype Building Model and HVAC System Summary for Complete Systems Costs

Building Type	Total Area (ft^2)	Primary HVAC System Summary
Secondary School	210,900	Variable air volume (VAV) system with energy recovery ventilation (ERV). Heating provided by central boiler plant. Cooling provided by central chiller plant.
Primary School	74,000	Packaged variable air volume system with direct expansion (DX) cooling and ERV. Heating provided by central boiler plant.
Medium Office	53,600	Packaged variable air volume system with DX cooling and gas-fired heating.
Stand-Alone Retail	24,700	Packaged constant volume rooftop units (RTUs) with DX cooling and gas-fired heating.
Small Office	5,500	Packaged constant volume RTUs with DX cooling and gas-fired heating.

The adjustments made to the prototype models in order to generate a comprehensive HVAC control point list included:

- Adjusting the number of VAV boxes
- Adding primary HVAC equipment redundancy such as boilers and/or chillers
- Adding central return fans to air handling equipment
- Adjusting the number of packaged constant volume RTUs to represent common industry RTU sizes: 5-ton units for the stand-alone retail building and 2.5-ton units for the small office.

A detailed description of these changes is included in Appendix C. The focus of this effort was not specifically to create a comprehensive list for all prototypical buildings, but to try to capture many typical HVAC system configurations across a range of building types and sizes.

Once a comprehensive control point list was created for HVAC system control, we used RSMeans cost information and GSA Schedule hardware cost data to estimate the total project costs and the cost breakdown between hardware and various labor categories. Front-end costs and other costs such as commissioning and testing and balancing were included and are discussed in detail in Section 4.

2.2.2.2 Regionalized Labor Rates

Project-specific data collected through the interview process and the associated costs are based on local pricing and labor rates for the region where the specific project is executed. Labor rates need to be normalized in order to compare any project-specific data with costs generated from the prototypical building models for a complete system described in Section 2.2.2.1. RSMeans provides labor rate adjustments based on the project year and location as well as a national average rate for a given year. Any adjustments to cost data related to regionalized or national average labor rates utilized RSMeans.

3 Qualitative Results: Barriers and Drivers

This section presents results from applying the qualitative methods discussed in Section 2.1 to analyze the qualitative data collected during the interview process. We asked the interviewees questions about the following topics:

- Building sensors and controls cost breakdown
- Barriers to implementing commercial building sensors and controls systems
- Drivers for implementing commercial building sensors and controls systems.

The building sensors and controls cost breakdown focuses on the interviewee-described numerical costs and percentages. The data summary that results from this category is in Section 5 because we compare it to the quantitative analysis in Section 4. The results of the second and third topics, the barriers to and drivers for implementing commercial building control systems are described in detail in this section.

3.1 Barriers to Implementing Control Systems

Table 2 summarizes the major barriers to implementing commercial building sensors and controls systems mentioned in the interview process.

Table 2. Interviewee-Identified Barriers for Implementing Control Systems

Identified Barrier	Barrier Description
High Cost	Systems may fail to meet a building owner's investment criteria because of high first costs. In addition, there is a perception that the costs for building sensors and controls systems are too high. This includes installation costs, replacement costs, and operations and maintenance costs.
Difficulty in Quantifying Savings	It is difficult to quantify the full value of building controls, including energy cost savings associated with control system installation and nonenergy benefits such as operations savings.
Product Incompatibility	There is a need for an industry standard ontology for building control systems, enabling plug-and-play applications across vendors.
Inconsistent Terminology in Vendor Communication	Vendor communication to owners can be complicated and inconsistent. Owners and representatives may not have adequate background knowledge of these systems, making informed decisions difficult.
Lack of Economies of Scale	There is limited cost advantage to scaling down control systems for smaller commercial buildings.
System Complexity	Systems are complex—they consist of numerous devices and controllers that require expertise to effectively and efficiently operate systems.
Lack of Expertise	Often personnel at individual facilities have limited training; have multiple roles, including control system operation; and may have to interface with multiple systems at various facilities.
Other Barriers	Other barriers include equipment complexities, split incentives and associated challenges, and cybersecurity considerations.

These barriers, as shown in Figure 5, fall naturally into three categories: system complexity, user skills, and financial. Although the initial hypothesis that costs (both implementation and ongoing maintenance) are barriers appears to be validated, our analysis revealed other important underlying barriers associated with the complexity of these systems and their lack of standardization, often requiring experts on staff and additional trainings to adequately maintain or make ongoing adjustments during operation. This result suggests that simple and interoperable systems that provide proven customer savings may contribute to an increased uptake of commercial building sensors and controls systems.

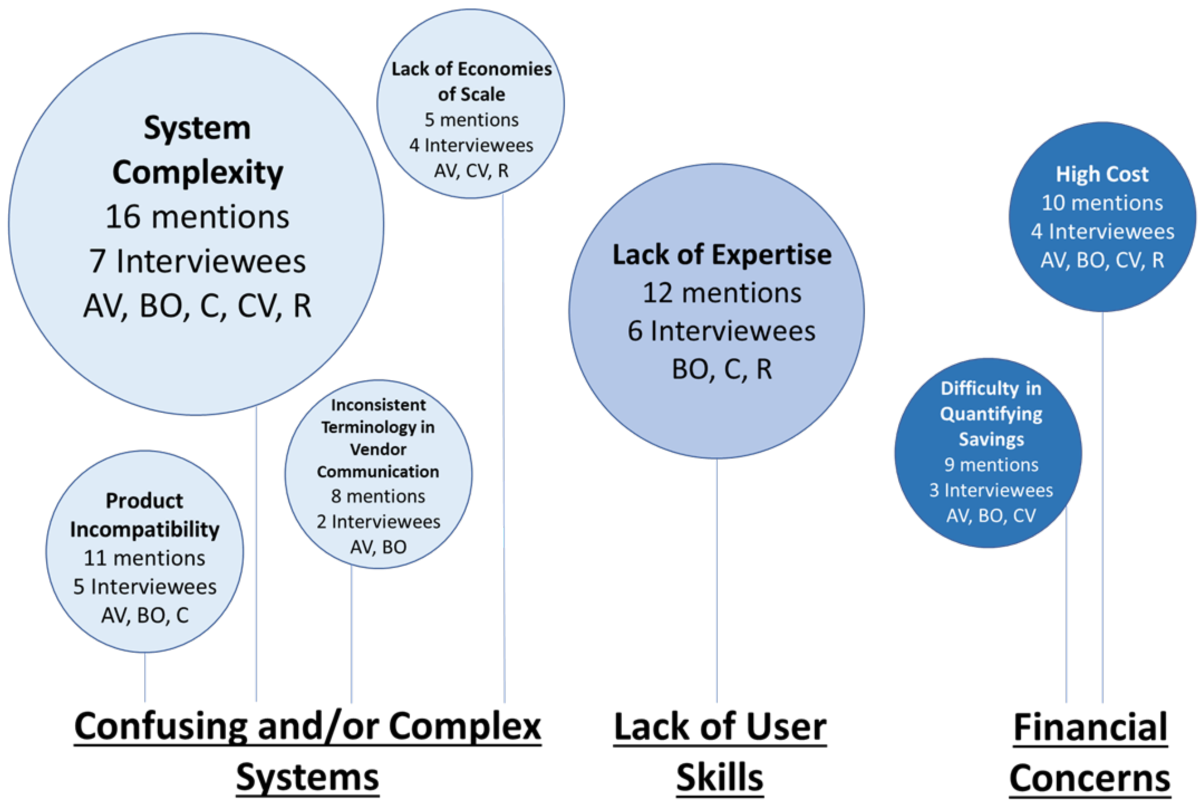

Figure 5. Barriers and number of mentions

Key: Building owners (BO), analytics vendors (AV), controls vendors (CV), contractors (C), and researchers (R)

Each barrier identified through analysis of the interviews is described in detail below. The descriptions stem directly from interview analysis.

3.1.1 High Cost

Although buildings owners might be excited about installing building controls, the systems may fail to meet their investment criteria because of high first costs. One analytics vendor said that "The issue is cost, not technical," arguing that technology is not lacking. There is a perception that the controls vendors with significant market share are expensive and do not negotiate, as evidenced by a second interviewee, a researcher. Also, a former controls company executive pointed out that "cost will be a driver but is now a critical barrier."

The high up-front cost of building controls systems is specifically noted from interview data. An analytics vendor said that typical customers "want cheap up front" despite the fact that the cheap option may not allow them to capture all the potential savings over the life of the system. He pointed out that there are some "forward-thinking customers" who would be interested in paying more up front to achieve larger savings. The large up-front cost of these systems could deter building owners who view the systems as optional.

A researcher hypothesized that the lack of market adoption is another factor that increased cost, stating, "[building controls] companies are working with very limited adoption; it's economy of scales." The researcher compares this to a sensor-based product ubiquitous in buildings, "at home we always have at least one sensor—the smoke detector." Whether or not ubiquity of building controls technology will reduce costs is yet to be determined, but increased use would likely impact pricing.

3.1.2 Difficulty in Quantifying Savings

Cost savings is a commonly used value proposition for building control systems. Studies have shown that the aggregated impact of widespread adoption may yield a 29% energy cost reduction across the commercial building section (Fernandez et al. 2017). We understand that a finding focused on the aggregated impact does not mean every building may achieve these same energy cost savings. Yet, based on the interview data, there is also a lack of quantified nonenergy savings for building sensors and controls systems that could improve the value proposition of these systems for more owners.

Communicating the value, including nonenergy benefits such as operational savings, is sometimes difficult. This lack of documented savings and value is a barrier because if the perceived value is less than the cost to install and operate, then building owners could decide against implementation.

High costs and a lack of quantified nonenergy benefits lead to a perception that return-on-investment targets and short payback periods will not be achieved. This is especially true for small building owners. A controls contractor commented, "Small buildings owners do not want to adopt mainly because of cost. It is a long investment for a small building owner." Similarly, an interviewed building owner said "2.5- to 3-year payback periods are typically expected for this technology, but the price points do not meet required paybacks and rates of return." There is a documented lack of implementation by small buildings (shown in Figure 1).

Proving value is important. One of the vendors said, "I think that's the issue, the cost and how do we show people that we can save a lot of money with sensors." Similar to other energy efficiency measures, proving and then capturing savings is a challenge. It is also important to prove the value of benefits other than energy savings. One analytics vendor stated, "Sometimes energy consumption goes up [after] retrofits because of the increased comfort." Adoption will increase as more building owners understand the true value proposition.

3.1.3 Product Incompatibility

Building controls manufacturers secure clients by maintaining highly proprietary systems and offering products that only work with their other products. Once a customer installs equipment, it is unlikely to work with another manufacturer's equipment. But this siloed and proprietary approach is blocking additional market uptake and the success of building control and automation companies. An emerging solution is semantic interoperability that allows devices from different manufacturers to integrate with each other in a plug-and-play manner.

Semantic interoperability enables digital systems to exchange data and the associated meaning of the data points between different information systems. There is a need for an industry standard ontology describing these systems, which would allow control systems from different manufacturers to automatically communicate with each other.

