DE-FOA-0002723
Request for Information (RFI): "Research and Development Opportunities in Energy Management Control Systems"

DATE: June 3, 2022
SUBJECT: Request for Information (RFI)

Description

Buildings are responsible for approximately three-quarters of all electricity use and typically more of peak power demand in the United States (U.S.) and offer a unique opportunity for cost-effective energy management as the nation's primary electricity users. Their energy demand results from a variety of electrical loads operated to serve occupants' needs. Many of these loads are flexible to some degree, and intelligent communications and controls can manage their use to enable energy and cost savings, thus making essential contributions to the decarbonization and economic growth of the U.S. built environment and energy economy (including through beneficial electrification) – while still meeting occupant productivity and comfort requirements.

Integrating state-of-the-art sensors and controls throughout the commercial building stock can lead to savings of as much as 29% of site energy consumption through a high-performance sequence of operations, optimized settings based on occupancy patterns, and correcting inadequate equipment operation or installation[1]. It can also enable 10%–20% of commercial building peak load reduction[2,3].

The U.S. Department of Energy's (DOE) Building Technologies Office (BTO) invests in the research and development (R&D), validation, integration, and deployment of the next generation of affordable, high-performance, cost-effective tools and technologies that will result in significant energy savings for and decarbonization of the national building stock – both commercial and residential. A core technical area necessary for achieving this goal is the integration of sensing, computing, communication, and actuation for improved monitoring and control of the built environment. As such, BTO maintains an active portfolio in energy management control systems (EMCS). In tandem with building energy modeling, EMCS covers the energy management of cyber-physical infrastructure.

[1] Fernandez, N., Katipamula, S. et al., (2017). "Impacts of Commercial Building Controls on Energy Savings and Peak Load Reduction." Pacific Northwest National Laboratory, PNNL-25985.
[2] Kiliccote, S., Olsen, D., Sohn, M. D. and Piette, M. A. (2016). "Characterization of demand response in the commercial, industrial, and residential sectors in the United States." WIREs Energy Environ., 5: 288–304.
[3] Piette, M.A., Watson, D.S., Motegi, N., Kiliccote, S. (2007). "Automated critical peak pricing field tests: 2006 pilot program description and results." Lawrence Berkeley National Laboratory, LBNL-59351.

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This RFI is comprised of the draft "Research and Development Opportunities in Energy Management Control Systems" ("EMCS RDO" or "RDO"), followed by specific questions about the issue and the draft RDO. BTO is interested in receiving input on both the specific questions and any elements of the draft RDO.

Purpose

The purpose of this RFI is to solicit feedback from industry, academia, research laboratories, government agencies, and other stakeholders on issues related to building energy management systems (hardware, software, cybersecurity, and interoperability). This information will be used by BTO to update its R&D strategy and support energy savings, emissions reduction, and cost reduction goals, and inform future strategic planning and adjustments to its R&D portfolio. This is solely a request for information and not a Funding Opportunity Announcement (FOA). BTO is not accepting applications.

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Any information obtained as a result of this RFI is intended to be used by the Government on a non-attribution basis for planning and strategy development; this RFI does not constitute a formal solicitation for proposals or abstracts. Your response to this notice will be treated as information only. EERE will review and consider all responses in its formulation of program strategies for the identified materials of interest that are the subject of this request. EERE will not provide reimbursement for costs incurred in responding to this RFI. Respondents are advised that EERE is under no obligation to acknowledge receipt of the information received or provide feedback to respondents with respect to any information submitted under this RFI. Responses to this RFI do not bind EERE to any further actions related to this topic.

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DRAFT RESEARCH AND DEVELOPMENT OPPORTUNITIES DOCUMENT

Chapter 1: Hardware

Building energy management hardware consists of sensors, sub-meters, and actuators that enable continuous monitoring and control of the built environment – both indoors and outdoors. Sensors collect data from the environment or object under measurement (e.g., energy consumption). Sub-meters provide a granular or resolute measurement of energy consumption data. Actuators control the electrical or physical states of equipment based on control signals or algorithms. This chapter focuses on sensors, sub-meters, and actuators that measure and monitor the built environment for aiding energy management and explicitly does not discuss hardware for other building functions (e.g., fire safety, security systems).

Commercial buildings often use a variety of sensors. These may include environmental sensors for temperature, occupancy, humidity, CO_2, air-quality sensors, or subsystem sensors relevant to equipment function such as duct pressure and airflow. The purpose of these sensors is to measure environmental and equipment conditions relevant to critical performance metrics such as occupant comfort, health, and productivity. Low-cost, wireless, and other advanced sensors are considered an "enabling technology" for a variety of building energy management strategies, including building commissioning, damper fault detection and diagnostics, demand-controlled ventilation, duct leakage diagnostics, and optimal whole-building control.

