Laying Down the Foundation: An R&D Roadmap for Energy Savings through Advancements in Smart Building Technologies

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ABSTRACT

The use of sensors, actuators, and controllers to improve operations and minimize preventable energy losses has been well-documented in the buildings sector, with up to 30% whole-building energy savings possible. While efforts to embed intelligence in buildings that enable "smart" operations for energy management have proliferated in the past two decades, they have generally lagged behind other sectors and applications (e.g., large-scale industrial process plants, automotive, aerospace).

This paper presents a research and development (R&D) roadmap for advancements in monitoring and control technologies for smart building operations. Beginning at the sensor node level, four interdependent focus areas are analyzed that build on one another through respective technology performance improvements and cost reductions. Prospective systems-level technology cost targets and energy performance goals are presented for each focus area based on quantitative estimates using BTO's Scout tool; these estimates are coupled with qualitative insights that account for technology characteristics not currently represented in the Scout analysis framework - for example, ease of installation and long-term maintenance (e.g., through automating the mapping, configuration, and commissioning of supported technologies). Finally, the portfolio-level impact of innovation is explored through the maximum adoption primary energy savings potential.

Introduction

The U.S. Department of Energy's (DOE) Building Technologies Office (BTO) invests in the research and development (R&D) of the next generation of high-performance, cost-effective tools and technologies that will result in significant energy savings for the national building stock – both commercial and residential. In addition to component-based technologies (e.g., heat pumps, windows, and lighting devices), one of the core technical areas of development necessary for achieving this goal is in cyber-physical systems that integrate sensing and actuation with computing and communications to monitor and control the physical environment. As such, BTO maintains an active portfolio in sensors and controls (S&C), which along with building energy modeling (BEM), each cover critical portions of the building energy management cyber-physical space. In fact, an aggregated annual energy savings of 29% can be achieved in the commercial sector alone through the implementation of efficiency measures using current state-of-the-art sensors and controls through strategies that include optimizing programmable settings and detecting and diagnosing operational problems. This translates into a 4-5% reduction of U.S. primary energy consumption (Fernandez et al. 2017). Despite these promising results, two main challenges have limited the opportunity for effective monitoring and control of building operations to ensure savings for high-efficiency components and equipment (e.g., heat pumps, windows, and lighting devices), as well as additional savings from more sophisticated control sequences and architectures.

First, building automation systems (BAS) are limited to 43% of commercial building floor space, predominately in the large commercial (>50,000 square feet) stock. This amounts to 46% of floor space in large commercial compared to only 8% of small buildings (<50,000 square feet) that incorporate automation (U.S. Energy Information Administration 2016). Small commercial buildings generally consist of basic controls (i.e. a thermostat with setback capability to control air temperature in the different building zone(s)). This discrepancy is due to the limited cost-effectiveness of the return on investment for centralized control through automation. The fewer zones within small buildings limits the anticipated energy savings from these systems which cannot sufficiently offset high upfront capital costs. On the other hand, large commercial buildings typically have dedicated energy management budgets along with personnel to operate and maintain these systems. Overall costs also decline with increasing number of points installed due to economies of scale (Granderson 2016). Similar to small commercial buildings, while rapid growth is currently underway, the installation of home energy management systems are still fairly limited overall in the residential sector with monitoring and control typically consisting of programmable thermostats for central and single-zone space conditioning. According to the EIA, 41% of residential buildings have a programmable thermostat installed, but only 12% use the programmable functionality. Furthermore, only 3% have a smart or learning thermostat that learns occupant behavior over time, eliminating user intervention (U.S. Energy Information Administration 2017).

Second, most systems currently installed in the existing building stock exclusively manage heating, ventilation, and air-conditioning (HVAC) and are rule-based, reactive, and designed to meet short-term thermal and ventilation loads. These systems are typically separated from control of other building end uses such as lighting. This not only limits their performance in meeting energy efficiency objectives, but also in effective interactions with the electric grid. In general, implementation of intelligence for building energy management has lagged behind other sectors and applications (e.g., large-scale industrial process plants, automotive, aerospace) due to several factors. This includes utilization in less operationally critical applications (e.g., occupant comfort instead of safety and security), the fragmented nature of the buildings market (e.g., owner owned and tenant occupied), the customized nature of incorporating intelligence into building equipment rather than integrating into the design process, and the diversity of systems configurations and limited modeling and integration capabilities for stochastic variables (e.g., occupants, weather forecasts).