The vendors described a need to resolve the product incompatibility barrier by developing an industry-accepted semantic interoperability standard. A controls vendor emphasized the need for a semantic interoperability standard. An analytics vendor described lack of standardization as the "biggest problem," and went on to say, "there is the technology, but there is no industry standard…But this needs to come from the policy, there need to be standards from ASHRAE."

Building owners are demanding a semantic interoperability standard. The analytics vendor said "The [big box stores] of this world will be pushing this [interoperability] effort…they have pushed the industry to build open protocol so that on the job everything just works together [controls companies] have to build software that allows that to happen." So, although there is a demand for interoperable control systems, it is not something that has been successfully accomplished.

Despite efforts to achieve semantic interoperability through the ongoing development of Project Haystack (Prairie et al. 2016); Brick Schema (Balaji et al. 2016); and ASHRAE's proposed Standard 223P, *Designation and Classification of Semantic Tags for Building Data* (ASHRAE 2018), plug-and-play equipment and products from different manufacturers are not yet commercially available. More work is needed by the industry to make this happen.

3.1.4 Inconsistent Terminology in Vendor Communication

Vendors differentiate themselves by using terminology that is specific to their products. The variety of terminology across vendors as well as the volume of terms makes it hard for building owners and customers to understand the meaning of terms. Statements from the interviews pertaining to consumers understanding the information and products coming from vendors were also categorized under this barrier.

Terminology poses a barrier in both its quantity and in its inconsistent application. A building owner stated that "Vendors can package things any way they want to, making it confusing for the customer. We want to create consistent terminology, so everyone is on the same page." Building owners need to have a clear idea of how the product functions to more effectively integrate it into systems in their buildings. The building owner previously quoted also noted that a "lack of organization is an issue. There is too much information, too many options, and therefore a lack of consistency and organization." There is an overload of information coming from the industry and system vendors on the range of options, making it difficult for building owners to identify what is actually needed for their building.

The terminology in descriptions and databases also changes, requiring relatively frequent updates from the building owner and resulting in additional complication. A building owner noted that there is a "rapid change in industry" and a "need to figure out if the customer can keep up with all of the industry changes." This refers both to the need to upgrade systems and building owners' need to understand the newly added layers of technology. There is a continuous learning process for these systems, and clear terminology would smooth the transition.

3.1.5 Lack of Economies of Scale

Building sensors and controls systems need to be adaptable so that they are appropriate to buildings of varying size and complexity. Costs of systems need to scale as well. The system architecture of many BASs originates from controlling industrial processes and other high-stakes and high-reliability implementations. Although these systems can meet high-performance standards in commercial buildings, they are often difficult to simplify for smaller, simpler buildings. Only 13% of small commercial buildings have adopted these systems (CBECS 2018) because traditional system architecture and components may not be best suited to lightweight, scaled-down, and simplified applications.

The lack of economies of scale has a significant effect on small building adoption; when the system is designed for a complicated building and involves many components, it cannot easily accommodate the simpler needs of a smaller building. A controls vendor said, "It is very hard to take something designed for the Pentagon and take it to the small buildings." Sensors and controls technology is designed for a much higher level of precision and performance than is needed for a small building that has fewer building systems to control.

This presents a challenge to increased market uptake in small and medium commercial buildings. If the existing commercial building systems cannot be scaled to smaller buildings, perhaps a different solution is needed that is specifically tailored to the needs of small building owners.

It is also difficult to scale residential building control technologies up for small commercial buildings. One analytics vendor pointed out that commercial buildings have more sensors and control points. Residential products are designed typically to include one sensor integrated with one controller (the thermostat). There do exist slightly more complicated residential controls, depending on the HVAC system, but even small and simple examples of these systems (e.g., RTUs) generally cannot be scaled or implemented in commercial building applications.

3.1.6 System Complexity

Sensors and controls systems are complex because there are so many components that need to be considered through the entire lifetime of the system and—although these components have specific jobs—they also must coordinate with each other, requiring maintenance and creating opportunities for failure. An average secondary school like the one described in Table C-3, for example, has one control point per 200 ft^2 (with many more calculated software points used for system control, operation, and any reporting to the user). Interviewee statements regarding confusion, a desire for simplicity or downsizing, and frustration with extra requirements were included in this category. This barrier refers to complexity in a variety of instances, including equipment installation, sensor technology, and pricing structure.

Installation and programming of building control systems are complex because they currently require special expertise. For example, a building owner of public schools said, "Without factory trained technicians, things don't work totally right." Adding to this complexity is that individual systems are not always designed to work with other technology or systems from other vendors. Using technologies from multiple vendors might require multiple trainings because the knowledge required to run each vendor's technology is specialized. A second building owner interviewee stated that the "ultimate goal is to have one control platform" for their entire building portfolio because the mix of platforms "don't work nicely with each other." Requiring staff to be trained on multiple systems or requiring multiple experts to adjust the systems makes running sensors and controls system labor-intensive and complex.

Confusing pricing structures add to the complexity of controls systems. Clear pricing data are difficult to obtain, and the structure varies greatly by contract, which takes time for the customer to understand. In highlighting the benefits of their own product that overcome the complexity barrier, a vendor said "Our pricing model is different. We think it [the pricing model] should be easy to use and easy to understand."

3.1.7 Lack of Expertise

Successful implementation of building control systems requires dedicated personnel with training and expertise on the system for both initial installation and ongoing operations and maintenance. Whoever is responsible for the operation of the control system ideally would understand the system well enough to use it effectively. Ensuring that people with the appropriate knowledge are involved with the system is a major barrier for sensors and controls uptake.

The benefits and operational success of the systems relies on the operator to understand how to use the system and interpret the data. An interviewee said that "You have to ask, 'Are they trained and able to operate and set the controls and module? Can they understand what the errors are and respond appropriately?'"

It can be cost-prohibitive to have a dedicated employee hired and appropriately trained to effectively operate the system and interpret the data. A school building owner described their system, saying that "We have facility managers in every school. These people are more custodial type oriented…We give them controls training to see if they can log on to the system." To be cost-effective, the organization combines facility operations and custodial responsibilities into the same role. Substantial training may be required in order to provide fundamental facility and system operation, and it was noted that this role and associated responsibilities can lead to difficulties with control system management. Many building owners cannot dedicate even that level of individualized attention, and struggle even more.

Another noted facet of this barrier tied to system complexity is that having a mix of systems from different vendors requires substantial user training including separate trainings for different systems, which is costly. To limit the impact of training on multiple systems, building owners are motivated to maintain a consistent subscription with one vendor. In discussing procurement processes during the interviews, the same school building owner quoted in the previous paragraph stated that "In the facility management, they move around to different schools," so having different systems with separate trainings makes the management process more difficult. There were also mentions of staff turnover being an issue for continued maintenance of control systems, so even if the system was running smoothly, it struggled with long-term success. A building owner noted this consideration, saying that "Institutional memory is lost when people leave the company. When you hire a new person, do they know what to do, or just reset everything and commission?" The barrier of a lack of knowledge demonstrates that issues arise continuously throughout the lifetime of a building and/or system. The initial setup and training are crucial, but this training should be reinforced and repeated over the lifetime of the system, even when the original motivation for installation is removed. This must be considered in the design of the system (making it intuitive to use and understand) and in the trainings.

This barrier, as with many others, is amplified for small buildings and buildings with smaller operating budgets. A building owner stated that "They also don't tend to have a dedicated employee to take care of this stuff. The manager on site usually isn't for facilities and doesn't have time to actually help with it." These systems require frequent supervision so this staffing shortage means that a small building will not adequately monitor energy consumption and other related data. Ultimately, this leads to longer payback periods for this investment, reducing the value proposition of the sensors and controls system and making wider adoption even more difficult.

3.1.8 Other Barriers

Three additional barriers emerged from the interview data but were not mentioned frequently.

Equipment. Currently, commercial building sensors and controls systems have many components. The bottom three conceptual layers presented in Figure 2 consist of many devices include sensors, controllers, software packages, wiring, conduit, etc. Updating and improving existing equipment is a challenge and requires significant investment. Continued technology advancements with control systems will unlock opportunities for additional energy savings and building-to-grid benefits, but current system architecture and costly equipment requirements pose a barrier to realizing these benefits.

Split incentives. Split incentives are a barrier to building controls implementation, especially in commercial real estate and any other situation where efficiency investments and energy burdens are split between owner and tenants. Because a controls upgrade is a significant cost and potentially a capital cost, landlords are not motivated to pay for it because energy cost savings mostly benefit tenants. One researcher said, "There is an issue about the split incentive…this is very important when looking at small- and medium-sized buildings" where this owner/tenant relationship is common.

Cybersecurity. Cybersecurity concerns also are a barrier, though not mentioned many times by the interviewees during this particular study. Owners expressed concern with building's data being stored in the cloud, as it allows digital pathways into the building computer systems. One vendor expressed an industry need to find a solution that addressed privacy issues and significantly reduced potential cybersecurity threats, which can be costly to businesses.

3.2 Drivers for Implementing Control Systems

A driver is a need or market pressure that leads to the uptake of technology. Market opportunities can be drivers if they are used to increase technology adoption. For building controls systems, drivers are reasons that building owners purchase these systems. The interviewees identified drivers by explicitly calling them out or by talking about the reasons why building owners implement the systems. Building owners identified drivers by declaring their own reasons for implementing systems. Contractors provided the same information, but in some instances may have generalized across many different clients.

Vendors often discussed features related to their control systems. For these to be characterized as a driver, the statement had to be validated by multiple interviewees. For example, if a vendor noted a feature, and the contractor identified it as a reason for many of their installations, then it is classified as a driver.

Our analysis yielded the drivers in Table 3 for implementation of commercial building sensors and controls systems in order of importance. We identified the drivers from the data and developed the importance ranking based on the emphasis interviewees placed on the drivers.

Table 3. Interviewee-Identified Drivers for Implementing Control Systems

Identified Driver	Driver Description
Operational Benefits	These systems modernize building operations and make the building easier to operate, which could translate to other benefits such as improved comfort, energy savings, and other nonenergy benefits.
Insight Into Operations	These systems compile building data that allow building owners to objectively assess the building's status and make appropriate changes. The data allow operators to perform root cause analysis of problems, understand space utilization, and adjust operation to improve performance.
Remote Access to Data and Controls	Systems often provide remote access to building operation data, so the engineer doesn't need to be in the building to control the building.
Cost Savings	These systems can help optimize building performance, saving the owner money over time.
Energy Savings	Sensors and controls systems save energy and reduce peak loads.
Ease of Use	Sensors and controls systems can be straightforward to integrate and they make building operations simpler.

In the following sections, we describe each driver, using evidence from the interviews.

3.2.1 Operational Benefits

Improved building operations, or operational benefits, emerged as one of the most important drivers in the interview data. Commercial building sensors and controls systems can make the building easier to operate. This can be accomplished in many ways, including automation of building schedules; seasonal changes; and, from a maintenance standpoint, reducing the need to call on technicians for system troubleshooting, at least for issues that can be diagnosed from the control system. By updating obsolete equipment to new systems, building owners have a modern system with dashboards that will help the building operator better understand the building. The building operates more efficiently, which translates to improved comfort, energy savings, and other nonenergy benefits.

