Commercial Building Sensors and Controls Systems: Barriers and Drivers

Preprint

Kristi Maisha,[1] Kim Trenbath,[2] and Ryan Meyer[2]

1 Vanderbilt University
2 National Renewable Energy Laboratory

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National Renewable Energy Laboratory
15013 Denver West Parkway
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Commercial Building Sensors and Controls Systems: Barriers and Drivers

Kristi Maisha, Vanderbilt University
Dr. Kim Trenbath, National Renewable Energy Laboratory
Dr. Ryan Meyer, National Renewable Energy Laboratory

ABSTRACT

Building sensors and controls systems, including building automation systems, comprise the sensor-based devices installed in buildings as well as the control and automation of those devices. Optimized sensors and controls systems could lead to 29% annual energy savings in commercial buildings and are integral to the growth of grid-interactive efficient buildings. Only 13% of small commercial buildings, however, have installed sensors and controls systems, largely because of cost barriers. To accelerate adoption, this work seeks to increase the transparency of system costs and identify specific barriers and drivers. To gather industry insights, the team reached out to building owners, vendors, and contractors and conducted 21 interviews with the goal of collecting cost data and market characteristics regarding building sensors and controls. We collected the cost data in the form of invoices and used it to develop a percentage-based cost category breakdown. The interview data were analyzed using grounded theory to identify overarching concepts such as barriers, drivers, and future directions. From this analysis, we found the primary barriers to be complex and confusing systems, lack of user skills, and financial concerns, and the primary drivers to be operational benefits, insight into operations, and remote access to data. The future directions analysis highlighted the potential technological solutions to address gaps and barriers, as well as predicted drivers to increase adoption. This greater understanding of the costs, barriers, and drivers associated with commercial building sensors and controls systems lays the groundwork for increasing system adoption, reducing energy consumption, and transforming the market.

Introduction

Buildings are the largest energy consumers in the United States, using up to 39% of total generated energy (EIA 2020), and thus are a relevant focus for energy efficiency efforts. Currently, the U.S. Department of Energy is investigating commercial building sensors and controls systems and energy information systems as strategies for improving building efficiency and reducing energy consumption. Building sensors and controls systems can include many types of sensors (occupancy, temperature, etc.) to monitor the status of the building and building equipment and controls (both hardware and software) to adjust building functions (turn lights off, adjust HVAC systems, etc.) (Domingues et al. 2016). They can also include building automation systems and building management systems, with opportunities to integrate various building systems and functions into a single platform (Domingues et al. 2016). The focus of this effort was on building automation systems and all control layers beneath for HVAC system control, which hence forth we identify as sensors and controls systems. Analytics layers functionality such as fault detection is not included in the scope as other efforts have focused here (Domingues et al. 2016, Kramer et al. 2020). If used properly, commercial building sensors and controls systems can result in a 29% reduction in building energy consumption through the implementation and automation of various energy efficiency control strategies (Fernandez et al.

2017). This would have a significant impact on the energy landscape of the United States, but there is currently not widespread enough adoption to see the desired energy savings.

Beyond the immediate energy savings benefits, building sensors and controls systems are necessary to improve U.S. building-to-grid infrastructure. These systems allow for greater interconnectivity between the building, utility, and energy sources (Neukomm, Nubbe, and Fares 2019). Building sensors and controls systems also lay the foundation for grid-interactive efficient buildings, which are energy-efficient buildings that can communicate with the grid, allowing for demand response, as well as optimize building operation to minimize energy costs, provide grid services, and maintain occupant comfort and productivity needs (Neukomm, Nubbe, and Fares 2019). As energy becomes increasingly important and energy production becomes more variable, grid-interactive efficient buildings become more important to make effective use of resources (Neukomm, Nubbe, and Fares 2019). This is important for renewables integration, occupant comfort, and complex control strategies (Neukomm, Nubbe, and Fares 2019). In order for portfolios of grid-interactive efficient buildings to emerge, more commercial building owners need to adopt building sensors and controls systems.