Residential buildings predominantly use a single sensor embedded in a centrally located thermostat to monitor and detect deviations in temperature from the desired set-point. The residential sector has dramatically benefited from smart thermostat technology advancements that automatically sense, communicate, and respond to ensure desired operations. These devices incorporate different sensors and algorithms that learn household occupancy, behavior, and comfort preferences to maintain comfort autonomously. Smart thermostats enable occupancy information-based algorithms that can save between 11% and 34% of energy without significantly risking the occupant's comfort level[4]. Aesthetics, convenience, and cost savings drive lighting control strategies by leveraging timers, dimmers, motion detection, or light detectors[5,6]. Emerging strategies include smart home hubs that integrate various technologies and smart home energy management systems to deliver occupancy-informed home energy use optimization.

Whole-building energy meters (e.g., electricity or natural gas meters) or sub-meters (e.g., plug-loads) aid in energy consumption monitoring of individual building systems and components and the building as a whole. Sensors and meters together inform environmental and equipment status at the whole-building, system, or component level.

The development of actuator technologies can advance building performance through improved energy efficiency, grid benefits, or enhanced comfort. Actuator technology developments are progressing from simple, bulky, loud, inaccurate, and less efficient technologies to scalable, integrated, quiet, precise, and novel alternatives for enabling improved awareness, communication, and synergistic coordination for control of energy devices.

1.1 Technical and Adoption Barriers

Current building management hardware has the following technical shortcomings and adoption barriers hindering the potential to save costs, energy, and emissions:

Cost
The cost to manufacture sensors, particularly at low volumes, can be prohibitive. Commissioning and maintenance expenses may result in an unattractive return on investment. Depending upon sensor placement, deployment in existing buildings can be cost-prohibitive or intractable. High hardware, installation, and maintenance costs can hinder the deployment of precise, variable actuators. Most existing sub-meter installations use traditional meters, requiring the exploration of retrofit pathways and increasing installation costs. High installation

[4] Wang, C., Pattawi, K., and Lee, H. (2020). Energy saving impact of occupancy-driven thermostat for residential buildings. Energy and Buildings, 211, 109791.
[5] CEE (2014). “Residential Lighting Controls Market Characterization.” Consortium for Energy Efficiency.
[6] Based on Residential Building Energy Consumption Survey (RECS) data (2015). U.S. Energy Information Administration. https://www.eia.gov/todayinenergy/detail.php?id=32112

and maintenance costs limit the widespread adoption of new hardware technologies, particularly in retro-commissioning.

Interoperability

A significant challenge for the rapid penetration of advanced hardware technologies is the lack of device-level and application-level interoperability. Hardware deployments are limited in terms of ease of use and ability to communicate among building devices. Consumers' benefits may be limited unless they purchase an entire solution from one vendor (i.e., "vendor lock-in").

Size

Traditional actuators have a relatively large form factor that limits the number of installation locations and control points in the building, potentially limiting widespread adoption.

Veracity

Energy utility companies typically do not share real-time energy metering data with building owners at full temporal resolution. As a result, building owners may install additional power sensors to have high-fidelity energy data. The discrepancy between these readings, which can occur for many reasons (e.g., lack of time synchronization, accuracy/uncertainty of calibration, measurement methods), can lead to misinterpretation and detrimental actuation.

1.2 Research Areas

The next generation of building energy management hardware should combat the challenges mentioned above and have the following capabilities:

- Automated and continual commissioning - Automated and continual commissioning extends hardware life, reduces installation and maintenance costs, decreases the possibility of failures, improves sensor and actuator network scalability, and saves energy. Building energy management hardware should automatically recognize and share their identity, location, state, power use, and sensing capabilities to the connected network. Hardware should continuously self-diagnose for degradation and faults and trigger appropriate corrective mechanisms.

- Sustainable power - Efficient sensing and communication hardware with sufficient energy harvesting has the potential to enable long-lasting power sources, reduce manufacturing costs, eliminate maintenance costs, and minimize the deployment footprint of new sensor packages.

- Sensor placement - Optimized sensor placement can reduce the number of sensors and technical requirements of each sensor necessary to meet the measurement and control performance required for a specific use case. When combined with communication (e.g., mesh network) or plug-and-play functionality, installation and maintenance barriers can be significantly reduced. Additionally, the ability to easily mount and re-mount to any surface can significantly reduce installation costs when retrofitting existing buildings.

The following are potential priority research areas for building energy management system hardware:

Near-term research areas

- **Develop hardware technologies with reduced installation and maintenance costs.** Sensor, sub-meter, and actuator solutions that enable self-configuration and self-commissioning with little to no engineering effort reduce installation costs. Technologies that do not require periodic re-calibration and can self-diagnose faults minimize maintenance costs, especially for small and medium-sized commercial buildings.

- **Develop the fundamental aspects of optimal sensor placement and configuration algorithms.** A large number of sensor nodes can provide an accurate estimation of building parameters but increases costs. Optimal sensor placement algorithms can dramatically reduce the number of deployed sensors without significantly impacting improved building operations.