Our analysis suggests that a driver related to operational benefits is the requirement that building owners replace obsolete control system components with modern systems. This occurs when an exact one-for-one replacement option of a broken control system component is no longer available. When this happens, building owners are driven to upgrade control system components, which often improves building operation and associated operational benefits. Therefore, an important exercise in capital improvement planning can be understanding and cataloguing equipment lifetimes and subsequently looking for synergistic opportunities to achieve deeper operational benefits when replacing equipment.

Another reason building owners procure sensors and controls systems is to access modern communication protocols such as BACnet. Referring to a client, a contractor said, “They have DOS-based STAPA controls. These are outdated…We have clients [that need to upgrade] to modern communication protocols. Energy is a driver, but not always the forefront... [we want them] to get with BACnet, a modern communication protocol.” The contractor prioritizes operations over energy savings as a driver for these systems.

A vendor also provided a statement that supports operational benefits being a driver. He said, “energy is important, but energy pales in comparison to operational savings.” He went on to say that both sensor data and operations drive implementation. “[A large nationwide bank] was sending trucks to all branches to fix thermostats, [convenience stores] were leaving the doors open and sensing those things helps. It’s a combination of both...but sensors will grow because of operational benefits.” Both energy savings and operational savings are reasons that drive building owners to install control systems, but the operational savings extend beyond the building and can include servicing and maintenance.

3.2.2 Insight Into Operations

Sensors and controls systems can collect vast amounts of data related to energy consumption and building system performance. This important driver allows building owners to objectively assess the status of their building and make appropriate changes.

Data allow for root case analysis, so building owners can identify and resolve deeper faults rather than being overwhelmed by the symptoms of those faults. Often, noncritical alarms that could indicate the development of a serious equipment problem are considered a nuisance and ignored. An analytics vendor stated that because of the variety of alarms and sensors that were installed, “Analytics can tell what the root cause is rather than look at each individual thing.” This improves the overall well-being of the building and helps prevent future incidents.

Another specific benefit arising from data availability is information about space utilization. Depending on the sensors installed, building owners can determine the occupancy patterns of different spaces and adjust the building accordingly. Another analytics vendor noted the system “can inform space utilization of rooms” and “we can tie into the HVAC systems.” Ensuring that only occupied areas of the building are temperature-controlled and lighted is a strategy that saves energy.

System performance data also allow operators to adjust limits. An example given by an analytics vendor was the ability to respond to peak load management signals and monitor the money spent on energy per month based on a budget. With easy access to data, building owners and operators can more easily track building performance metrics and make operational decisions to reduce cost and/or improve building efficiency.

3.2.3 Remote Access to Data and Controls

The ability of a building manager to access building data and control the building remotely is a clear driver. Cloud-based data visualization allows building managers responsible for multiple buildings to easily track building operations from one location. A contractor described a use case: “Small buildings don't [need] a building engineer in the building all the time. For example, there is one person in charge of twelve 2,400 ft^2 buildings. If [these building operators] could have some remote access online, they can see this and understand the [building’s] issues. And then they can select where to travel to.” Remote data access and control streamlines building operation and is beneficial for both large and small buildings. There is an advantage of remote control to start and stop systems, reset system control points, and change operations so the local building occupants can continue their work without having to worry about changing HVAC systems.

3.2.4 Cost Savings

Cost is generally the bottom line for building decisions. In developing a successful business case for sensors and controls systems, significant immediate and sustained monetary savings are very necessary.

Vendors noted that systems needed to be marketed with monetary savings. Different analytics vendors stated that “time and money conquer all” and that “taking something and adding value to it will drive an owner to install a new system.” Benefits need to be translated and quantified in dollar terms to show that there will be savings from the system. The different operational benefits need to be translated into actual dollar values to show the ultimate potential.

Vendors also highlighted the ability of their technologies to lower costs as driving the purchasing decisions of their clientele. Different controls and analytics vendors mentioned characteristics such as “[building owners can attach] any sensors that you want to attach, we aren’t charging per point” or that “we are seeing a lot of wireless sensors that are helping a lot over that capital cost.” This demonstrates that vendors want to differentiate themselves with financial benefits, as that is what will attract more consumers to their systems.

Monetary solutions that are not from the vendor side were also noted as a driver for installation. In particular, a building owner noted that their system installation was made possible because “taxes, subsidies, and incentives cut down the cost of capital.” Financial models that support these systems can serve as a driver if the costs are not reduced from the vendor side.

3.2.5 Energy Savings

Although energy savings is certainly a driver, the interviewees stated that it was not as much of a driving force as other aforementioned drivers. From the interview data, the transformative vendors are currently focusing their market strategy on drivers other than energy. In one instance a vendor expressed excitement for reducing the building’s load at peak hours, which requires more building control than straightforward energy reduction. The vendor stated, “There is lots of interest in peak load management…we'll back off and make changes to ensure they're not hitting that peak every month.”

3.2.6 Ease of Use

Ease of use includes straightforward integration or simpler building operation. The driver was identified mostly by vendors through highlighting easy-to-use product characteristics. Controls that need less maintenance as well as those that are aggregated and use straightforward analytics platforms were praised for improving intuitiveness of the system.

Straightforward integration also refers to sensor-control integration, where all the components of the system work well together to provide ease of use and commissioning. This includes small buildings integration, where development of a system that works well for small commercial buildings will greatly impact future adoption. Key strategies for straightforward integration include wireless sensors, wireless communication, and interoperability standards.

3.2.7 Other Considerations

Internet of Things. An interesting technological development that could catalyze market offers and adoption for building control systems is the Internet of Things (IoT). IoT refers to smart devices with internet connectivity that can also connect to one another through communications protocols including Wi-Fi. IoT devices are often wireless.

One researcher noted that there's a lot of opportunity to incorporate IoT capabilities into sensors and controls systems. If done correctly, this can cut costs. The researcher said, "Typically you look at that space, the [large controls companies]: the price will not come down when working with them. The alternative approach is IoT, and that one is really a bottom-up approach." The integration of IoT into building controls is an area of emerging technology.

4 Quantitative Results

This section discusses the quantitative analysis of project cost data and cost breakdown for BASs with integrated HVAC system controls.

To understand and compare the costs associated with the various projects encountered in the industry for commercial building sensors and controls systems, we first classified projects into the following project scope categories (excluding pneumatic to DDC conversions, which were outside the scope of this effort):

1. **Complete system.** Scope includes all components and support infrastructure.
2. **Upgrade existing system, partial to full upgrade**. Scope includes controller replacement at the automation layer but may also include varying degrees of field controller and/or field device replacement. This category often excludes conduit and wire replacement and differs from the "complete system" category in that all components are not replaced. This type of project impacts the automation controller layer, as well as the field controller and field device layers discussed in the Background section.
3. **Upgrade front end**. Scope consists of replacement of primary front-end software and hardware including computer(s), servers, printers, and primary communication cables, often referred to as trunk cables. This category excludes any controller replacement, whether it be an automation controller or a field controller closer to a field device. This type of project impacts the automation software layer discussed in the Background section.

The following sections present project costs and cost breakdown.

4.1 Complete System Project Cost Breakdown

A number of labor categories were identified through data analysis and the following list describes—at a high level—typical tasks falling into these labor categories as they are referenced throughout the following analyses:

- **General contractor fee** is the contractor markup price for various services involved in coordinating the project scope and can include costs associated with insurance and permitting in addition to labor to oversee project execution. RSMeans was used to generate general contractor fees based on total project cost.
- **Commissioning** is the dynamic confirmation of system performance, ensuring the control system interacts with HVAC system and dynamically responds as intended and required.
- **Installation labor** is the physical labor to install hardware components, wiring, conduit, etc.
- **Testing and balancing labor** is the static testing of system operation, which can involve the labor associated with setting HVAC system design points (e.g., minimum/maximum damper positioning) for any new control components installed as part of the project. Testing also provides a quantitative assurance of system operation and balancing ensures engineered design set points such as airflow are met.
- **Programming and graphics labor** includes the labor for software programming of control algorithms into controllers or other components impacted by the scope of the project as well as front-end labor for graphics and other user interface specified requirements.

- **Engineering labor** is engineering oversight to ensure implementation is meeting design requirements, as well as system design and specification as necessary.
- **Hardware costs** include costs for control system components such as sensors, actuators, alarms, controllers, front-end devices (workstations), wiring, conduit, etc.

Figure 6 shows the cost breakdown for the five complete system costs that were created using the methodology described in Section 2.2.2.1. National average labor rates are used in this comparison. The number of system control points are included for each building to aid in comparison and discussion and the results are summarized in Table 4.

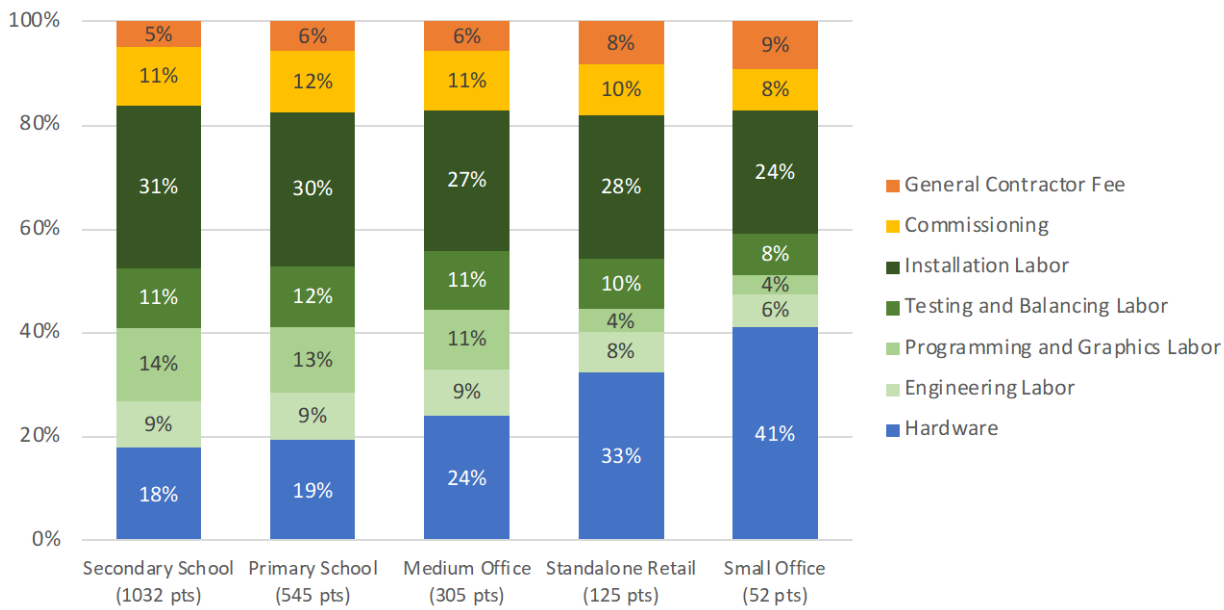

Figure 6. Cost breakdown comparison for complete control systems

Note: The number of system control points for each building is included in parentheses.