This paper outlines prospective systems-level technology cost targets and energy performance goals for four interdependent focus areas. These research areas are analyzed within the context of achieving these targets and goals. Advancements in the strategies presented are intended to manage multiple building subsystems (e.g., HVAC, refrigeration, and lighting) at the whole-building level; execute more complex strategies over longer temporal periods (e.g., hours and days rather than minutes) and at multiple spatial scales (e.g., occupant, zone, whole-building, campus); incorporate diagnostics, predictions (e.g., occupancy patterns, weather forecasts) and prescriptions along with current state information; and employ optimization techniques rather than rules. The sector-wide energy impact potential from successful realization of the technology development strategies is also evaluated.

R&D Focus Areas

Four interrelated focus areas of research are identified and described in this section that build on each other and are aimed at: (1) reducing the cost and improving the accuracy of sensing and sub-metering along with the development of new sensing modalities (e.g., occupancy and building equipment health); and (2) optimizing replacements to rule-based controls over longer time periods (e.g., hours and days rather than minutes) and multiple spatial scales (e.g., occupant, zone, whole-building), as well as incorporating additional inputs (e.g., occupancy patterns, weather forecasts).

Multi-Functional, Wireless Sensor Networks

Advancing wireless sensor networks that are fully automated, plug-and-play, and capable of monitoring multiple parameters through effective power management will enable a low-cost approach to accurately detect and diagnose faults, failures, and resulting inefficiencies in building equipment and subsystems, while also allowing for optimal and localized whole-building control opportunities to improve building operations along with reducing energy use.

Advanced Controls

Developing and optimizing integrated building control schemes at the whole building level with predictive, prescriptive, and learning capabilities to correct for faults and respond to environmental and building equipment conditions over longer temporal and spatial periods will ensure anticipated energy savings for high efficiency building equipment and their associated control strategies.

Granular Equipment Sub-Metering

Advancing pervasive sub-metering such that all relevant equipment and plug loads are metered at a low cost and with sufficient accuracy for unique identification will provide essential data to maximize and verify energy savings, as well as provide critical information on the state and usage patterns of specific equipment to enable monitoring-based commissioning and facilitate the optimization of fault detection and diagnostics of operational faults along with control strategies.

Occupant-Centric Sensing and Controls

Incorporation of accurate, real-time recognition of individual and group-level occupant presence and estimation of comfort in building control schemes will allow for optimized building services (i.e. space-conditioning, lighting, and plug loads) at a localized level that will reduce energy consumption resulting from unnecessary space conditioning, lighting and ventilation while maximizing occupant productivity.

Analytical Framework

Methodology

The Scout analysis program (Harris et al. 2016) is utilized to set unit-level technology cost and energy performance targets for the identified focus areas. Scout is an open-source software tool developed by BTO that estimates the primary energy use, CO_2 emissions, and operating cost impacts of building energy conservation measures (ECMs) at a national scale, also supporting ECM cost effectiveness assessments. The analytical framework used to set cost targets and energy performance goals for S&C ECMs consist of the following steps:

- Set the desired market entry year,
- Set the segment(s) of baseline energy use that the technology applies to,
- Set a desired range of energy performance for the technology at market entry,
- Set a cost-effectiveness threshold for the technology at market entry, and
- Determine the unit-level installed cost that satisfies the cost-effectiveness threshold based on the above parameter settings

For the purposes of the analysis included in this paper, a special Scout module was developed that iteratively adjusts each ECM's unit-level cost input until a user-defined cost effectiveness or payback period threshold was achieved within a certain tolerance.