CBECS survey data shows that only about 13% of small to medium commercial buildings (50,000 square feet or less) have adopted building automation systems for HVAC control, indicating that there are significant barriers to implementation (EIA 2018). Looking at related building technologies such as demand response or fault detection and diagnosis, the high initial cost or the lack of savings relative to the high cost is a major barrier (Ma and Jorgensen 2018). Additionally, difficulty in long-term use, complexity of the system, or negative effects on occupant comfort are major considerations (Ma and Jorgensen 2018). Improving adoption and the implementation experience requires identification of the specific primary barriers for building sensors and controls systems so they can be addressed and the primary drivers so they can be highlighted.

This study is framed by the following research questions:

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

Addressing these question gives the reader some background on commercial building sensors and controls. It also provides the reader with an understanding of the cost challenges and a description of the pathways for increasing adoption of the technology.

Methodology

We used qualitative research methods to address our research questions. Our data collection plan included interviewing sensors and controls experts using a semi-structured interview protocol. The interview data provided insight into the characteristics of the industry and technology that impact costs as well as the implementation barriers and drivers. During the interviews, we also attempted to collect cost data that included a cost category breakdown.

We were interested in speaking to a comprehensive set of industry experts—including building owners, contractors, and vendors—because each could provide insight from a slightly different perspective. Using the overarching research questions for framing, we developed an interview protocol for each industry expert type. Building sensors and controls cost questions focused on both cost categories and return on investment. We also asked about the decision to install a system, the procurement process, and the future of building sensors and controls. The protocols can be found in Trenbath et al. (2022). The series of questions started with general open-ended questions leading into more focused questions of barriers, drivers, and costing. We vetted the interview protocols with two research engineers who have worked in the commercial building realm for 10–20 years.

We developed a data collection outreach strategy that excited the external contacts about the project. We planned and launched a campaign that marketed the benefits of participation to potential interviewees. We compiled a list of experts and recruited participants using a designed flier. We recruited participants through email outreach as well as outreach on social media (LinkedIn). We set up interviews with experts who responded to our outreach.

We conducted 21 interviews with a total of 28 experts. When multiple people were interviewed, they represented the same organization. At least two NREL 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 summaries of information. At the end of the data collection process, each interview had an associated set of notes.

At the end of each interview, we asked the interviewee for cost data. One building owner provided invoices from recent projects that had the costs broken down by cost category. We used these data to create a cost category breakdown.

We analyzed the interview data using grounded theory (Glaser and Strauss 1967). The interview quote data were read, interpreted through a lens defined by the research questions, and then coded based on this interpretation. Through this process, data trends emerged, allowing the quotes to be categorized (as a barrier, driver, etc.) and then further subcategorized (a barrier might be attributed to high cost, system complexity, etc.). The data for each category were consolidated in a spreadsheet containing the quote, the code/interpretation, and all associated metadata (name, date, organization, expert type) to identify trends and opportunities for deeper analysis. The full grounded theory analysis was validated by having multiple researchers who were present at the interview evaluate the data.

Through the analysis, we identified trends across multiple interviews. We documented these trends in an analysis write-up as characteristics of the current state of costs in the commercial building sensors and controls market.

Results

The results of this study characterize the costs, barriers, and drivers of commercial buildings sensors and controls systems. In this section, we summarize the interview results.

Interview Breakdown

We interviewed 28 experts during 21 different interviews. Additional experts provided insight. Figure 1 shows the industry role of each interview.

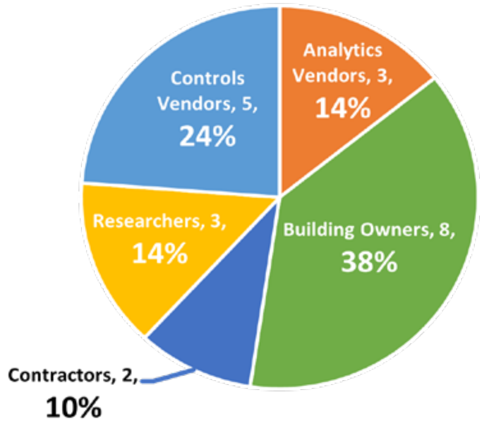

Figure 1. Breakdown of interviews by industry role. There are 21 interviews total.