Observed trends emerged from the comparison shown in Figure 6. More complex HVAC systems with more system points required more labor relative to hardware than the more simplified systems. Control systems with more system points require additional time and labor to not only install hardware, but to also program control algorithms into the automation system. This leads to a larger proportion of costs going toward labor categories.

Similarly, simpler HVAC system types required less labor compared to more complicated HVAC system types, leading to a greater portion of the overall project cost for hardware (as shown in Figure 6). The secondary school, primary school, and medium office showed between 70%–78% of project costs went to the various labor categories, whereas the stand-alone retail and small office projects showed between 51%–52% total project costs for various labor categories.

Table 4 provides the calculated total system cost, the number of control points for each system, and the floor area of each building.

Table 4. Complete System Cost Summary of Five Prototypical Commercial Buildings

Building Type	Floor Area (ft^2)	Total System Cost ($)	Control System Points	Total System Cost per Building Area ($\$/ft^2$)	Total System Cost per Control System Points ($/point)
Secondary School	210,886	$1,090,150	1,032	$5.17	$1,056
Primary School	73,958	$558,100	545	$7.54	$1,024
Medium Office	53,625	$321,400	305	$6.00	$1,054
Stand-Alone Retail	24,692	$154,300	125	$6.25	$1,235
Small Office	5,502	$78,000	52	$14.18	$1,500

Figure 7 shows a side-by-side scatter plot comparing project costs with building size, and project costs with the number of system control points.

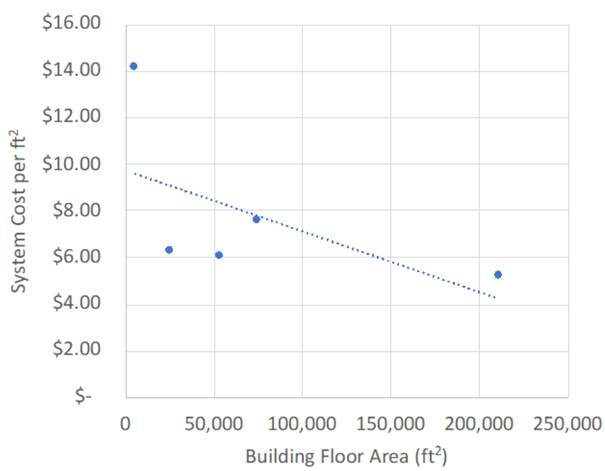

Figure 7. Comparison between complete system project costs relative to the building size (left) and the number of control system points (right)

System costs increase as both the building size and number of control system points decrease. This quantitatively demonstrates the lack of economies of scale barrier discussed in Section 3. This can also be seen from the data summarized in Table 4. The cost per building area for the small office prototype is almost 3 times greater than the costs per floor area for the largest prototype building—the secondary school. In contrast, the system cost per control system point increases by roughly 50% between the secondary school (largest number of control points—VAV system with central boiler and chiller plant) and the small office (smallest number of system points—packaged RTU system).

4.2 Upgrade Existing System Cost Breakdown

In addition to the complete system costs and cost breakdown, we collected data for two projects from the stakeholder interviews that provided a detailed cost breakdown. Both projects were upgrades to an existing control system, primarily focused on replacing controllers with some project scope replacing other outdated or faulty system components throughout the facility. These projects therefore varied in scope from the results shown in Section 4.1. Both projects were high schools in the same school district. Figure 8 summarizes the cost breakdown for these two projects. The cost data come directly from the project-specific source and are not adjusted or normalized for any national labor rate considerations.

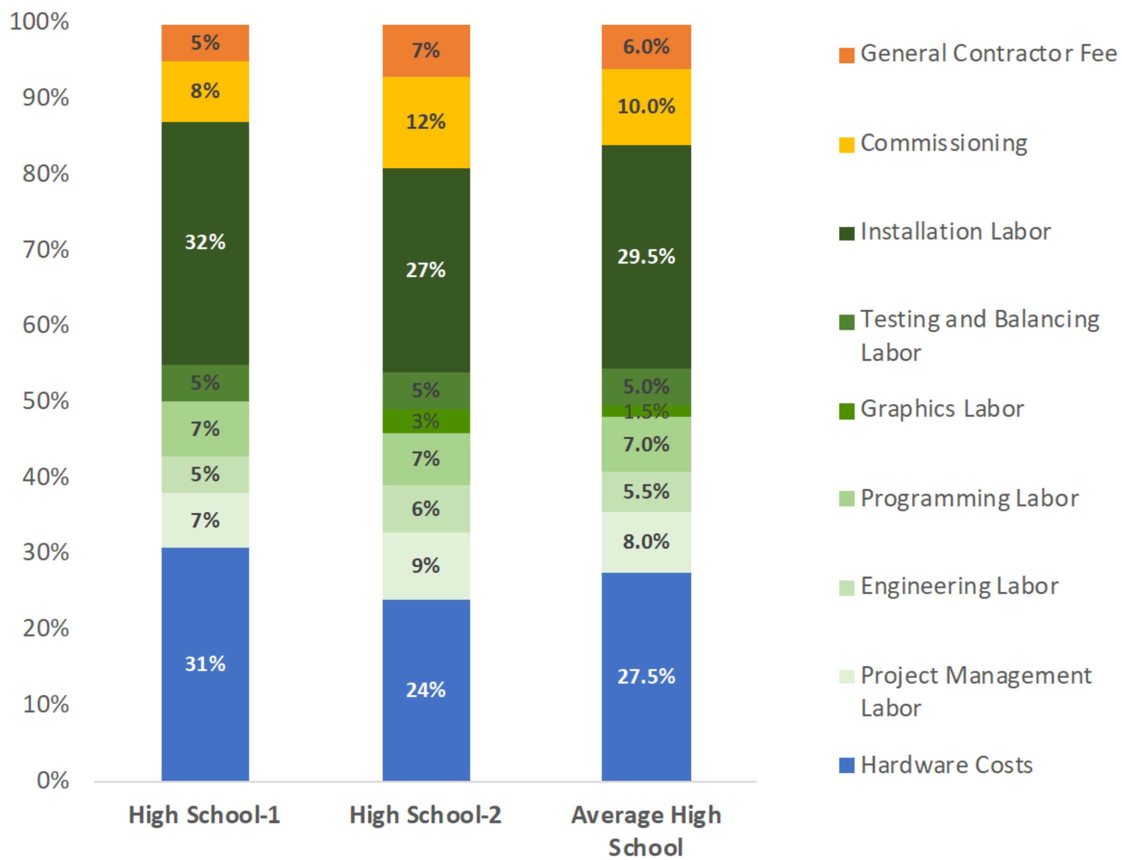

Figure 8. Project-specific cost stack summary

Based on data from the schools, hardware costs account for 27.5% of the project cost on average, and 72.5% goes to labor and other markups for projects upgrading existing systems. This result aligns well with the complete system cost breakdown shown in Section 4.1 for the associated prototypical secondary school, further validating the methodology discussed in Section 2.2.2.1.

4.3 Cost Summary for All Projects

Project costs for all data collected through the interview process and through the methodology described in Section 2.2.2.1 were summarized by project scope classifications defined above in Section 4. These project costs were divided by building floor area. Figure 9 summarizes this project data. Minimum, maximum, and average costs for projects in each scope category are placed next to each column in Figure 9.

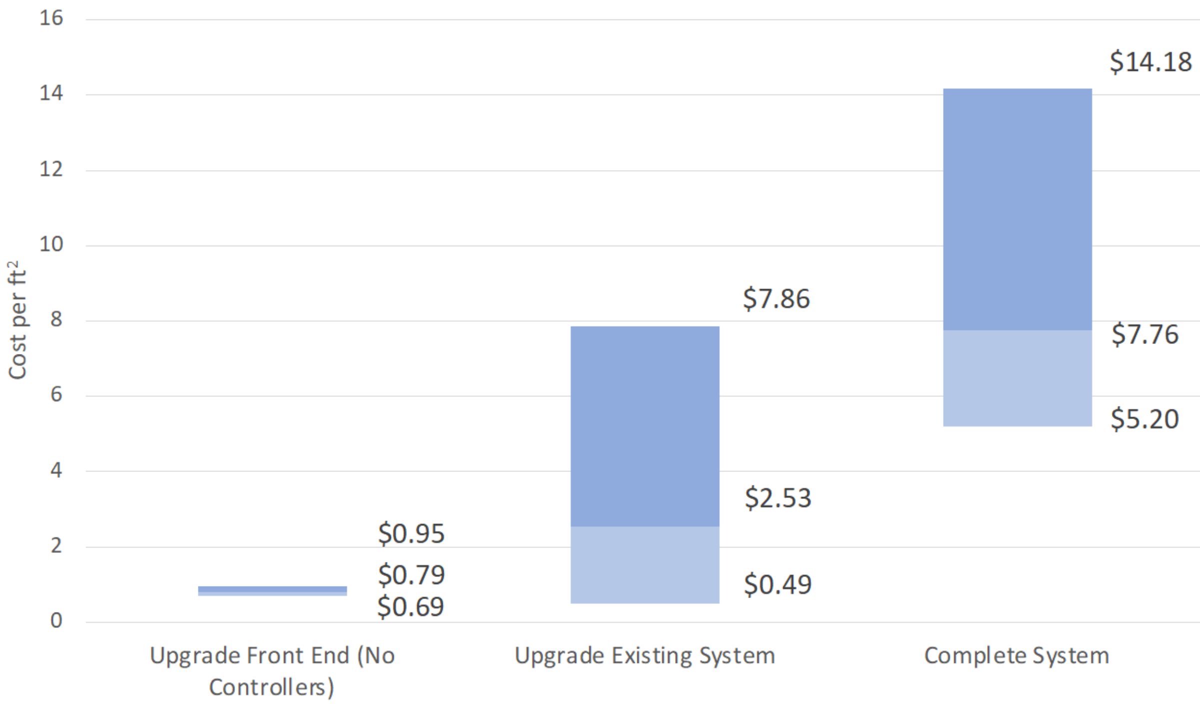

Figure 9. Total project cost per square foot based on project scope classification

It is important to note that the labor costs for the data collected through project invoices and project estimates were normalized to national average labor rates from RSMeans based on labor tables with data from Q4 of 2021. All data points shown in the figures and table in this section are based on national average labor rates. Section 4.4 discusses the impact of labor rates across the country on both projects costs and the associated cost breakdown. Labor rates changing over time and associated macroeconomics will further impact costs for these projects.

Table 5 presents a total project costs per square foot minimum, maximum, and average for each scope classification. Details for the various project sources can be found in the footnotes of Table 5.

Table 5. Total Project Cost per Square Foot Data Summary

Scope Category	Minimum Cost per ft^2 [$\$/ft^2$]	Maximum Cost per ft^2 [$\$/ft^2$]	Average Cost per ft^2 [$\$/ft^2$]	Sample Size
Upgrade Front End (No Controllers)	$0.69	$0.95	$0.79	3[a]
Upgrade Existing System	$0.49	$7.86	$2.53	13[b]
Complete System	$5.20	$14.23	$7.60	5[c]

[a] Data sources include estimates using RSMeans for prototypical buildings
[b] Data sources include interviews and industry-provided information
[c] Data sources include estimates using combination of RSMeans and U.S. General Services Administration schedules for prototypical buildings

We observed a wide range of costs for the complete system category as well as the upgrade existing system category compared to the complete system and front-end upgrade categories. The range can be attributed to the complexity of the HVAC system as discussed in Section 4.1 and ultimately the number of control system points. Building area is not consistently an indicator of system costs compared to the number of controlled points.