S&C ECMs improve upon the performance of comparable baseline technologies (e.g., technology configurations without the S&C ECM applied) through either an increase in efficiency or more effective systems-level operation. ECMs are defined by applicable segment(s) of baseline energy use, market entry and exit years, and unit-level installed cost, energy performance and lifetime. The lifetimes of target ECMs are set to be consistent with that of the comparable baseline technologies. To calculate the total primary energy savings, CO_2 emissions, and cost impact potential of an ECM and ECM cost effectiveness, Scout compares ECM cost, performance, and lifetime to the current and projected cost, performance, and lifetime of the comparable baseline technologies for the relevant end use(s).

In general, evaluating enabling sensor and control technologies with systems-level impacts is more challenging than assessing conventional building efficiency technologies. Scout maps simulation-based estimates of the end-use level savings potential of S&C ECMs to a national scale by applying these estimates to baseline projections of archetypal commercial building energy use. This framework establishes apples-to-apples comparisons of traditional, equipment-focused efficiency improvements (e.g., more efficient heat pump or higher insulating window measures) alongside systems-level efficiency improvements (e.g., a controls measure for more energy efficient building operation). Scout also utilizes a market share-based measure competition approach, where measures accessing the same baseline segments of energy use with similar cost effectiveness will yield similar savings after adjusting for competition. The market shares of each ECM are calculated based on incremental capital and operating cost relative to comparable business-as-usual technologies. This capability is particularly useful when evaluating S&C measures with end-use-level impacts against equipment improvements that apply to the same end use(s).

Measure Definitions and Descriptions

This section describes the S&C ECMs that were developed to represent each of the identified R&D focus areas. In general, key ECM inputs are based on results from relevant literature on these technologies. As such, ECM scopes are limited to the end uses and types of technical approaches for which data from the literature are available. This includes the ECM's applicable segment(s) of baseline energy use: for example, in the existing literature, large commercial office buildings tend to be the most prevalent subsector for sensor and control technologies. While initial emphasis is thus placed on a particular subsector where data are available, expansions in ECM application to broader segments of baseline energy use and new parts of the buildings sector are assumed for future years, as the technology advances and becomes more widely used.

For wireless sensor networks, the ECM is defined by a potential energy savings at market entry of 17% (8-30%) for HVAC and 35% (10-60%) for lighting (Kazmi et al. 2014), along with an average 10-year lifetime (Dietrich and Dressler 2009). To focus on performance improvements without prescribing the particular sensing configuration, a target cost output in units of $/node is selected for this ECM.

The advanced controls focus area is represented by an ECM with 20% (15-30%) energy savings at market entry for HVAC (Roth et al. 2005; Frey and Smith 2008) and an average 15-year lifetime for the automated fault detection and diagnostics (AFDD) features of the focus area. While reports on savings from predictive and learning-based control strategies exist, they are still fairly nascent for incorporation into an ECM at this stage and are therefore not considered in the analysis.

The energy savings from sub-metering alone is fairly low (< 5%) and not persistent over time, but can enable savings through the energy consumption data collected (U.S. General Services Administration 2016). As such, the objective of sub-metering in the context of this paper is to support advanced controls by comparing monitored data with an appropriate baseline to more effectively diagnose operational or design-based faults and more effectively develop and optimize control strategies. To represent this impact, the previously mentioned ECM for advanced controls is augmented to include an additional 5% savings for HVAC at market entry (Goetzler et al. 2011), enabled by the sub-metering focus area.

Finally, the occupant-centric sensing and controls area is represented by two ECMs. The first focuses exclusively on occupancy monitoring. For this ECM, 15% (10-40%) potential energy savings for both HVAC and lighting (Nguyen and Aiello 2013; Williams et al. 2012) is used. The second incorporates occupant comfort and preferences with 20% (10-40%) savings for HVAC and 30% (10-60%) for lighting (Ghahramani, Jazizadeh, and Becerik-Gerber 2014; Williams et al. 2012). As with wireless sensor networks, in order to be agnostic to the technical approach pursued, a target cost output in units of $/occupant is selected for this pair of ECMs. These cost units also emphasize the importance of the occupant in driving the energy consumption needs, and in turn, the necessary technology development and innovation. The lifetime of the occupant-centric sensing and controls ECMs is assumed to be 10 years, consistent with that of the enabling wireless sensor network technology.