- **Develop sub-meters with flexible placement methods.** Incorporating metering in previously inaccessible spaces can expand the opportunity space for intelligent energy and demand management. Installation approaches that do not disrupt electrical power connectivity, existing networks, or building operations reduce installation costs and improves adoption.

- **Develop low-cost retrofit sensor technologies.** Retrofitting buildings with advanced sensor technologies without rewiring existing networks reduces installation costs and increases its adoption, especially in small and medium-sized commercial buildings. Low-cost wireless sensor networks with improved connectivity enable energy savings through advancements in control schemes in existing buildings.

- **Develop sensor technologies with long operational-power lifetimes.** More efficient computing hardware, energy-aware algorithms, and low-energy network topologies permit higher frequency sensing and automated operations. Longer-lasting power supplies through more efficient energy harvesting or higher capacity energy storage will improve the mean time between sensor power source replacement or recharge.

- **Develop advanced actuators.** Low-cost, low-power, miniaturized (small and lightweight), durable actuators that do not require resource-intensive re-calibration can enable highly granular building energy management. Intelligent actuators with two-way communication can provide enhanced operational performance and easy fault detection.

Long-term research areas

- **Design, develop, and create deployment pathways for autonomous and long-lasting sensor solutions.** Autonomous hardware solutions that are interoperable, self-configuring, self-commissioning, and can self-diagnose for faults or performance degradation can facilitate novel, low-cost deployment. Autonomous sensors with low-power sensor connectivity for cost-effective deployment and maintenance help realize scalable sensor networks in buildings.

- **Design, develop, and create deployment pathways for advanced sub-meters**. Energy measurements for installed building equipment and energy loads of interest at revenue-grade accuracy for residential and commercial buildings expand analytical capabilities that can lead to energy savings and more significant energy efficiency investments. Metering across relevant building energy consumption with self-calibration can significantly reduce costs and increase adoption.

- **Design actuators with embedded intelligence.** Next-generation actuators with embedded intelligence enable context-aware operations and two-way communications. They can proactively remedy fault modes and avoid performance degradation. Intelligent actuators could enable the cooperative and synergistic operation of multiple actuators for robust building automation.

Chapter 2: Software

Building management software is a combination of supervisory control algorithms, user interfaces, and communication networks. Together, it can automate the control of various building subsystems. Supervisory control algorithms manage whole energy systems and coordinate many local controllers. It implements high-level algorithms and strategies aimed at objectives like reducing energy costs. User interfaces enable owners and operators to monitor operations, provide feedback, and specify their needs. Communication networks facilitate information exchange and integrate the hardware and software components in a building energy management system. This chapter discusses supervisory control algorithms and user interfaces, while Chapter 4 discusses communication networks as part of Focus Area 4.

Large commercial buildings use energy management control systems (EMCS) to monitor and control heating, ventilation, and air-conditioning (HVAC). Some EMCS also integrate control of lighting and other subsystems. An EMCS incorporates information from a range of outdoor environmental (temperature, humidity), indoor environmental (temperature, humidity, CO2), and equipment (on/off state, inlet and outlet temperatures, flow rates) sensors. The information determines the implementation of schedules (e.g., thermostat set-points for occupied and unoccupied hours) and rules (e.g., economizer set-point resets based on the outdoor temperature and humidity) to reduce energy use. Newer, high-end EMCS may also include the ability to detect and diagnose HVAC equipment faults and provide actionable recommendations to the building operator. Medium and small commercial buildings often have several packaged unitary systems (e.g., rooftop units) instead of a central HVAC system. In these configurations, there may be lower operational and convenience benefits to a centralized EMCS, and the capital cost may become prohibitive.

Integrated energy management systems for homes have historically received little attention. However, there is currently rapid adoption of technologies such as smart thermostats that support energy management and voice-activated home assistants that integrate with "connected" water heaters, appliances, lighting, and electronics. This transformation makes widespread automated and integrated energy management a nearer-term proposition for homes than for small and medium commercial buildings[7]. Additionally, small commercial buildings may benefit from the same solutions applied to residential systems, including communicating thermostats and smart lighting controls.

Any advancements in supervisory building control technology should improve or have no impact on occupant comfort and productivity. The development of occupant-centric operations relies on improved monitoring of occupant conditions, improved understanding and modeling of occupant comfort, interactions, and behaviors, and incorporation of these parameters into control strategies. Collecting the time-varying and scenario-driven occupant preferences and priorities for building operations and understanding the level of detail required for incorporation into control algorithms is still an active area of research.

[7] NEEP (2016). "The Smart Energy Home: Strategies to Transform the Region." https://neep.org/sites/default/files/resources/SmartEnergyHomeStrategiesReport_3.pdf

The current deployment of automated EMCS across the building sector focuses on energy efficiency and cost savings within occupant needs and comfort. Legacy systems do not focus on providing grid services by harnessing demand flexibility. Increased adoption and improvements in building sensing and control algorithms could improve demand response in terms of occupant experience, acceptability, and grid service provision capability.