Figure 10 summarizes project cost data based on project scope divided by the number of control points (hardware points) for comparison to cost per square foot.

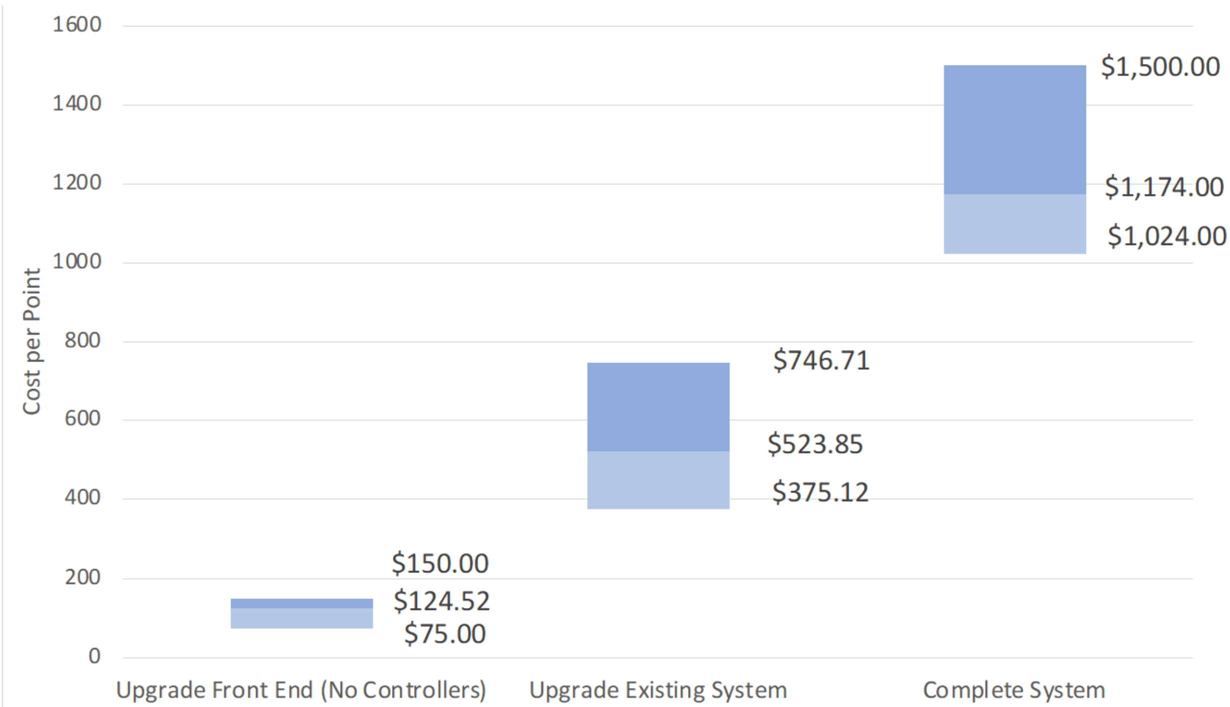

Figure 10. Total project cost per control point based on project scope classification

In all cases, presenting project cost by the number of control points narrowed the range of costs, most noticeably for projects either upgrading an existing system or considering a complete system. It seems that determining system costs based on the number of control points may be more reliable for project estimating than building area.

4.4 Regional Variations in Labor Cost

Given our findings that various labor categories make up most of the costs associated with these projects, we consider labor rates and their variations across the United States in this section, referencing the secondary school as a representative example. The following discussion and figures use the secondary school prototypical building.

Many factors affect labor costs, such as cost of living, ease of access in the project site, and ease of transportation. According to RSMeans 2021, Q4 labor cost estimation, the national average hourly rate for BAS-related labor was $68.20. This labor rate has been used thus far for any cost data points discussed in Sections 4.1 and 4.3. Section 4.2 used actual project data with specific local labor costs.

RSMeans also provides labor rates for different cities in the United States and Canada. Figure 11 summarizes the percentage labor rate differences for selected cities compared to the national average. The values range from 36% cheaper for Dallas, Texas, to 80% more expensive for New York, New York.

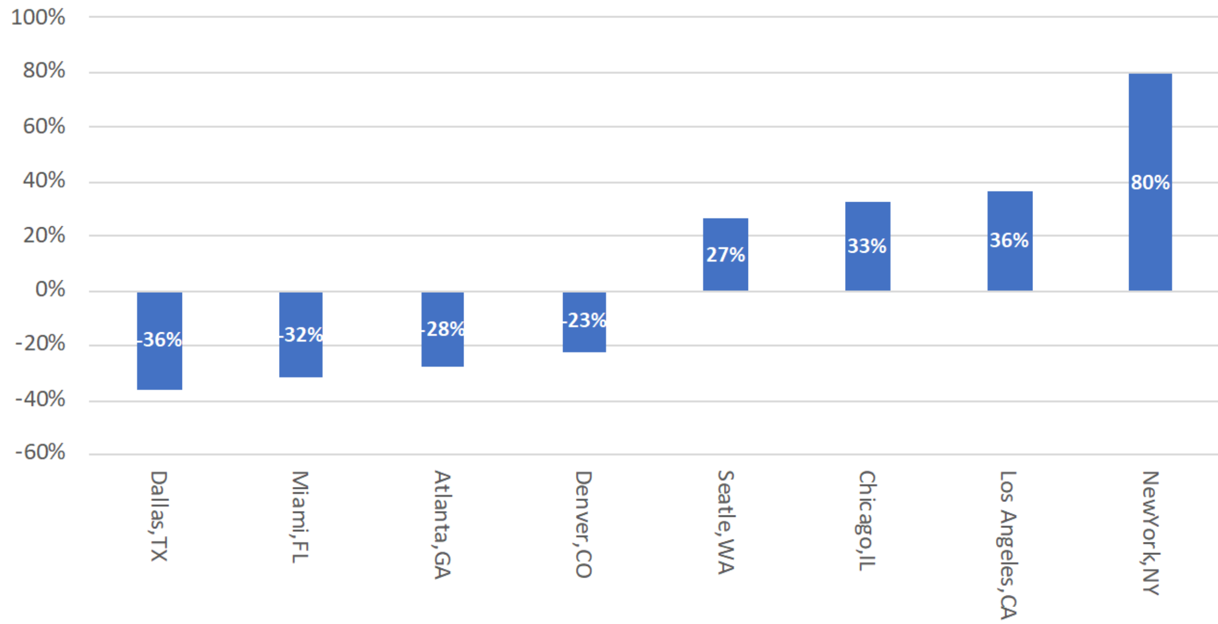

Figure 11. Percentage labor rate difference from the national average

To understand the impact of various labor rates on control system project costs, especially for projects dominated by these costs, we compared the total system cost for the secondary school protoypical building using various labor rates shown in Figure 11. For this comparion, the hardware cost is assumed to remain constant based on the GSA schedules, which represent national contracts. It is important to point out that hardware costs can vary regionally, and contractor pricing and markup can also vary by the service provided and the details of negotiations with specific project contractors. This comparison seeks to highlight the observable impact of total project costs based solely on variability in regional labor rates and therefore holds the hardware costs constant. Figure 12 shows the complete system project costs for the secondary school prototypical building using labor rates associated with various cities around the United States.

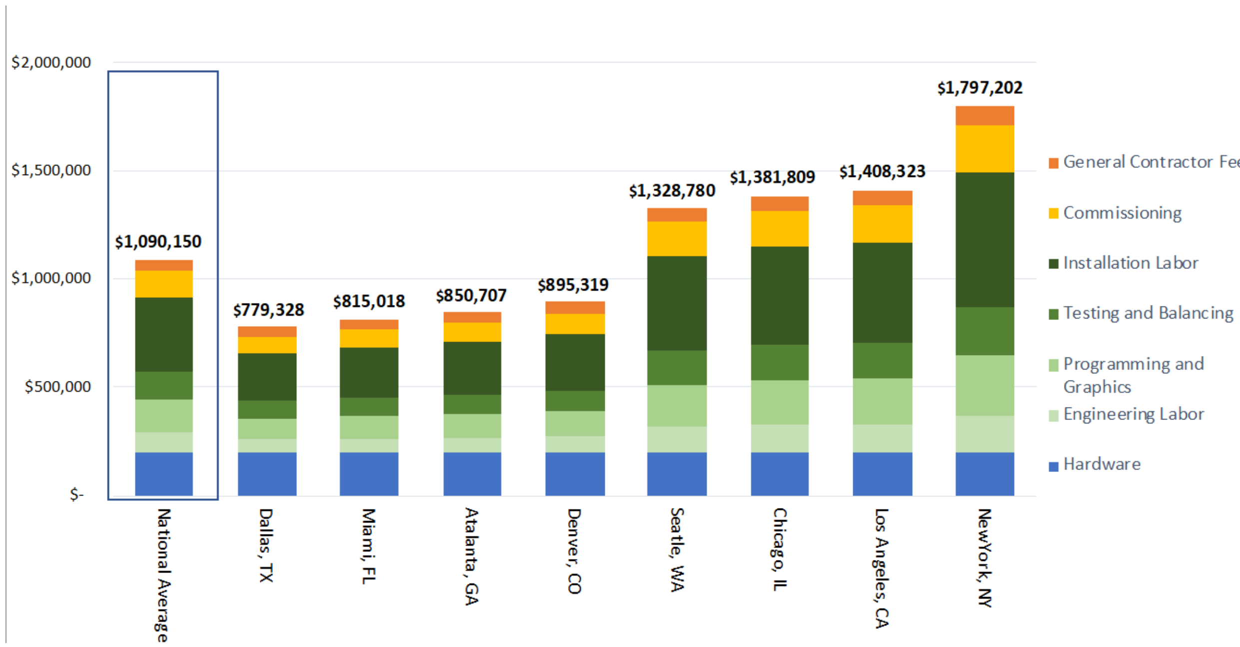

Figure 12. Complete system project cost variations by region for secondary school prototypical building

As can be seen from the figure, a project that costs $1,044,430 based on the national average rate would cost $1,662,888 in New York, New York, and $717,888 in Dallas, Texas. Project costs shown in Figure 12 represent a complete system project scope classification for a prototypical secondary school. This methodology was discussed in Section 2.2.2.1 and additional details are available in Appendix C.

5 Costs from the Interviewee Perspective

We asked interviewees to estimate the costs for building sensors and controls systems. Some interviewees were able to quote actual ranges of costs for projects and systems. These costs may differ from costs calculated in Section 4. Section 4's cost analysis comes from data in GSA schedules and RSMeans and represents the average expected cost. In this section, we use cost data points from interviewees who regularly review sensors and controls system prices. These interviewees regularly see price quotes and invoices. In Section 5.1, we present a summary of these interviewee cost estimates. Some interviewees identified cost categories and pointed out which ones were more prevalent. These are summarized in Section 5.2. Some interviewees estimated the percentage of a few of the cost categories, which are summarized in Section 5.3. We end this section with a summary of the vendor pricing structure in Section 5.4.