For the technological innovations already underway in each focus area, a 2020 market entry year was chosen. The exception to this approach is the comfort-driven occupant-centric ECM, which remains an emerging technological field that requires a longer time horizon for broad commercialization. As such, the market entry year is set to 2025 for the comfort-driven controls ECM.

All ECM installed cost targets were calculated in Scout based on the anticipated energy performance assuming a one-year payback period. Note that given the cost sensitivities for sensor and control technologies in this sector, the more aggressive end of the typical one to three-year return on investment for initial market entry was selected.

Looking beyond ECM market entry, further ECM cost reductions are assumed with increased adoption over time. In the case of the wireless sensor network focus area, 2030 goals are evaluated by assuming additional cost reductions at a fixed energy savings performance level, reflecting the enabling quality of the focus area in meeting the objectives of the other focus areas. Specifically, it is assumed that lower-cost monitoring will accelerate the performance capabilities and adoption of controls technologies more broadly, thus helping drive down costs and improve performance levels for the occupant-centric and advanced controls focus areas. In these other focus areas, a fixed cost is assumed over time with energy savings performance increasing by 2030 to the high end of the possible range established from literature, given additional performance features incorporated into control schemes.

Finally, while performance improvements such as longer lifetime can be quantified and captured in Scout calculations, others, such as reduced sensor drift or improved calibration, cannot be. Such improvements are included as qualitative considerations in the analysis, given their importance to fundamental developments required to further automate the applicable technologies in a way that will facilitate the realization of their associated energy performance through improved installation and maintenance.

Results

R&D Focus Areas and Goals

Tables 1 summarizes the ECM cost targets and energy performance goals calculated with Scout for the ECM's market entry year and the year 2030 based on innovations targeted for each of the S&C focus areas along with the market entry threshold for initial development already underway. The resulting technical potential of primary energy savings is also included for the year 2030. The results, which are also presented in Figure 1 with plots of the target cost versus energy performance for each ECM developed, are dependent on the technology development strategies described further in this section. These include systems-level solutions to installation and maintenance barriers that ultimately limit the performance and widespread adoption of these technologies. The goals for each focus area are interconnected and build on each other in a similar fashion to the technology development and performance features discussed.

The cost targets for multi-functional wireless networks are initially based on market entry in 2020 for single family homes and large commercial offices buildings only, with an expansion to the entire residential and commercial sectors by 2030. This expansion will require enhancing wireless communications and infrastructure; extending the operational power lifetime of the sensor nodes; eliminating measurement drift and extending the accuracy of transducers and nodes; developing modular designs, flexible placement methods, and reducing materials and manufacturing costs of both the nodes and associated components; and automating the recognition, configuration and calibration processes. These solutions will also have applicability to use cases where a single variable is being monitored. While the energy savings remain static, increasing their pervasiveness through more aggressive cost targets with these performance improvements in sensing and wireless network infrastructure will support the development of subsequent research area technologies.

In Table 1, at both market entry and 2030, the cost targets are higher for the commercial sector compared to the residential sector. This is due to the smaller number of nodes per square foot assumed and the larger energy savings potential based on the larger amount of energy use per square foot for the commercial sector. The reduction in cost by 2030 is more aggressive for the commercial sector, where a 50% reduction is necessary to achieve an average one-year payback period. The 2030 targets for the rest of the focus areas assume the same one-year payback cost numbers as for the market entry years, but push towards the higher end of the performance and energy savings ranges enabled by ubiquitous wireless sensing; this drives the payback period for associated ECMs to less than one year by 2030.