The experts represented five different industry roles:

- Building owners own and operate commercial building(s) with sensors and controls systems and make purchasing decisions. They represented K–12 schools, higher education, retail, state government, and the federal government.
- Contractors are companies that provide building control engineering and are mostly independent of a hardware vendor.
- Controls vendors are manufacturers and sellers of building automation systems and commercial buildings controls or control system implementers.
- Analytics vendors are companies that develop and sell analytics platforms such as energy information systems that can provide supervisory controls.
- Researchers are advanced building controls experts with a deep understanding of building controls technology or the controls market.

We separated vendors into two types—controls vendor and analytics vendor—because their products support separate functions of building automation and control. Controls vendors often have proprietary technologies and pricing models, which they use to maintain and grow their market share. Analytics vendors tend to pitch their products as market disruptors and highlight the differences in their offerings. During the interviews, both vendor types discussed the industry at large, but usually focused on describing their own products.

Building owners represent the largest percentage of participants. Building owners' focus often went beyond the initial installation and cost of the system; their priorities are to make the maintenance and utilization of the systems as easy as possible. For this reason, building owners often based future decisions and vendor choices on their past experience with vendors.

Contractors made up the smallest proportion of participants but could provide a wide breadth of knowledge. They work with many different vendors and building owners, so they have a high-level understanding of the industry and the ability to compare different options.

We also interviewed three researchers who provided expert advice but were not in charge of the day-to-day operations of their institution's building. Researchers who were consulted for this study are actively involved in sensors and controls systems work, and, similarly to contractors, had observed a wide range of projects and could provide industry-wide observations.

Cost Categories

This work sought to understand the different cost categories that contribute to the total cost of a building sensors and controls system and their relative contributions. The invoices provided by a building owner during the interview included cost breakdowns by hardware, software, and various labor categories for two projects in high schools from the same school district. These projects included upgrades to an existing HVAC building automation system to conform with new district standards, as well as replacing controllers and any outdated field devices throughout the facilities. The scope of both projects were similar in size and HVAC system, with some difference in the number of controllers and system points affected by the upgrade. Figure 2 shows the percent breakdown of these costs and Table 1 summarized the cost per square foot. The cost data come directly from the project-specific source.