5.1 Cost Values

This section includes tables of interviewee-estimated costs (Table 6 and Table 7). We group them by project scope.

Table 6. Cost Values Stated by Interviewees

<table>
<tr><th>Project Scope</th><th colspan="2">Cost</th><th>Description</th></tr>
<tr><td>Upgrade Front End</td><td colspan="2">$0.03–$0.06/ft^2</td><td>An analytics vendor listed the typical range for their initial system setup. This does not reflect the total cost because the vendor's pricing model also has licensing costs.</td></tr>
<tr><td rowspan="6">Upgrade Existing System</td><td>Building size range (ft^2)</td><td>Cost range ($)</td><td rowspan="4">A school system building owner listed these cost ranges for buildings within their system. These costs are said to be on the lower end of nationwide cost ranges.</td></tr>
<tr><td>40,000–50,000 ft^2</td><td>$75,000–$100,000</td></tr>
<tr><td>100,000–150,000 ft^2</td><td>~ $150,000</td></tr>
<tr><td>200,000–300,000 ft^2</td><td>$300,000–$400,000</td></tr>
<tr><td colspan="2">$0.36–$4.80/ft^2 with an average of $1.79/ft^2</td><td>A contractor listed ranges for full sensors and controls project upgrades.</td></tr>
<tr><td colspan="2">$55,000 for 150,000 ft^2 building + $32,000/floor</td><td>A contractor gave the costs for a specific office building that did upgrades on the front end and on controls. This was on the lower end of the cost range. The additional cost of $32,000 was noted as a separate upgrade to DDC controls.</td></tr>
<tr><td rowspan="2">Complete System</td><td colspan="2">$1,000/point but newer technologies driving prices down toward $500–$600/point</td><td>A controls vendor listed these costs for sensors and controls systems, stating that due to changes in installation and communication, costs have gone down, but are still too high for small buildings.</td></tr>
<tr><td colspan="2">$5,000–$15,000 for small buildings</td><td>A controls vendor gave this cost range for their small building systems and noted that this was</td></tr>
</table>

Project Scope	Cost	Description
		the cost range required for systems to be competitive and feasible for small building owners.

Some of the interviewees stated that the maintenance costs are significant. Table 7 includes some examples that they provided.

Table 7. Maintenance Costs Stated by Interviewees

Recurring Cost Type	Cost	Description
Analytics Maintenance	\$0.03–\$0.06/ft^2/year	An analytics vendor noted that the annual subscription rate for overseeing and maintaining the system was similar to initial setup costs
Regular Maintenance and Software Upgrades	\$6,000/92,000 points/5 years	A building owner stated the cost for regular maintenance and upgrades of the sensors and controls system software. It was noted that this system with 92,000 points is one of the largest, perhaps putting these costs on the higher end of the national range.
Licensing	\$499/zone/year	A vendor stated their licensing costs noting that licensing by zone incentivizes building owners to have more points and ultimately collect more data. This vendor includes controls and analytics in this cost.

These tables are straight from the interviewees, and therefore they do not represent industry averages. We present them to provide anecdotal data points.

5.2 Cost Categories

This work sought to understand the different cost categories that contribute to the total cost of an advanced commercial building control system. We asked the interviewees to name the sensors and controls cost categories, and they responded by listing cost categories and associating them with differing levels of importance. These cost categories for the most part overlap with the cost categories in Figure 6. Here are interviewee-mentioned cost categories that they think are major contributors to the total cost. We group categories that respectively fall into labor and equipment together.

- Labor—Mentioned subcategories are engineering labor, installation labor, wiring labor (mentioned separately by some interviewees, yet part of installation labor), programming labor, project management labor
- Equipment—Mentioned subcategories are BAS sensors and controls, meters

- Software
- Contractor costs
- Commissioning costs
- Maintenance costs.

Similar to quantitative analysis, there are many different categories of labor. The interviewees identified these labor categories as making up a significant portion of the cost stack. The quantitative analysis supports this perception, with more than 60% of costs attributed to labor categories.

We did not include maintenance costs in the cost stack because these costs are not realized during installation. Maintenance costs include cost to update the system with the latest software, maintaining data, and updating data visualizations. Maintenance costs also include any licensing or subscription fees. The interviewees listed maintenance as a significant cost, showing there is even another category of costs over the product lifetime.

5.3 Cost Category Percentages

Three interviewees described the percent of total cost for some of the cost categories. Many other interviewees chose not to provide percent estimates for cost categories and stated that they didn't know these numbers. Table 8 below summarizes these percentages.

Table 8. Cost Category Percentages From Interviews

Cost Category	Percentage	Notes	Source (interviewee type)
Overhead, Labor, and Profit	25%–33% of the installing vendor's invoice	The profit (4%–10%) is included in this number. The overhead includes administration such as accounting.	Building owner who previously worked as a vendor
Profit	4%–10% of the installing vendor's invoice		Building owner who previously worked as a vendor
Hardware	18%–20% 8%–10% technology hardware (sensors, controls) 10% is basic hardware (meters, relays)		Controls vendor
Installation Labor	40% of the invoice		Controls vendor

The results from interviewee statements can be compared to the cost stack in Figure Figure 9. The hardware cost for a complete system shown in Figure 9 is 23%, which is close to the 18%–20% estimate from the interviewee. It is important to note that Figure 9 is not a complete cost stack, and excludes general contractor fee, profit, and project management labor, so if these are added, the hardware cost percentage could go down, and be closer to the interviewee estimate.

One interviewee estimated that profit is 4%–10%. Profit was not a line item in the data used to develop Figure 6.

5.4 Pricing Structure

Many vendors compete to install sensors and controls systems in buildings around the country, so total costs tend to be similar across the industry. That total cost, however, can break down in many different ways, and there is no standard for how the price is calculated or distributed. This makes it very difficult to get a clear cost breakdown, because it is usually the entire system being priced, not individual components.

Different vendors have demonstrated different methods of estimating prices. One has a standard building model with a certain number of points that comes at a standard cost. The vendor then evaluates the specific building and adjusts that standard model based on size and complexity to provide a specific estimate.

Another vendor focuses on the controller and zones rather than points. This vendor felt that pricing by point or square feet discouraged building owners from installing more sensors, which could result in insufficient data for analytics and monitoring. Their clients purchase the controllers and pay a license fee per zone. The vendor felt that this system made the pricing much easier for the customer/building owner to determine.

Finally, a third vendor indicated that the pricing structure, and the ultimate product, could differ based on the procurement process. Competitive bidding drives prices down, and the profit margins are very slim. This vendor felt this leads to a gap in the system. When working and communicating directly with the building owner in a design-build process, the costs are higher and the system implementation takes more time, but the vendor felt that there is more opportunity to incorporate beneficial tools and features and, ultimately, deliver greater value.

6 Discussion and Future Work

The key findings that arose from the qualitative and quantitative analyses include:

- **Most of the cost is labor.** Data analysis shows that less than half of the installation project costs for commercial building sensors and controls systems is for hardware and system components, and that proportion drops to less than one-third of the cost for many HVAC system types. As the control system becomes less complex, or there are fewer controlled points, hardware accounts for a higher proportion of system costs. This is because there are fewer labor-intensive activities such as control algorithm programming as well as testing, balancing, and commissioning. This finding was also consistent with qualitative interviewee statements.
  - This finding is highlighted in Figure 6 and Table 4 in Section 4 of this report.
  - Although the cost breakdown changed as the number of controlled system points decreased, it is important to note that actual system installations for buildings similar to the prototypical small office building may be limited, as Figure 1 shows.
- **The complexity of control systems is a barrier to adoption.** These complex systems often require significant specialized labor to install and maintain. However, based on interview data, commercial building sensors and controls systems are often maintained by building staff with a wide range of skill sets and would therefore benefit from simplification. For example, the facilities management staff should be able to understand these systems, find control schedules, and update control schedules. Control systems should be designed for ease of use as opposed to requiring special training.
  - A couple of the experts we interviewed said the most efficient way to implement controls is for the field devices, controllers, and control algorithms to be embedded within the equipment with a supervisory software layer coordinating and managing all equipment. This conceptually eliminates the field controllers or combines field controllers and field devices with the equipment. It also may eliminate automation controllers if onboard controllers can communicate directly with the automation software. Therefore, the control systems will have controllers at the "edge" similar to the way edge computing networks function. This strategy also eliminates some of the conduit and wiring needed to connect control points to intermediate controllers.
  - We can also hypothesize that the complexity of these systems and requirements for specialized labor also result in significant labor costs for installation and upgrades discussed in the previous key finding and shown in the quantitative data analysis in Section 4.
- **Systems need consistency across controls technologies** so that users of one system can understand another system. These systems should be intuitive, similar to smart phones and websites that are intuitive for all users.
  - Some control systems contain proprietary software and require a trained technician to update, which is costly to the end user. Also, some technologies only work with technologies manufactured by the same company. For example, some retail organizations must all use the same platform in order for their data to show up on remote dashboards.

The cost and work required to change vendors is much greater than the cost to stick with one vendor. Ideally, systems should be both interoperable and interchangeable.

  - If systems were interoperable and interchangeable, the automation controller layer and field controllers layer could be significantly reduced or in some cases eliminated from the system architecture (shown in Figure 2). From the cost breakdown analysis, the majority of the cost is labor for many projects—both new installations and upgrades—and much of this requires specialized labor such as control logic programming as well as testing, balancing, and commissioning the system. Removing these controllers will shave costs from systems, not only by reducing hardware costs, but, more importantly, by reducing the need for specialized labor.

This work focused on establishing a cost breakdown and summary of key barriers and drivers of more widespread adoption of commercial building sensors and controls systems. Based on the key findings, a number of market opportunities come to light:

- Commercial building sensors and controls vendors with **technology that shifts away from the traditional sensors and controls architecture and associated infrastructure** shown in Figure 2. Although some analytics vendors have developed platforms that connect to existing traditional BASs, the more disruptive technologies do not depend on existing systems. Instead, they incorporate modern computational and connectivity capabilities that didn't exist when traditional BASs were developed. These capabilities include machine learning, cloud computing, and internet-connected control points (i.e., IoT connected lighting systems). With these capabilities, the automation software connects directly to IoT-enabled field devices, eliminating automation and field controllers and much of the hardware that needs manual updating.
  - These technologies are commercially available, but face the challenge of market adoption, including uptake from customers and competition from the more traditional vendors.
  - There is an opportunity to support the adoption of these technologies through incentives and policies.
  - There is also the potential to increase uptake in the small- to medium-sized building sector, because many buildings in this sector do not have BASs. These technologies may provide an economical alternative to traditional BASs.
- There are other market needs such **demonstrating the return on investment** for commercial building sensors and control systems. This value proposition should quantify savings, include those of energy, cost, and time, as well as quantify the operational benefits discussed in Section 3.1.2. Case studies can demonstrate the value to building owners, so future work should include quantifying the holistic value of sensors and controls systems.
- The largest opportunity for commercial building sensors and controls systems is the **implementation into small- to medium-sized commercial buildings**, most of which do not yet have these systems. Cost-effective versions of the new technologies that eliminate the need for field and automation controllers are good options.
  - There must be low first costs scaled to fit the needs of the small- to medium-sized commercial building.