Table 1. Cost targets, energy performance goals, and overall technical potential energy savings for ECMs associated with the targeted areas of research for sensor and control technologies

Focus Area	Relevant ECM	Sector	Installed Cost		Energy Performance *(HVAC, Lighting)*		2030 Energy Savings Technical Potential
			Market Entry	2030 Target	Market Entry	2030 Goal	
Wireless Sensor Networks	Plug-and-play sensors	Residential	$35/ node	$29/ node	17%, 35%		1.14 quads
		Commercial	$115/ node	$57/ node			0.99 quads
Advanced Controls	AFDD	Commercial	$0.12/ ft^2 floor	$0.14/ ft^2 floor	20%, N/A	30%, N/A	1.18 quads
Granular Equipment Sub-metering	AFDD and sub-metering	Commercial	$0.14/ ft^2 floor		25%, N/A	30%, N/A	1.18 quads
Occupant-centric Sensors and Controls	Occupancy Counting	Residential	$70/ occupant		15%, 15%	30%, 40%	2.31 quads
		Commercial	$36/ occupant				1.10 quads
	Occupancy Comfort	Residential	$92/ occupant		20%, 30%	40%, 60%	3.14 quads
		Commercial	$49/ occupant				1.49 quads

Advanced control capabilities at the whole-building level must effectively coordinate loads in a hierarchical or distributed fashion. In addition to near real-time actuation to match the time interval resolution of improved monitoring and enhancing the forecasting capabilities and inputs of stochastic variables other than occupancy (e.g., weather), a combination of model predictive (both physics-based and data-driven) capabilities along with machine learning techniques, such as deeply layered artificial neural networks to train building controls to recognize complex patterns in real-time digital representations of building environments will be targeted. Improvements in automated fault detection and diagnostics will complement the development and optimization of these more sophisticated control strategies through the use of similar physics-based model and data-driven approaches. Automated recognition and systems configuration, including data point mapping and naming convention harmonization, are also all necessary. As noted, the cost targets and energy performance goals are currently limited in this focus area to AFDD for the commercial sector. The stage of development in this area precludes full evaluation of all technological performance features (e.g., model-predictive control) in Scout across both the residential and commercial sectors. In this instance, an initial increase in the installed cost target along with a higher energy performance should be observed with the incorporation of more sophisticated control strategies, similar to the results obtained for incorporation of comfort features in the occupant-centric sensors and controls category.

Advanced sub-metering will enhance the performance of advanced control strategies by leveraging enhancements to wireless communications and networking. In addition, enhancing the hardware accuracy and long-term calibration; improving load disaggregation and non-intrusive monitoring techniques; reducing the overall systems cost through modular design and materials development of connectivity hardware; and automating configuration with existing or new building automation infrastructure are all necessary for achieving the cost targets and enabling the additional savings applied to advanced controls. At this stage, these numbers are limited to the commercial sector based on the data available, but the technological innovations identified will also be impactful to the residential sector for both standalone energy monitoring and incorporation into control strategies as applications in homes are more fully explored.

Occupant-centric sensors and controls exhibit a higher installed cost target at both market entry and 2030 for the residential sector compared to the commercial sector. This is true for both developments in occupancy and comfort sensing capabilities due to lower occupant densities in homes. Two stages of development are targeted in this focus area for moving beyond over-simplified representations of occupants and their actions in buildings. First, improved occupant counting or presence recognition will require overcoming the physical limitations and accuracy of current techniques along with reduced cost approaches (e.g., proxy sensing). In addition, improving indoor air quality monitoring and comfort estimation is necessary for developing comfort-driven controls. For both occupancy detection and comfort estimation, dynamic models and hierarchical control algorithms are targeted that incorporate these enhanced parameter inputs with improved equipment response time, direct occupant engagement and feedback, and automated recognition and configuration with existing building automation infrastructure. Note in Table 1 that the inclusion of comfort feedback in control schemes yields in a higher cost target compared to occupancy detection alone given the higher energy savings potential of this ECM.