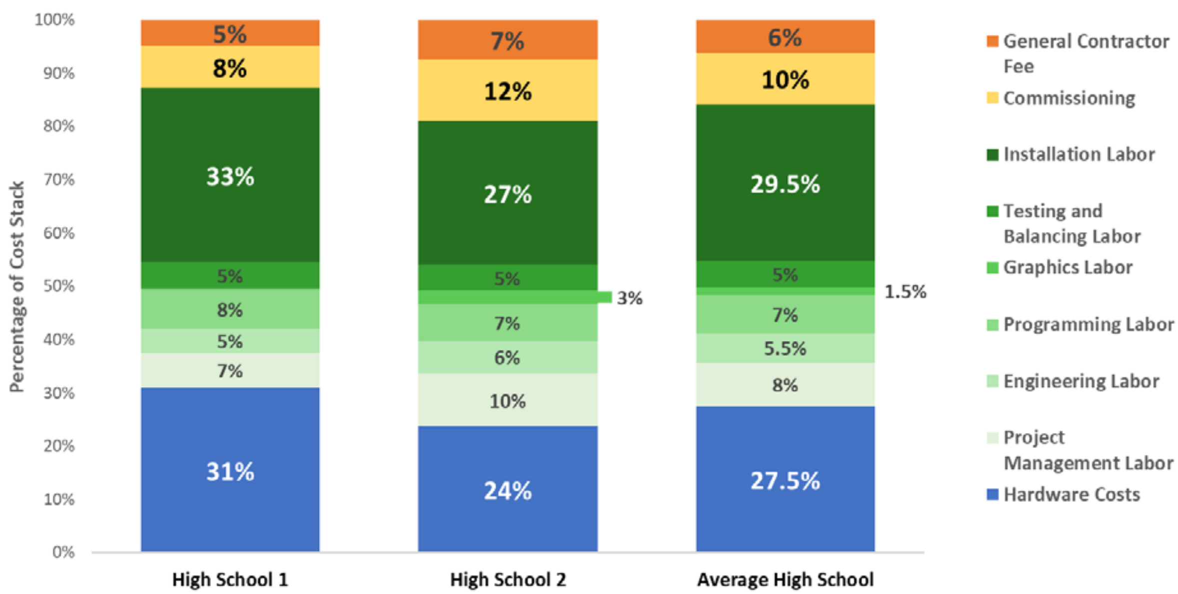

Figure 2. Cost category breakdown for two high school sensors and controls projects.

Table 1. Cost per square foot breakdown for two high school sensors and controls projects

Cost category	Cost per square-foot range
General contractor fee	$0.10–$0.11
Commissioning	$0.16
Installation labor	$0.38–$0.68
Testing and balancing labor	$0.07–$0.10
Graphics labor	$0.04
Programming labor	$0.10–$0.16
Engineering labor	$0.09
Project management labor	$0.13–$0.14
Hardware	$0.34–$0.64
Total	$0.98–$1.33

The description of the nine cost categories given in Figure 2 are in Trenbath et al. (2022). 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. Installation labor is significant, at 29.5% of the total cost. Beyond the aforementioned cost categories, ownership of building sensors and controls systems have additional costs, such as those for system maintenance or subscription fees.

The interview data contained information on the expert perceptions of the largest cost categories. They identified many of the cost categories in Figure 2. One significant cost category not included above is maintenance costs, which was not included in the invoice because these costs are not realized during installation. Two interviewees emphasized that wiring costs are a large part of installation labor.

In the qualitative interview data, two experts—a controls vendor and a building owner with previous controls vendor experience—were able to give percentage ranges for several categories. The controls vendor gave a hardware cost percentage range from 18% to 20%, with 8% to 10% coming from the technology, and 10% coming from metering hardware. The installation labor percentage was given at 40%. The remaining 40% to 42% of the cost was attributed to engineering and project management. The building owner gave an overhead labor and profit range from 25% to 33% of the total cost, with the profit margin range specifically given as 4% to 10%. Largely, the categories and percentages between the invoices and the qualitative interview data are quite similar. Having similar cost percentages and relevant categories helps to validate them both.

The discussion surrounding each category can better inform the categories that should be targeted for cost reduction. For instance, the invoice data show that installation labor contributes the greatest percentage of the cost, which indicates a need to reduce installation labor costs. From interview data, multiple interviewees mention labor as a major category, and vendors have indicated that they are actively working to reduce that cost, further validating that finding. Interviewees also noted that the wiring component should be highlighted as a major cost because of the installation labor being time-consuming and costly. Furthering the understanding of this cost category, interviewees cited cybersecurity concerns as a barrier for switching to wireless sensors and controls. Thus, by focusing on reducing the wiring components and on relieving cybersecurity concerns, the industry can reduce installation labor costs.

Pricing Structure

Many different vendors compete to install sensors and controls systems in buildings across the country, so interviewees noted that the total system cost tends to be comparable across the industry. There is, however, no standard for how the price is calculated or distributed. A controls vendor stated that "companies are *very* particular about the details of the costing" and that there are "no third-party tools that do this." This makes it difficult to get a clear cost category breakdown, because it is usually the entire system being priced, not individual components.

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

A different 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 was detrimental to providing sufficient data 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 to determine.

Finally, another vendor indicated that pricing structure, and 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 greater value.

Procurement Process

Procurement processes differ across building owners and can impact the total cost. Understanding the steps of procurement provides insight into points for potential profit markup and the cost breakdown. Two primary procurement methods emerged from the data—open bid and sole sourcing. In this section, we describe the two procurement methods, interviewees' vendor decision-making factors, and procurement challenges.