- In addition, maintenance costs must remain low and the owner should see a return on investment within a few years. This opportunity exists because it is easier to install a new system on a building that doesn't have one than it is to retrofit an existing system.

There will be more opportunities for complex controls on all commercial buildings as electric vehicle charging becomes more prevalent. Building owners and operators will need to encourage electric vehicle charging at times when electric demand charges are lower. Some electric vehicle charging technologies are beginning to incorporate price signals and demand response to charging schedules. But it will be important for commercial building sensors and controls systems to incorporate these loads to provide building managers with a view of whole-building energy use, and therefore allow them to identify the best opportunities for energy and cost savings.

Field devices are beginning to have computational capabilities and therefore the algorithms needed for building controls can be done through edge computing. Edge computing for building controls is emerging and therefore research is needed to develop and validate this technology. Future research could include technology research and development, laboratory validation, and field validation of edge computing and new control system architectures.

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Appendix A. Sensors and Controls Cost Data Summary

For all tables, average cost is of all the data for each component.

Table A-1 summarizes HVAC-related sensors and controls costs. RSMeans provides labor and hardware costs separately, but most of the HVAC-related costs are provided as lumped (hardware + labor) costs. The tables provide minimum, maximum, and average costs for the major sensors and controls categories. Sample Size in the table indicates the total number of components for which cost information was available in each category; the minimum, maximum, and average values are computed from this information.

Table A-1. Summary of HVAC Sensors and Controls Costs From RSMeans

Component	Description	Min Cost	Max Cost	Average Cost	Sample Size
Sensors	Devices that detect environmental conditions; includes temperature, humidity, and pressure sensors	$465	$3,450	$1,165	14
Alarm Digital Input/Output	Alarm sensors and controls to stop/turn off systems; includes fire, high-temperature, and smoke sensors	$340	$975	$541	3
Controller MUX Panel	48- to 128-point MUX panel	$5,275	$7,225	$6,250	2
DDC Controller	16- to 32-point controller	$840	$5,425	$3,180	3
Front End Costs	General hardware needed to set up a control system; includes computers, printers, and cables.	$3.80 (cable per foot)	$6,350	$1,561	10
Application Software	Software for the maintenance and optimization of various aspects of the HVAC system	$685	$1,950	$615	8

Table A-2 summarizes the cost information obtained from the GSA website. The website hosts negotiated prices with vendors for various hardware including sensors, actuators, and controllers. Many major sensors and controls vendors have provided their pricing, including Siemens, Johnson Controls, Honeywell, and Trane. The GSA website only includes hardware costs and does not provide labor and installation costs or any programming costs necessary to get a system up and running. Because of the large volume of data available on the website and the difficulty of processing the data, we only considered cost information from three vendors: Siemens, Johnson Controls, and Honeywell. The sample size provides the total cost information from the three vendors for each category. The minimum, maximum, and average costs are computed from the combined information.

Table A-2. Cost Information From the U.S. General Services Administration

Component	Description	Min Cost	Max Cost	Average Cost	Sample Size
Sensors	Devices that detect environmental conditions; includes temperature, humidity, and pressure sensors	$14	$2,109	$529	20
Alarm Digital Input/Output	Alarm sensors and controls to stop/turn off systems; includes fire, high-temperature, and smoke sensors.	$39	$655	$245	4
DDC Controller	16- to 32-point controller	$262	$4,800	$1,138	10
Controller MUX Panel	48- to 128-point MUX panel	$1,684	$10,428	$6,056	4

Appendix B. Interview Protocol

B.1 Interview Protocol Introduction for all Interviewees

DOE's Building Technologies Office has estimated that optimized performance with advanced sensors and controls could lead to an aggregated 29% annual energy savings across all commercial building types. Increasing adoption of sensors and controls sets the stage for future developments in energy efficiency efforts, such as with GEBs. Smart control systems are essential for GEBs to provide effective communication and load flexibility for optimal grid operation. GEBs can provide comfort for building occupants, sell services to the power grid, and cut costs and pollution (Satchwell et al. 2021)

Despite these benefits, only 8% of small commercial buildings in the United States have adopted advanced sensors and controls systems such as a BAS (CBECS 2012). One of the greatest barriers to implementation is installation and maintenance costs. More information about the costs of these systems is needed to help accelerate adoption, leading to realized energy savings and increased GEB potential.

The purpose of the interviews is to gather information that:

1. Informs the development of a cost stack for advanced sensors and controls technology. The cost stack will include ranges for hardware, software, labor, installation, commissioning, calibration, maintenance, and other category costs.
2. Identifies adoption barriers of building sensors and controls technology.

This information will help the uptake of smart sensors and controls technology by providing insight into the technology adoption barriers. DOE will use the results of this study to design and fund projects intended to overcome barriers. The study will yield the clarity needed to advance adoption.

**Interviewers' Note: Ask the bolded question first, then ask the follow-up questions if additional information is needed.*

B.2 Interview Protocol Questions—Building Owners

1. **Please describe your role in your company and your experience with commercial building sensors and controls technology.**
   Please describe the company you work for—size, location, clients.
   How long have you been in this role?

2. **Describe the process that you use to procure building sensors and controls.**
   What requirements and considerations do you have?
   What basic offerings are common to most building sensors and controls bids?
   When closing a contract with a vendor, what leads you to your decision to work with this vendor?

3. **Do you own or operate any buildings where you did not install a building sensors and controls system? In a future building, would you install a building sensors and controls system? Why or why not?**
   What would make the procurement process easier?
   What changes would you make?
   Would you use the same company?
   What is the typical return on investment for sensors and controls systems?

4. **Please provide as much information as possible about the current costs of building sensors and controls systems. What are the cost categories?**
   What factors impact the costs?
   What are the annual maintenance costs?
   What was your reaction to the final cost? Was anything unexpected?
   What percent of total construction and/or maintenance cost is controls?

5. **What do you envision as the future of building sensors and controls?**

6. **Would you be willing to provide example pricing data such as bid sheets, purchase orders, and invoices?**

B.3 Interview Protocol Questions—Contractors

1. **Please describe your role in your company and your experience with commercial building sensors and controls technology.**
   Please describe the company you work for—size, location, clients.
   How long have you been in this role?

2. **Describe the process that you use to procure building sensors and controls.**
   What requirements and considerations do you have?
   What basic offerings are common to most building sensors and controls bids?
   When closing a contract with a vendor, what leads you to your decision to work with this vendor?

3. **Do you own or operate any buildings where you did not install a building sensors and controls system? In a future building, would you install a building sensors and controls system? Why or why not?**
   What would make the procurement process easier?
   What changes would you make?
   Would you use the same company?

4. **Please provide as much information as possible about the current costs of building sensors and controls systems. What are the cost categories?**
   What factors impact the costs?

What are the annual maintenance costs?
What percent of total construction and/or maintenance cost is controls?

5. **What do you envision as the future of building sensors and controls?**

6. **Would you be willing to provide example pricing data such as bid sheets, purchase orders, and invoices?**

B.4 Interview Protocol Questions—Vendors

1. **Please describe your role in your company and your experience with commercial building sensors and controls technology.**
   Please describe the company you work for—size, location, clients.
   How long have you been in this role?

2. **What is typically the return on investment for sensors and controls systems?**
   What are the energy savings, if any?

3. **Please provide as much information as possible about the current costs of building sensors and controls systems. What are the cost categories?**
   What are the cost ranges for each category?
   What factors impact the costs?
   Could you describe the pricing structure for the system?
   What are the annual maintenance costs?

4. **What do you envision as the future of building sensors and controls?**
   What areas is your company focusing on in the future?

5. **Would you be willing to provide example pricing data such as bid sheets, purchase orders, and invoices?**

Appendix C. Building Automation System Cost Estimation Using U.S. Department of Energy Prototypical Reference Building Models

A BAS includes various control points including digital/analog control inputs/outputs as well as numeric points such as set points. Depending on building size and type of HVAC system, the total number of hardware, software, and control points could vary from building to building. To estimate the BAS cost for a complete system, we used DOE commercial prototype building energy models. Some details of the models, particularly for HVAC system configurations, were modified and those details are discussed extensively throughout this section. Table C-1 summarizes the quantity and type of HVAC systems used in the building models after associated adjustments were made that are discussed in subsequent sections of this appendix.

Table C-1. Summary of HVAC System Types in the U.S. Department of Energy Reference Building Models

Building Type	Total Area (ft^2)	HVAC System	Quantity
Secondary School	210,887	Constant speed air handing unit (AHU) with ERV, two-stage DX cooling, gas heating	5
		Variable speed AHU with ERV and VAV box with reheat; heating and cooling provided by central chiller and boiler	4
Primary School	73,958	Constant speed AHU with ERV, two-stage DX cooling, gas heating	3
		Variable speed AHU with ERV and VAV box with reheat, two-stage DX cooling, heating provided by central boiler	4
Medium Office	53,625	Variable speed AHU with VAV box with electric reheat, two-stage DX cooling, gas heating	3
Stand-Alone Retail	24,692	Constant speed RTU, two-stage DX cooling, gas heating	5
Small Office	5,502	Constant speed RTU, two-stage DX cooling, gas heating	2

Based on the HVAC system types, we identified the required control inputs/outputs as well as the necessary software programs for running the system. Table C-2 provides a summary of the control points and programs based on HVAC system type.