2.1 Technical and Adoption Barriers

Current building management software has the following technical shortcomings and adoption barriers hindering the potential to save costs, energy, and emissions:

Optimal operations

Currently, building management operations are typically implemented as rules, such as thermostat set-point schedules for occupied and unoccupied hours or economizer set-point resets based on outdoor air temperature and humidity. Rule-based controllers are characterized by a large number of tuning parameters selected exclusively for each system and building and are often reset during seasonal transitions. Rule-based systems are intuitive but do not necessarily lead to optimal operation.

Managing uncertainty

Optimization-based methods are greatly affected by uncertainties in weather, occupancy, sensing, measurement, and communications, causing modeling errors. The errors jeopardize the reliability of optimization-based methods to provide energy-efficient operations and grid services.

Automated integration, coordination, and commissioning

The adoption of building commissioning processes is limited due to its labor-intensive nature and associated high costs. Lack of effective commissioning leads to incorrectly installed equipment, increasing energy costs.

Value proposition

Cost-benefit trade-offs for advanced control strategies are difficult to assess due to existing technical challenges, uncertainty in guaranteed savings stemming from implementation and verification errors, as well as uncertainty in model or training data accuracy requirements and corresponding computational efforts compared to projected cost savings from performance improvements.

Capital expenditure
Setting up building management infrastructure is often an expensive process. It typically relies heavily on multiple contractors with varying expertise, time-consuming installation procedures due to a lack of standardized data taxonomy, and tailored modeling and control design for each building system. Alternatives or dramatic cost reductions are necessary for installing building automation infrastructure in buildings without existing equipment due to a limited number of total zones and points that do not make the large up-front capital investment cost-effective.

Control interpretability
Currently deployed rule-based control algorithms automate traditional building-operator logic providing explicable solutions. In contrast, optimization-based methods may provide unintuitive solutions making it difficult for operators to interpret, tune, and adjust according to their needs.

Interoperability
One of the most significant obstacles to the penetration of autonomous and transaction-based building controls is the lack of standardized, interoperable hardware and software that can interconnect across multiple vendors, equipment types, and buildings. Automation and control systems' installation tends to be unique to each building and for each equipment manufacturer and therefore exhibits no economies of scale for later installations.

Building owner, occupant, operator engagement
Split incentives structures among owners, tenants and operators, and a lack of customer, owner and operator education, interest, and awareness in new product development and implementation are significant deployment barriers for new control technology. Additionally, comparing performance features across products is difficult without an established baseline, especially for risk-averse owners and operators.

2.2 Research Areas

To combat the above-mentioned challenges, the next generation of building energy management software is characterized by the following capabilities:

- Multi-objective optimization - The built environment can have multiple objectives at any given time, depending on trade-offs among user preferences (e.g., reduce energy costs, improve occupant comfort, provide resilient operations, reduce emissions, minimize equipment degradation, provide grid services). A multi-objective optimizer provides a solution as close as possible to the desired value of each of the set objectives.

- Predictive, adaptive, and robust control - Built environment operations are characterized by uncertainties in occupancy patterns and preferences, sensing measurements, weather, and energy demand, flexibility, and prices. Predictive control is the system's ability to anticipate trends in the various factors that influence the built environment. Adaptive control modifies system operations based on measured data to achieve optimal performance, while robust control guarantees performance requirements in the presence of uncertainties.

- Explainable solutions - Modern optimization methods provide solutions based on evaluating various factors and possibilities related to the built environment. While effective, they provide non-intuitive solutions that building operators find difficult to understand, tune, or trust. Building energy management software should provide transparency in algorithmic decision-making to promote acceptability by all stakeholders (owners, operators, and occupants).

- Automated and continuous commissioning - Automated and continual commissioning extends equipment life, reduces the possibility of failures, and saves energy. Systems components must automatically share their identity, status, and availability with advanced building controls and operate successfully as an integrated system when necessary. Some examples of contributing technology include self-identifying equipment, self-configuring controls, automatic installation verification, continual monitoring and testing, and self-diagnosis of faults and degradation.

- Usability and interaction - Building energy management system software need a human interface that accepts and dynamically incorporates real-time feedback from building operators and occupants. It enables users to provide their preferences or priorities and feel empowered to change or reverse situations they dislike.

- Market-based coordination - A EMCS plays a vital role in harnessing building demand flexibility. They should include market-based coordination techniques that securely negotiate with the grid to respond within a required timeframe and provide the requested service to the grid within acceptable occupant comfort and productivity constraints.

- Integration of HVAC, envelope, and lighting management - Multiple building systems can be integrated to share sensors and data for improved functionality and flexibility. Depending on the building needs, integration can influence space conditioning, thermal comfort, and energy savings.

- Integration with electricity generation and storage - Integration of building systems with on-site electricity generation and storage enables greater flexibility of energy use reducing energy costs and carbon emissions.