Open bid. In an open bid process, the building owner works with an architect or engineering firm, contractor, or energy service company to design the sensors and controls system with given specifications and requirements. Then the design is opened to bids from controls vendors. Vendors provide a bid that aims to achieve the lowest price possible. Sometimes vendor participation in the bidding process is limited. This was a common method for the public entities that we interviewed, such as government organizations and public schools. Despite the prevalence, several interviewees identified challenges with this method. Building owners noted that this process could result in having multiple systems from different providers, which they thought were inconvenient to operate, especially because the various systems required more training. Vendors noted that in aiming to provide the lowest cost possible and narrowing their profit margins, they had to sacrifice some quality and value.

Sole sourcing. For sole sourcing, the building owner commits to working with a specific vendor for their entire building portfolio. This method was not commonly used by building owners interviewed in this study but was noted as an aspirational goal because of the ease of procurement and reduced requirements for staff training. This method can also increase vendor input during the design process. A vendor noted that this allowed them to add more value to the system, even if the cost, and implied profit margins, were higher. For public entity building owners, this higher cost along with reduced transparency were obstacles to using this method.

Decision-making factors. Interviewees elaborated on their experiences with procurement, noting some of the factors that determine their vendor choices and some of the challenges they faced. These factors aid in understanding the priorities of building owners and potential drivers for greater adoption. Almost everybody discussing this noted cost as a major factor, but most said that cost was not the only consideration. Instead, these building owners employed a method using the best value, where cost is included along with other crucial factors. Factors include the availability of trained technicians to install and program the system, the amount of experience the company has with similar types of buildings, how proprietary their system is, and if/how they outsource parts of the installation or system development process.

Procurement challenges. These procurement challenges relate to a *specific* experience recounted by an individual building owner on procuring a system from specific vendors:

- When the building owner has limited funds, they must pick which projects are most urgent and leave outdated systems in place.
- Different equipment has different lifetimes, so each must be procured separately, complicating the upgrade procurement processes.
- The building owner must have a large portfolio to negotiate a reduced cost.
- Public entities are subject to many rules on costing and transparency, removing the option of sole sourcing.
- If there are a variety of systems in an owner's building portfolio that do not interface well with one another, then the staff must undergo training for each individual system, which requires staff labor hours.
- For some sensors and controls systems, a representative from the original manufacturer, rather than the contracted engineer or programmer, is needed to correctly set up the software and analytics.

The interviews were primarily conducted with stakeholders who install and sell building sensors and controls systems. A procurement challenge known to engineers but not revealed through this process is value engineering, in which pricing constraints can lead to a less robust system or to eliminating the sensors and controls system altogether.

Barriers to Implementing Commercial Building Sensors and Controls Systems

The experts identified different barriers to implementing commercial building sensors and controls systems. Table 2 summarizes the major barriers, which are the ones mentioned by multiple interviewees. The table includes the barrier name and a description of each. After the table, we provide more context for each barrier. Barriers are ordered by researcher perspective and grouped for intuitive understanding.

Table 2. Interviewee-identified barriers to implementing commercial building sensors and controls systems

Identified barrier	Barrier description
High cost	Systems may fail to meet 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 advanced 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.

Identified barrier	Barrier description
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	Advanced control systems are not cost-effective when scaled down to smaller commercial buildings.
System complexity	Advanced controls systems are complex—they consist of numerous devices and controllers that require expertise to operate systems effectively and efficiently.
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.

High cost. Although building owners might be excited about installing building controls, the systems may fail to meet their investment criteria as a result of high first costs. There is a perception that the controls vendors with significant market share are expensive and do not negotiate.

Difficulty in quantifying savings. Cost savings is a commonly used value proposition for advanced building control systems. Based on interview data, there is a lack of quantified nonenergy savings for these systems that could improve the value proposition for building owners. When building owners perceive value to be lower than the cost to install and operate, they could decide against implementation.

High costs and a lack of quantified nonenergy benefits leads 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.”