Table C-2. Control Points Based on Model HVAC System Type

HVAC Equipment Type	Control Inputs			Control Outputs			Control Programs
	Name	Unit	Type	Name	Unit	Type	
Constant Speed AHU With ERV, Two-Stage DX Cooling, Gas Heating	Mixed air (MA) temp	°F	Analog	Outdoor air damper opening	%	Analog	High-temperature alarm
	Cooling coil supply air temp	°F	Analog	Return air damper opening	%	Analog	Low-temperature alarm
	Heating oil supply air temp	°F	Analog	MA damper opening	%	Analog	High-humidity alarm
	Supply fan status	On/off	Digital	DX stage 1 start	On/off	Digital	Low-humidity alarm
	Return fan status	On/off	Digital	DX stage 2 start	On/off	Digital	DX stage control
	DX stage 1 status	On/off	Digital	Supply fan start	On/off	Digital	Supply/return fan on/off control
	DX stage 2 status	On/off	Digital	Return fan Start	On/off	Digital	Economizer program
	Gas heat status	On/off	Digital	Gas heat start	On/off	Digital	Outdoor air damper control
	Zone relative humidity	%	Analog				ERV on/off program
	Space temp	°F	Analog				Filter alarm
	Filter air differential pressure	InWC[a]	Analog				
	Space static pressure	InWC[a]	Analog				
	Fire alarm	On/off	Digital				
	Duct smoke alarm	On/off	Digital				
	Duct high-temperature alarm	On/off	Digital				
Variable Speed AHU With VAV Box With Electric Reheat, Two-Stage	MA temp	°F	Analog	Outdoor air damper opening	%	Analog	High-temperature alarm

HVAC Equipment Type	Control Inputs			Control Outputs			Control Programs
	Name	Unit	Type	Name	Unit	Type	
DX Cooling, Gas Heating							
	Cooling coil supply air temp	°F	Digital	Return air damper opening	%	Analog	Low-temperature alarm
	Heating coil supply air temp	°F	Analog	MA damper opening	%	Analog	High-humidity alarm
	Supply fan variable frequency drive (VFD) feedback	°F	Analog	DX stage 1 start	On/off	Digital	Low-humidity alarm
	Supply fan status	°F	Analog	DX stage 2 start	On/off	Digital	DX stage control
	Duct static pressure	%	Analog	Supply fan start	On/off	Digital	Hot discharge air set point reset program
	Return fan VFD feedback	On/off	Digital	Return fan start	On/off	Digital	Economizer program
	Return fan status	InWC[a]	Analog	Gas heat start	On/off	Digital	Outdoor air damper control
	Filter air differential pressure	%	Analog	Supply Fan Speed	%	Analog	Supply/return fan on/off control
	Freeze sensor	On/off	Digital	Return fan speed	%	Analog	Supply/return fan VFD program
	Return air temp	InWC[a]	Analog				Hot water valve program
	Space static pressure	On/off	Digital				Filter alarm
	Zone relative humidity	%	Analog				
	Space static pressure	InWC[a]	Analog				
	Fire alarm	%	Analog				
	Duct smoke alarm	%	Analog				
	Duct high-temperature alarm	On/off	Digital				

HVAC Equipment Type	Control Inputs			Control Outputs			Control Programs
	Name	Unit	Type	Name	Unit	Type	
Variable Speed AHU With ERV and VAV Box With Reheat, Heating and Cooling Provided by Central Chiller and Boiler	ERV leaving air temp	°F	Analog	Outdoor air damper opening	%	Analog	High-temperature alarm
	ERV motor status	On/off	Digital	Return air damper opening	%	Analog	Low-temperature alarm
	MA temp	°F	Analog	MA damper opening	%	Analog	High-humidity alarm
	Cooling coil supply air temp	°F	Analog	Cooling coil valve opening	%	Analog	Low-humidity alarm
	Heating coil supply air temp	°F	Analog	Heating coil valve opening	%	Analog	Chilled water valve program
	Supply fan VFD feedback	%	Analog	Supply fan start	On/off	Digital	Cold discharge air set point reset program
	Supply fan status	On/off	Digital	Return fan start	On/off	Digital	Hot discharge air set point reset program
	Duct static pressure	InWC[a]	Analog	Supply fan speed	%	Analog	Economizer program
	Return fan VFD feedback	%	Analog	Return fan speed	%	Analog	Outdoor air damper control
	Return fan status	On/off	Digital	ERV motor start	On/off	Digital	Supply/return fan on/off control
	Filter air differential pressure	InWC[a]	Analog				Supply/return fan VFD program
	Freeze sensor	On/off	Digital				Hot water valve program
	Return air temp	°F	Analog				ERV on/off program
	Space static pressure	InWC[a]	Analog				Filter alarm

HVAC Equipment Type	Control Inputs			Control Outputs			Control Programs
	Name	Unit	Type	Name	Unit	Type	
	Zone relative humidity	%	Analog				Freeze alarm
	Space static pressure	%	Analog				
	Fire alarm	On/off	Digital				
	Duct smoke alarm	On/off	Digital				
	Duct high-temperature alarm	On/off	Digital				
Single-Stage Heat Pump With Backup Gas Heating	MA temp	°F	Analog	Outdoor air damper opening	%	Analog	High-temperature alarm
	DX supply air temp	°F	Analog	Return air damper opening	%	Analog	Low-temperature alarm
	Heating coil supply air temp	°F	Analog	MA damper opening	%	Analog	High-humidity alarm
	Supply fan status	On/off	Digital	Gas heat start	On/off	Digital	Low-humidity alarm
	Return fan status	On/off	Digital	Supply fan start	On/off	Digital	DX control
	Filter air differential pressure	InWC[a]	Analog	Return fan start	On/off	Digital	Economizer program
	Return air temp	°F	Analog	DX start	On/off	Digital	Outdoor air damper control
	Space static pressure	InWC[a]	Analog	Smoke damper open	Open/close	Digital	Supply/return fan on/off control
	Zone relative humidity	%	Analog				Filter alarm
	Fire alarm	On/off	Digital				
	Duct smoke alarm	On/off	Digital				
	Duct high-temperature alarm	On/off	Digital				
	DX status	On/off	Digital				
	Gas coil status	On/off	Digital				

HVAC Equipment Type	Control Inputs			Control Outputs			Control Programs
	Name	Unit	Type	Name	Unit	Type	
	Zone temp	°F	Analog				
VAV Box With Hot Water Reheat	VAV zone temp	°F	Analog	VAV damper opening	%	Analog	VAV damper control
	VAV airflow	CFM[b]	Analog	VAV reheat coil valve opening	%	Analog	Reheat valve control
	VAV discharge temperature	°F	Analog				
VAV Box With Electric Reheat	VAV zone temp	°F	Analog	VAV damper opening	%	Analog	VAV damper control
	VAV airflow	CFM[b]	Analog	Electric reheat coil start	On/off	Digital	Reheat on/off control
	VAV discharge temperature	°F	Analog				
Chilled Water System	Primary pump status	On/off	Digital	Chiller start	On/off	Digital	Chiller enable program
	Secondary pump status	On/off	Digital	Primary pump start	On/off	Digital	Chiller lead/lag program
	Secondary pump speed feedback	%	Analog	Secondary pump start	On/off	Digital	Primary pump lead/lag program
	Secondary chilled water loop differential pressure	InWC[a]	Analog	Secondary pump speed	%	Analog	Secondary pump lead/lag program
	Chilled water supply temp	°F	Analog	Isolation valve	Open/close	Digital	Primary pump on/off
	Chilled water return temp	°F	Analog				Secondary pump on/off
	Chilled water flow	GPM[c]	Analog				Secondary pump VFD control
	Chiller status	On/off	Digital				Chilled water reset program
	Chiller power	kW	Analog				Chiller alarm control

HVAC Equipment Type	Control Inputs			Control Outputs			Control Programs
	Name	Unit	Type	Name	Unit	Type	
							Primary pump alarm control
							Secondary pump alarm control
Hot Water System	Primary pump status	On/off	Digital	Boiler start	On/off	Digital	Boiler pump alarm
	Secondary pump status	On/off	Digital	Primary pump start	On/off	Digital	Hot water supply temp alarm
	Secondary pump speed feedback	%	Analog	Secondary pump start	On/off	Digital	Hot water set point reset program
	Secondary hot water loop differential pressure	InWC[a]	Analog	Secondary pump speed	%	Analog	Combustion damper control
	Hot water supply temp	°F	Analog	Isolation Valve	Open/close	Digital	Boilers lead/lag control
	Hot water return temp	°F	Analog				Boiler pump on/off Control
	Hot water flow	GPM[c]	Analog				Boiler pump VFD control
	Boiler status	On/off	Digital				Boiler modulation program
	Boiler gas meter	kW	Analog				

[a]InWC: inches of water column; CFM: [b]cubic feet per minute; [c]GPM: gallons per minute

EnergyPlus reference building models are primarily developed for estimating building-level energy consumption. To utilize these models for estimating hardware, software, and control points, some adjustment needed to be made that reflected real building applications. Those adjustments included:

1. **Addition of return fans.** All the DOE prototypical models put supply fans (only) in the air loop. Most commercial buildings have supply, return, and sometimes exhaust fans. In general, the need for exhaust fans could vary from building to building and it is difficult to infer from reference building models. We added the return fans.
2. **Equipment redundancy**. In real buildings, it is common to provide redundancy to equipment that serves multiple zones and critical facilities. We added redundant equipment including a chiller, a boiler, a chilled water pump, and a hot water pump in the reference building models.

3. **Adjusting the number of VAV boxes**. Because of the physical constraints such as partition walls and/or limitations of duct sizing in the plenum, multiple VAVs might be needed to serve certain areas. The reference building models assume one VAV per zone irrespective of its size. From an energy consumption estimation perspective, this assumption is valid, but it requires adjustment for estimating control points. We have limited the maximum space area served by a single VAV to 1,065 ft^2 and adjusted the number of VAVs in the reference building models accordingly. This value is based on the size of a single classroom in the DOE secondary school building reference model, and it is comparable to the average classroom size for secondary schools in the United States (1,024 ft^2). Even if this is based on classroom size, we used the same assumption for primary school and medium office.
4. **Adjusting the number of packaged RTUs for stand-alone retail and small office**. Packaged RTU systems are widely available in the commercial building HVAC market and come in discrete, incremental sizes: e.g., 2-ton, 2.5-ton, 5-ton, etc. The reference building models were adjusted to more accurately represent the number of RTUs for the stand-alone retail and small office building. An industry standard rule of thumb of roughly 500 ft^2/ton of cooling was used to determine the appropriate count for RTUs. For the stand-alone retail, we chose five 5-ton units as an appropriate size and count based on the building size. For the small office building, we chose two 2.5-ton units.

After applying the adjustments, we estimated the control points related to each system. Depending on the level of controls needed and the geographical location of the buildings, there could be some variation in the required sensor points even for similar HVAC system types. For example, in areas where no economizer is recommended (e.g., areas with outdoor air quality issues), the AHU might not have a mixed air temperature sensor because the mixed air temperature is usually used to control an outdoor air damper for economizer operation.

The control point lists we estimated are based on the most commonly used sensor and data points for each system. We categorized the data points as control inputs (digital/analog inputs) and control outputs (digital/analog outputs). Accurate estimation of these inputs and outputs helps to properly estimate the hardware and software requirements for the BAS system as they are directly correlated with the number of sensors and actuators needed. Set points and other intermediate values (e.g., controller tuning parameters) needed in the BAS don't require any input/output and are not included in the building control points list. In addition, BAS cost implications for these are captured in the labor categories such as installation labor and programming labor. Table C-3 and Table C-4 summarize the results.

Table C-3. Summary of Digital/Analog Inputs/Outputs for the U.S. Department of Energy Prototypical Building Models

Building Type	Total Area (ft^2)	Digital Input	Digital Output	Analog Input	Analog Output	Total	ft^2/Control Point
Secondary School	210,887	82	62	585	303	1,032	204
Primary School	73,958	60	46	272	167	545	136
Medium Office	53,625	26	82	120	77	305	176
Stand-Alone Retail	24,692	40	30	40	15	125	198
Small Office	5,502	13	10	23	6	52	106

Table C-4. Comparison of Control Points Estimated From U.S. Department of Energy Prototypical Reference Building Models and Field Data

Project Type	ft^2/Control Point: From Field Data	ft^2/Control Point: Estimated From Reference Building Models	% Difference
Secondary School	217	204	6%
Primary School 1	243	136	77%
Primary School 2	184	136	35%