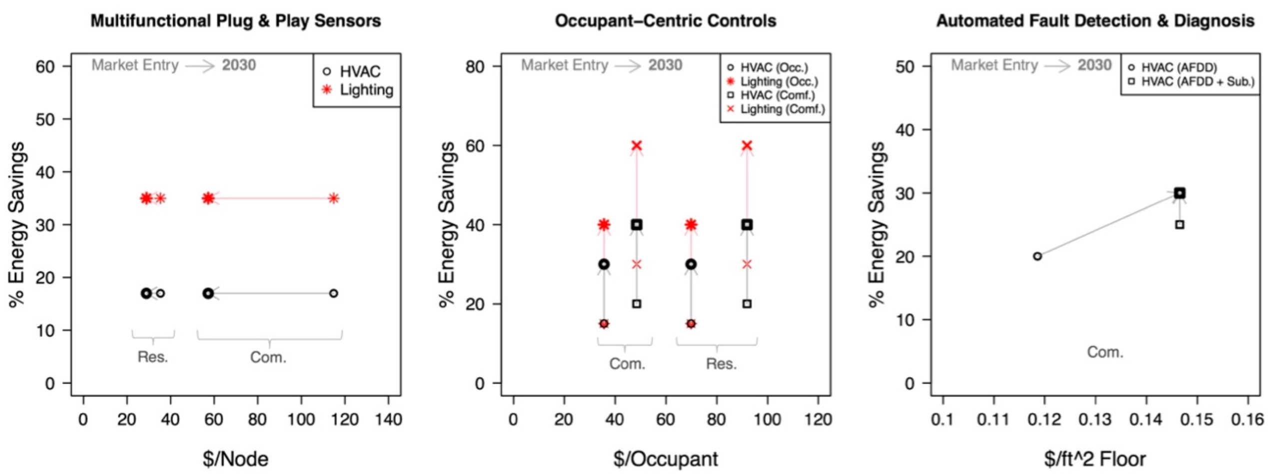

Figure 1. Cost and energy performance targets for the ECMs associated with sensor and control technologies.

Overall Energy Impact Potential

The potential overall primary energy savings potential was also evaluated both for individual ECMs and at a portfolio level across the designated S&C focus areas and applicable end-uses. Table 1 includes the results for each ECM under an adoption scenario that does not include interactions or competition between ECMs, thus representing each ECM's savings potential when considered in isolation. In this scenario, each of the ECMs for S&C exhibit at least one quad of primary energy savings by 2030 with the appropriate technological advancements. As noted, further savings should be possible for focus areas where not all improvements are represented by the ECMs. The savings potential for the residential sector ECMs are higher than the commercial sector ones due to higher projected baseline residential energy consumption.

Aggregating ECM impacts to a collective, portfolio-level, Figure 2 shows the primary energy savings potential as a function of all applicable end-uses. As expected, space conditioning (heating and cooling) exhibits the largest savings potential, which correlates with its total energy consumption compared to other end-uses. Overall, S&C technologies are anticipated to save 1.4 quads in 2030 and 3.8 quads in 2050 with further technological advancements and sophistication of the approaches identified in the focus areas. This is equivalent to roughly 10% of total primary energy consumption from the buildings sector in 2017.