Based on the above discussion, the following are potential priority research areas in building EMCS software:

Near-term research areas

- **Develop the fundamental and practical capabilities of advanced control methods for commercial buildings.** Advances in the model acquisition, control architectures, adaptability, and robustness to uncertainty can manage building loads in a way that maximizes energy savings and the availability and responsiveness of load flexibility while minimizing occupant impacts. The control methods should adapt to available building hardware and maximize the equipment life cycle.

- **Evaluate control algorithms for residential and small commercial buildings through field tests.** Residential deployment of a predictive control framework faces fewer challenges than commercial buildings due to the reduced scale and complexity. The developed fundamental aspects need practical validation in actual buildings.

- **Develop methods for occupancy detection and integration of comfort and behavior measurements.** Occupant thermal comfort and preferences are key inputs to achieving building energy management objectives. Improved monitoring of occupancy conditions (e.g., presence, comfort, and adaptive behavior), improved understanding and modeling of occupant interactions and behaviors, convenient methods of registering occupant preferences, and incorporation of these parameters into the EMCS control algorithms can improve occupant comfort and productivity.

- **Standardize data pre-processing for data-driven techniques.** Data-driven approaches require a lot of data to make acceptable decisions in the control environment. Systematic pre-processing methods can significantly improve the performance of deployed algorithms.

- **Develop the capability to forecast aggregate building demand flexibility.** Buildings can support the clean energy transition by using inherent demand flexibility for grid services to support greater penetration of variable renewable energy sources. Accurate demand and demand flexibility forecasts are critical to reliable electricity supply and delivery, other power system operations, and infrastructure development.

- **Develop the practical capabilities of an automated and cost-effective market-based coordination package for grid services.** Transactive energy is a promising, market-based coordination approach to managing building-to-grid services. Advances are required in automated price-capacity curve estimation and open-source software development compatible with existing demand response programs and dynamic pricing structures.

Long-term research areas

- **Develop a co-design framework for HVAC system configurations, controls, and sensing.** Including HVAC system configuration, control strategies, and sensor configuration for different HVAC system types and different control applications in building design can improve performance and grid-service reliability. The framework should include varied applications like high-performance control (using either rules or models), fault detection and diagnostics, and load shedding and shifting for grid response.

- **Design, develop and create deployment pathways for autonomous building software solutions for commercial buildings.** Autonomous solutions are interoperable, self-configuring, self-commissioning, and adaptive to occupant and grid needs. They ensure "optimal" operation to maximize benefits to the building owners and the electric grid.

Chapter 3: Cybersecurity

The increasing connectivity and growing complexity of smart buildings increase the potential for vulnerabilities. Data published by IntelligentBuildings shows that half of the buildings they assessed in 2018 had Internet-connected devices that could be accessed remotely, and 95% of the buildings either had no disaster recovery plan or had not changed default configurations and ports.[8] This illustrates a lack of cybersecurity awareness and implementation of best practices by building operators. Cyber threats and vulnerabilities, or even the perception of increased risk,

[8] Gordy, Fred. April 2019. "The State of BAS Cybersecurity." AutomatedBuildings.com. http://automatedbuildings.com/news/apr19/articles/ib/190318022808ib.html

could hinder the adoption of smart, connected technology in buildings and impede the realization of energy efficiency goals[9].

Commercial building control systems communicate using a mix of Information Technology (IT) and Operational Technology (OT) protocols over a dedicated field bus (mostly RS-485). Residential systems are a mix of IT and dedicated field bus wireless protocols such as Zigbee. Typically, an IT group is responsible for overall cybersecurity in enterprise systems and typically tasked with cybersecurity risk management. In contrast, OT groups are tasked with the well-being and function of individual building systems such as heating, ventilation, and air conditioning (HVAC), lighting, and elevators. OT staff are responsible for maintaining the operational status of building systems for occupant comfort and convenience. Service availability is most important to their mission, and cybersecurity is a relatively new concern. On the other hand, IT security staff are more familiar with cybersecurity risks and mitigation strategies but are often unfamiliar with OT systems and how they are becoming connected[10]. The connection of OT systems to IT networks has become quite common, and these systems have become both vectors (i.e., an entry point enabling access to broader enterprise IT systems) and occasionally direct targets of cyberattacks. It is now common for building HVAC (and possibly lighting) system controls to be IP-enabled, and there is a proliferation of Internet of Things (IoT) devices emerging to support energy-efficient building operations. Additionally, devices and systems like elevators that traditionally are not networked are increasingly becoming IoT devices because of the ease of use an Internet connection affords.

Numerous relevant cybersecurity resources and activities in the building domain and adjacent fields are available across federal agencies, industry organizations, and vendor and IoT best practices[11]. The following are some cybersecurity resources and guidance developed across the federal government:

1. National Institute of Standards and Technology (NIST) Framework for Improving Critical Infrastructure Cybersecurity (NIST-CSF) guides how organizations can assess and manage cybersecurity risk. It is not limited to any single sector and is flexible enough for use by organizations with mature cybersecurity postures and those with less developed programs.