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 success of building control and automation companies. There is a need for an industry standard ontology for building control systems enabling plug-and-play applications across vendors. An emerging solution is semantic interoperability that allows devices from different manufacturers to integrate with each other in a plug-and-play manner (Bergmann et al. 2020).

Inconsistent terminology in vendor communication. Vendors differentiate themselves by using terminology that is specific to their products. This inconsistent terminology across vendors poses a barrier because it is confusing and takes a long time to understand. 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. 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 what options there are, making it difficult for building owners to identify what is actually needed for their building.

Lack of economies of scale. Commercial building sensors and controls systems are often difficult to simplify for small/medium buildings. These systems are designed for a complicated building and involve many components, but they cannot easily accommodate the simpler needs of a smaller building. A controls vendor stated, "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, resulting in costs that are unreasonable for small buildings.

It is a challenge to achieve advanced building control system 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.

System complexity. Sensors and controls systems are complex because there are so many components that need to be considered during 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

Installation and programming of building control systems are complex because the systems 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 also 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 systems labor-intensive and complex.

Lack of expertise. Success with advanced building controls 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. This is a challenge for building owners who only have a few people on staff (like small buildings) and who have turnover.

These barriers, as shown in Figure 3, fall naturally into three categories: confusing and/or complex systems, user skills, and financial considerations. Although the initial hypothesis that costs are barriers appears to be validated, our analysis revealed other important underlying barriers such as system complexity, product incompatibility, and inconsistent terminology. These barriers often result in the need for experts on staff and additional trainings to adequately maintain or make ongoing adjustments during operation. This result suggests that straightforward and interoperable systems that provide proven customer savings may contribute to an increased uptake of advanced sensors and controls.