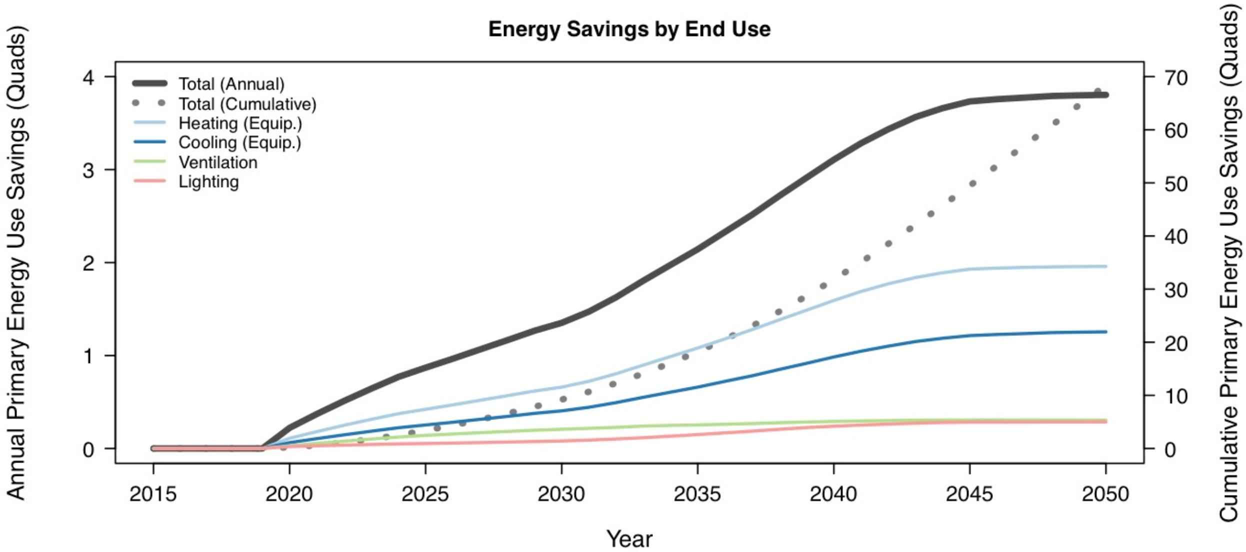

Figure 2. Maximum adoption energy savings potential in total (annual on the left axis and cumulative on the right axis) and across applicable end uses (annual on the left axis) for technological innovations in sensors and controls for the buildings sector.

Discussion

The overall timeline for technology development is based on the energy performance improvements that need to be achieved within the designed time frame in order to achieve the goals calculated in Scout. Actual timelines will also be dependent on advancements outside of the building energy management sector (e.g., microelectronics, data analytics, and machine learning) due to the interdisciplinary nature of this field. Ultimately, the specific sensing elements and features, as well as control architectures and schemes implemented in a given building or sector will depend on the existing load management strategies and building automation infrastructure along with the building configuration, usage, and requirements (International Agency 1991). Developing appropriate testing frameworks and procedures with which to benchmark and evaluate approaches will be useful in guiding additional innovation. Optimizing the level of intelligence will also be necessary to avoid redundancy or unnecessary computational resources. The level of penetration of performance features targeted within each R&D focus area is influenced by the building sector and subsector type. For example, automating the point mapping process will be most critical to large commercial buildings that consist of thousands of monitoring and control point nodes.

Cross-cutting approaches that can be explored across the identified focus areas to enable the targets and goals laid out include advanced materials and manufacturing; virtual sensing to estimate measureable quantities that are either difficult and expensive to monitor or for which installation of physical sensors is impractical or challenging; harmonizing data labeling and automating the point mapping process for sensor, actuator, and control points; and building energy modeling, including the simulation of controllers and dynamic conditions along with unifying energy simulation with physical implementation and verification of building controls. These approaches are a combination of already established concepts where recent advancements in other sectors have made them more promising and viable solutions to explore in the building sector along with more nascent concepts that require tight coordination with other sector to leverage emerging insights and findings from each other.

Current data limitations on the breakdown of energy consumption preclude calculation of goals in Scout for end-uses other than space-conditioning and lighting (e.g., plug loads). Data collection and analysis is currently underway to be able to represent miscellaneous electric loads in the future. An additional limitation to the end-uses, sector, and performance features defined within individual ECMs is due to availability of estimated savings from case studies in the literature. As the technology matures, more resources will become available to contribute to the robustness of future projections. Finally, limitations on the accuracy of building prototype models (i.e. model inputs and simulation of building monitoring and control systems), also impact the assessment of anticipated energy savings from the targeted advancements. Improvements to sensing and monitoring can be leveraged to address this limitation in the future.

While not included in this paper, market and deployment barriers will also need to be considered at the early stages of technology development due to the quickly evolving nature of this sector and to ensure alignment with industry needs. To meaningfully participate in grid transactions, control systems will also need to quantify potential energy savings, demand flexibility, and impact on occupants and energy-related building services.

Conclusions

This paper presents R&D strategies for technology development through 2030 along with the expected cost targets and energy performance goals in four interrelated focus areas that will address the current limitations in adding and optimizing intelligence for building energy management at scale. These results are calculated using the BTO Scout analysis program and analyzed for the sector, subsector, and end-use where data is currently available. Technology development, however, is more broadly targeted. The potential overall primary energy savings potential and impact of innovation is also evaluated both for individual ECMs and at a portfolio level across the designated S&C focus areas and applicable end-uses for a longer time horizon of 2050. By making building operations "smart" through more sophisticated monitoring and control strategies, roughly 4 quads of primary energy can be saved by 2050. This is equivalent to approximately 10% of total energy consumption for the buildings sector in 2017.

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