[9] Reeve et al (2020). "Challenges and Opportunities to Secure Buildings from Cyber Threats. Pacific Northwest National Lab (PNNL). https://www.energy.gov/eere/buildings/articles/challenges-and-opportunities-secure-buildings-cyber-threats

[10] Crowe et al (2019). "Summary of outcomes of the 2019 cybersecurity roundtable." Prepared for U. S. Department of Energy. https://betterbuildingssolutioncenter.energy.gov/resources/summary-outcomes-2019-cybersecurity-roundtable

[11] Reeve et al (2020). "Challenges and Opportunities to Secure Buildings from Cyber Threats". Pacific Northwest National Lab (PNNL). https://www.energy.gov/eere/buildings/articles/challenges-and-opportunities-secure-buildings-cyber-threats

2. DOE's BTO and the Federal Energy Management Program (FEMP) jointly funded the development of the Buildings Cybersecurity Framework (BCF).[12] Later, FEMP expanded the framework to become the Facilities Cybersecurity Framework (FCF)[13] to address cybersecurity in buildings across critical infrastructures by adapting the NIST Framework and other industry best practices for buildings stakeholders. The BCF and FCF provide guidance to facilitate building-cybersecurity risk-management efforts and increase an organization's cybersecurity posture by identifying security gaps and actionable advice.

3. The Building Cybersecurity Capability Maturity Model (B-C2M2) provides a methodology to self-assess and improve cybersecurity capabilities for building IT and OT systems[14].

3.1 Technical and Adoption Barriers

Current EMCS have the following cybersecurity technical and adoption barriers hindering the ability to address vulnerabilities in building systems:

Legacy systems
Many legacy building systems and technologies have limited computational, bandwidth, storage, and memory capabilities. This often limits the ability of devices to host cybersecurity solutions, such as monitoring and encryption, and lacks the availability of security patches that protect against cyberattacks.

Workforce education and training
The increasing responsibilities to respond to cybersecurity challenges are not accompanied by the necessary tools, technology, and workforce development to train and respond to a rapidly evolving cyber threat.

Lack of stakeholder cyber situational awareness
With rapid innovations in technology, there have been improvements in performance, cost, and functionality in building technology. However, cybersecurity awareness and preparedness have not kept pace, resulting in cybersecurity resource gaps that limit stakeholders' ability to identify and respond to the evolving cyber threat.

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[12] Mylrea, M., Gourisetti, S. N. G., and Nicholls, A. (2017). An introduction to buildings cybersecurity framework. In 2017 IEEE symposium series on computational intelligence (SSCI) (pp. 1-7). IEEE.
[13] Gourisetti, S. N. G., Reeve, H., Rotondo, J. A., & Richards, G. T. (2020). Facility Cybersecurity Framework Best Practices (No. PNNL-30291). Pacific Northwest National Lab. (PNNL), Richland, WA (United States). https://www.osti.gov/biblio/1660771
[14] Glantz, C., Somasundaram, S., Mylrea, M., Underhill, R. and Nicholls, A. (2016). "Evaluating the maturity of cybersecurity programs for building control systems." ACEEE Summer Study on Energy Efficiency in Buildings.

Risk evaluation and vulnerability assessments
Building technology stakeholders need tools and resources to understand how to evaluate and prioritize vulnerabilities to cyber threats within their equipment, systems, buildings, and facilities. They need to incorporate how they manage risk from cyber threats into a range of standard operating and business processes.

Detection and mitigation
Cyber-attacks are often not detected because of a lack of monitoring, logging, and visibility of critical cyber assets. Securing these systems requires proactive cyber risk management and new operational processes that will allow managers, operators, and owners of building technologies to identify, understand, and mitigate cyber threats appropriately.

3.2 Research Areas

Based on the above discussion, the following are priority research areas in building cybersecurity:

- **Develop retrofit solutions.** Legacy systems and infrastructure are often installed with an expectation of decade-plus lifespans and correspondingly may lack the ability to encrypt data and receive security updates due to lack of firmware capability (e.g., limited bandwidth or storage) or vendor support. Retrofitting existing technology to support defense against emerging cyber threats will require specialized attention and consideration.

- **Develop vulnerability assessments.** Vulnerability assessments help stakeholders quantify, evaluate, and test for the effectiveness and timeliness of different cybersecurity vulnerability mitigation technologies and strategies. R&D is required on hardware and software solutions for vulnerabilities in cyber-physical interactions, working to address vulnerabilities without impacting energy performance.

- **Develop threat detection algorithms.** Advanced intrusion and threat detection algorithms enable stakeholders to proactively instrument and monitor systems for effective response and mitigation efforts. Tools and methods must enable cyber analytics, merge information streams, and leverage threat intelligence to provide a complete picture of advanced adversary activity.

- **Develop cybersecurity standards.** Stakeholders need to understand better which existing standards can be applied to specific building technologies. Research on testing frameworks and procedures to help standardize and quantify protection capabilities will address gaps in cybersecurity standards, validating and strengthening outdated, conflicting, or underdeveloped standards as appropriate.