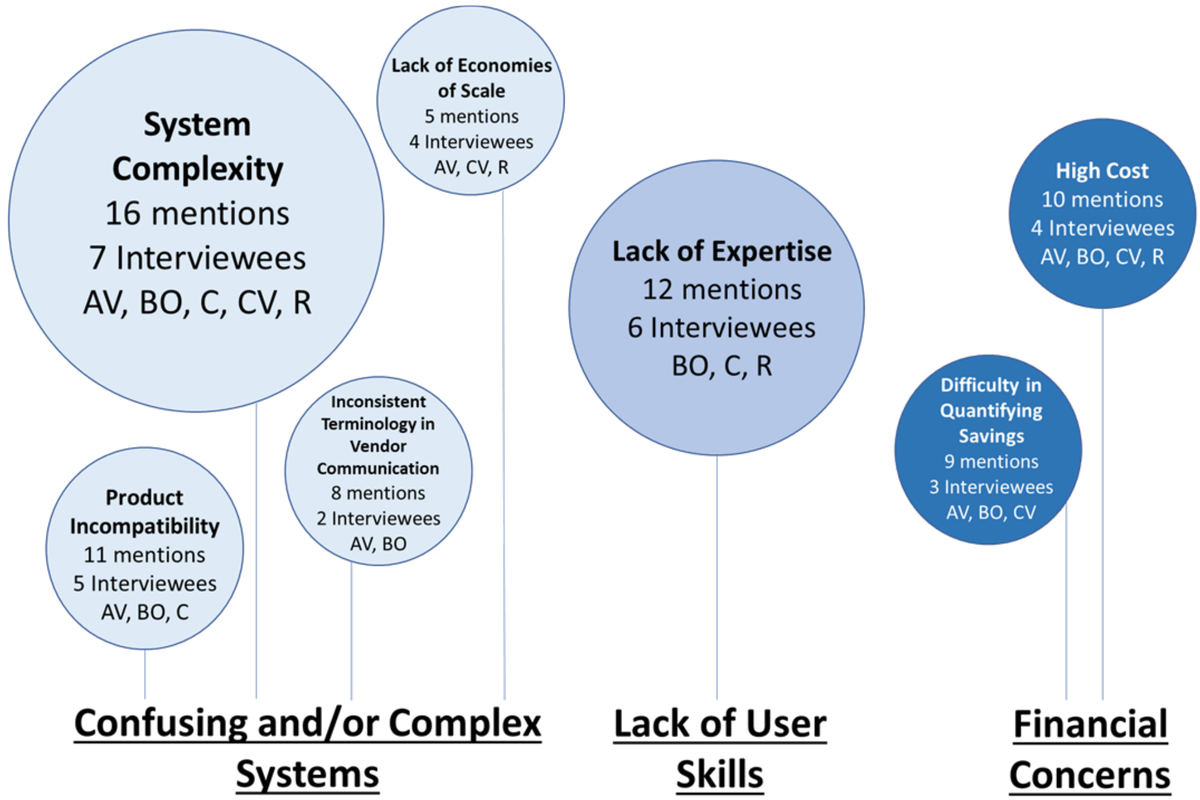

Figure 3. Names of barriers and the number of mentions.
Key: Building owners (BO), analytics vendors (AV), controls vendors (CV), contractors (C), and researchers (R)

Other barriers. Three additional barriers emerged from the interview data but were mentioned less frequently (fewer than four times). Sensors and controls systems involve a lot of hardware and equipment including sensors, controllers, software packages, wiring, and conduit. ***Updating and improving this equipment*** (i.e., replacement or software updates) requires significant investment.

Split incentives occur 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, property owners are not motivated to pay for it because energy cost savings mostly benefit tenants.

Owners expressed ***cybersecurity concerns*** with having the building's data stored in the cloud because 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 that can be costly to businesses.

Drivers for Implementing Commercial Building Sensors and Controls Systems

Interviewees identified drivers explicitly or through discussions of what motivated building owners to implement sensors and controls systems. Table 3 summarizes the major drivers in order of the emphasis placed by interviewees and reflected in researchers' insights. After the table, we provide more context for each driver.

Table 3. Interviewee-identified drivers for implementing commercial building sensors and controls 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	Systems often provide the building engineer with remote access to building operation data, so the engineer does not 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 that are straightforward to integrate and that make building operations simpler.

Operational benefits. 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—reduced need to call on technicians for system troubleshooting, at least for issues that can be diagnosed from the control system. These benefits save energy and labor.

Building owners also procure advanced controls in order to access modern communication protocols such as BACnet. Finally, system upgrades provide opportunities to replace equipment that has become so obsolete that it is impossible to find replacement parts. The replacement system often improves building operation and associated operational benefits.

Insight into operations. Sensors and controls systems collect energy consumption and building system performance data. The systems then use this information to provide insights useful for building operation such as root cause analysis, space utilization, occupancy patterns, and building performance. With these insights, building owners can objectively assess the status of their building and make appropriate changes.

Remote access to data. Cloud-based data visualization allows building managers responsible for multiple buildings to easily track building operations from one location. A contractor said, "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 square foot 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."

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. Benefits need to be translated and quantified in dollar terms to show that there will be savings from the system.

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.

Ease of use. 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 the intuitiveness of the system.

Future Directions

Interviewees described several changes and evolutions that they expect to see within the sensors and controls system industry to improve market adoption in the future. These are based on frustrations experienced with existing systems, identified gaps, and emerging technologies. These future directions are summarized in Table 4.

Table 4. Future directions for commercial building sensors and controls

Future direction	Description	Quote
Internet of Things	A major push from both customers and vendors is to incorporate the Internet of Things into sensors and controls systems. Sensors and equipment will be connected to the internet and utilize data to improve facility management and savings. This also allows for easier connections and updates to older systems.	"[The Internet of Things] is where it's at; it's unbelievable what it can do."
Wireless communication protocols	Although some building owners currently avoid wireless connections for a number of reasons including privacy concerns, several vendors and building owners feel that wireless or Bluetooth connected sensors and controls are a primary future direction. They provide lower capital costs by reducing wiring needs and improve overall connectivity.	"Wireless is going to be key, what is going to be prevailing."
Machine learning and	Machine learning and AI have substantial opportunities to improve the effectiveness and automation of controls, although	"The way the AI will work is that the