Chapter 4: Interoperability

Interoperability is the ability of devices and software systems to reliably exchange data and meaningfully interpret (and act on) that data. Interoperability is a critical technical and market gap/barrier to connected technologies in buildings.

Electronic communication is a hierarchy of protocols operating at different layers. Interoperability at a given layer requires compatible protocols within that layer and the layers below. The Open System Interconnection (OSI) model defines seven layers, but for this discussion, we group them into three. At the bottom are physical data layers that define the medium and the properties of signals exchanged. Ethernet, Wi-Fi, Bluetooth, and Zigbee are physical data layer protocols. In the middle are network layers that define the form, routing, and delivery of messages. Network protocols include Transmission Control Protocol/Internet Protocol (TCP/IP) and Secure Sockets Layer/Transport Layer Security (SSL/TLS). 6LoWPAN is an emerging standard for low-bandwidth IPv6 over low-power personal area networks with potential connected homes applications. On top are application layers that define the internal structure and semantics of the messages sent. HTTP (web), IMAP (e-mail), and SMS (text messaging) are examples of application layer protocols. BACnet (www.ashrae.org/technical-resources/bookstore/bacnet) is the most common application layer protocol for commercial building automation. At the device level, OpenHEMS is an emerging concept that works using APIs to integrate multiple devices. In the building space, most of the activity is taking place at and above the application layers.

BACnet allows building equipment and software to discover one another on a network and to exchange messages. It specifies the semantics of some parts of messages but attaches no semantics to others, leaving them to higher-level applications, specific vendors, or installations. One higher-level interoperability gap that has received recent attention is the need for standard semantic models of buildings and their systems. A semantic model is not a set of messages between entities in a building but rather an overarching description of those entities, their capabilities, and their relationships to one another. This type of model allows applications such as advanced control, monitoring, fault detection and diagnosis, and even grid services to automatically configure themselves to different buildings, allowing them to scale. We call this subset of interoperability "semantic interoperability." Ideally, semantic models would also support interoperability between applications across different stages in the building life cycle from planning, design, and architecture, engineering, and construction, to commissioning, maintenance, and operations.

Semantic modeling is well defined and fairly well established in building design and construction in the form of Building Information Modeling (BIM). BIM does not accommodate all the information needed to support all design and construction analyses and applications. In particular, it does not fully support energy analysis. After translation from BIM, energy-specific information is typically added to the energy analysis application. Semantic modeling is emerging in existing building applications such as energy auditing with schemas such as BuildingSync and CityGML/EnergyADE.

Semantic modeling in building operations is less standardized. Within EMCS, it is heterogeneous and highly dependent on vendor and installer. To the degree that semantic information is standardized and exchanged, it is in the form of naming conventions and sets of tags like the ones described in Project Haystack (https://project-haystack.org/). Haystack can describe entities and some relationships but is not based on a formal data modeling framework that supports generalized queries and automated conformance and completeness checking. Applications and services typically implement internal semantic models but do so in inconsistent, duplicative, and potentially conflicting ways[15]. The development and maintenance of semantic models and their use in configuring and deploying new applications is generally not automated and requires general expertise with the underlying software and knowledge of the specific building and its systems.

The recognition of the importance of semantic modeling and interoperability has redirected the ASHRAE Standard 223P to the proposed new title of "Semantic Data Model for Analytics and Automation Applications in Buildings." This proposed standard would develop a semantic modeling framework for building operations. The framework will draw from and extend existing building ontological frameworks such as Brick Schema (https://brickschema.org), Semantic Sensor Network (SSN) ontology (www.w3.org/TR/vocab-ssn/), Smart Appliance REFerence (SAREF) ontology (https://saref.etsi.org/), and others. The framework will support translation to-and-from existing Haystack models and perhaps other building relevant semantic models such as BIM and BuildingSync.

ASHRAE Standard 223P will also include an evaluation framework that can be used to test installations for conformance to the standard. To support specific use cases such as system-level fault-detection and diagnosis, Subsets or "model views" of the standard that are sufficient to

[15] Benndorf, G.A., Wystrcil, D. and Réhault, N. (2018). "Energy performance optimization in buildings: A review on semantic interoperability, fault detection, and predictive control." Applied Physics Reviews, 5(4), p.041501.

support those use cases will be defined. The evaluation framework can be parameterized to check for completeness against this model view in addition to conformance to the standard.

4.1 Technical and Adoption Barriers

Semantic interoperability in building faces the following technical and adoption barriers:

Proliferation of semantic data modeling frameworks
Bespoke (pseudo) semantic data models (e.g., naming conventions, other metadata) reflect the specialized needs of different industries (e.g., retail, healthcare, building controls, energy) and even of different building systems such as lighting, HVAC, plug loads, refrigeration, and rooftop photovoltaics (PV), electric vehicles (EVs), and stationary batteries. Different organizations are trying to create formal models that encompass subsets of these systems and use cases, but these efforts are themselves uncoordinated.