Future direction	Description	Quote
artificial intelligence (AI)	there is currently low market adoption. These systems are based on algorithms that take inputs from the building and the environment and adjust controls accordingly. This makes the overall system more intuitive and improves the occupant experience.	preliminary algorithm and the sensor data will send some key information into the cloud and adjust the AI weighting factors."
Sensor types	Interviewees identified some gaps in sensor data collection, meaning that future systems will have different sensor types. Specifically, they noted that sensors and controls systems could benefit from having more zone sensors as well as infrared sensors to assess occupancy more accurately than relying on the building schedule.	"I thought a lot about infrared…I see this as the future."
Privacy solutions	Interviewees noted that certain system components provide major potential benefits for sensors and controls systems such as cameras and data collection of occupant behavior patterns. These technologies, however, come with significant privacy concerns. The industry will need to find privacy solutions to integrate them into buildings and reap the improved functionality.	"The privacy issues are holding the technology back."
Edge intelligence	Edge intelligence will play a significant role in improving system functionality and small building integration. Devices and equipment will be manufactured with built-in controllers and computing functionality to improve system efficiency. The equipment will connect to the larger sensors and controls systems. This allows buildings owners to avoid highly engineered custom systems and data transfer costs while still reaping the benefits of control.	"We are actually thinning it [software] down to put it on the devices, moving it towards the edge."
Future drivers	Interviewees also noted the future drivers that will lead to industry changes. Regarding greater adoption of sensors and controls systems, they mentioned that legislation, lack of technicians, reduced system costs, and utility rebates will be major factors. From the vendor perspective, these systems will be marketed as a tool for functionality, such as improving comfort, rather than a tool for saving energy. For edge intelligence and open protocol, it was noted that building owners with large portfolios will push vendors to manufacture such devices.	"[It will be] legislation or lack of technicians that drives people through."

Discussion

This research uncovered the factors that influence the costs, the barriers, and the drivers of commercial building sensors and controls systems through a qualitative research study. Increased market adoption of these systems will save energy and provide the infrastructure needed for grid-interactive efficient buildings. To increase adoption, however, implementation barriers need to be overcome. The identified drivers provide a pathway for the future.

Many of the barriers are related to the perception of high costs resulting from the difficulty of quantifying the impacts of operational and nonenergy benefits. There are a lot of complexities within the technology itself as well as the level of knowledge required to work with it. The future directions (See Future Directions section and Table 4) show pathways for overcoming these barriers.

Complex systems often require significant specialized labor to install and maintain. The industry has an opportunity to streamline the technology for the user so that it can be maintained by anyone who works in the building. For example, the facilities management staff should be able to understand these systems and find and update control schedules. Advanced control systems should be designed for ease of use as opposed to requiring special training.

Some sensors and controls systems contain proprietary software that requires training to update, which is costly to the end user. Also, some technologies only work with technologies manufactured from the same company. For example, some retail organizations must all use the same platform 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. The sensors and controls industry has the opportunity to make systems both interoperable and interchangeable.

A couple of the experts we interviewed said the most efficient way to implement controls is for the controls to be within the equipment with a software layer controlling all equipment. This eliminates some of the hardware, equipment, conduit, and wiring needed in these systems (See "Edge Intelligence" in Table 3). There is the opportunity for control to occur on the "edge," similar to the way edge computing networks locate information processing close to where things and people produce or consume the information.

The future directions of commercial building sensors and controls systems are pushing them to be more connected and streamlined. This could enable market uptake from smaller building owners, who currently cannot benefit from economies of scale.

Although this paper identifies opportunities to advance building sensors and controls, a lot of work is needed to accomplish fully-controlled, grid-interactive efficient buildings. This paper's summaries of expert interviews can be pathways to market transformation. This can be encouraged through policy changes. For instance, it would be valuable to develop an industry standard ontology to address product incompatibility, test security protocols and specifications to address cybersecurity barriers, and find solutions for split-incentive barriers from a policy perspective. Controls companies can also foster this transformation by providing products that address the needs of the building owners.

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