Large outdated installed base
Many installed BAS and EMCS are programmed with limited or even no semantic data models and would need to be upgraded to become conformant with a new standard.

Lack of semantic data model-driven applications and services
In a classic chicken-and-egg situation, there is little incentive to create semantic data models in new installations or to upgrade existing systems because there are no applications and services that can take advantage of semantic data models.

Vendors, operators, and installers engagement
The existing workforce is not familiar with semantic modeling, its capabilities, workflows, and applications.

4.2 Research Areas

Based on the above discussion, the following are priority research areas in semantic interoperability:

- **Harmonize semantic data model standards.** Select and promote an existing semantic modeling standard for building applications or create one that pulls together existing efforts and combines the best features of different systems to promote acceptance and adoption by their existing champions and user bases.

- **Develop minimum requirements for different use cases of semantic data modeling.** A common semantic modeling framework will support a wide range of applications. However, individual installations will not be interested in all these applications. Develop minimum semantic data modeling requirements for different applications and use cases to give vendors and installers precise targets for the information they need to represent.

- **Develop semantic data model conformance and completeness testing tools.** Develop open and trusted tools that can evaluate existing installations for conformance to the standard and completeness relative to target use-cases. These tools can also help guide and educate installers in creating conformant and complete models.

- **Develop translation tools that ease the transition to semantic data modeling for existing systems.** There is a significant installed base of BAS and EMCS that use limited or ad hoc semantic data modeling. Automating or even mostly automating the transition of these existing systems to true, complete, and conformant semantic modeling will lower barriers to adoption.

- **Engage stakeholders to promote semantic modeling and interoperability.** Existing market actors may have short-term incentives to resist the adoption of semantic interoperability. Engagement with a diverse group of stakeholders, including vendors, installers, building owners and operators, and standards and professional organizations focused on the benefits of semantic interoperability, is critical to the successful development and adoption of semantic interoperability.

Request for Information Categories and Questions

Category 1: Hardware

1. In reference to the Technical and Adoption Barriers listed in Section 1.1 of the above draft:
    a. Are there any missing technical and adoption barriers for advancing state-of-the-art building energy management hardware? If so, please describe.
    b. Have any of the listed barriers already been sufficiently addressed through current state-of-the-art? If so, please describe.
    c. Are there barriers in the adoption of state-of-the-art hardware specific to disadvantaged and/or underserved communities? If so, please describe.
2. In reference to the Research Areas listed in Section 1.2 of the above draft:

  a. Are there any missing high-level capabilities of next-generation building energy management hardware to combat the identified technical and adoption barriers in section 1.2? If so, please describe.
  b. Are there any missing near-term (5-10 years) research areas for building energy management system hardware? If so, please describe.
  c. Which research areas should BTO prioritize? Please justify in detail.
  d. Are there any missing long-term (>10 years) research areas for building energy management system hardware? If so, please describe.
  e. In your opinion, should any of the listed near-term and long-term research areas be omitted from this discussion? If so, please justify in detail.
  f. Are any of the identified research areas disproportionately less impactful to disadvantaged and underserved communities? If so, in what ways can the process be improved to remedy the inequities?

3. Please provide feedback on how Chapter 1 may identify/address equity considerations to ensure the benefits of R&D investments in EMCS hardware reach disadvantaged communities.

Category 2: **Software**

4. In reference to the Technical and Adoption Barriers listed in Section 2.1 of the above draft:
   a. Are there any missing technical and adoption barriers for advancing state-of-the-art building energy management software? If so, please describe.
   b. Have any of the listed barriers already been sufficiently addressed through current state-of-the-art? If so, please describe.
   c. Are there barriers in the adoption of state-of-the-art software specific to disadvantaged and/or underserved communities? If so, please describe.
5. In reference to the Research Areas listed in Section 2.2 of the above draft:
   d. Are there any missing characteristics of next-generation building energy management software to combat the identified technical and adoption barriers in section 2.1? If so, please describe.
   e. Are there any missing near-term (5-10 years) research areas for building energy management system software? If so, please describe.
   f. Are there any missing long-term (>10 years) research areas for building energy management system software? If so, please describe.
   g. Which research areas should BTO prioritize? Please justify in detail.
   h. In your opinion, should any of the listed near-term and long-term research areas be omitted from this discussion? If so, please justify in detail.

        i. Are any of the identified research areas disproportionately less impactful to disadvantaged and underserved communities? If so, in what ways can the process be improved to remedy the inequities?
6. Please provide feedback on how Chapter 2 may identify/address equity considerations to ensure the benefits of R&D investments in EMCS software reach disadvantaged and historically underserved communities.

Category 3: Cybersecurity

7. In reference to the Technical and Adoption Barriers listed in Section 3.1 of the above draft:
    a. Are there any missing technical and adoption barriers to addressing cybersecurity vulnerabilities in building systems? If so, please describe.
    b. Have any of the listed barriers already been sufficiently addressed through current state-of-the-art? If so, please describe.
8. In reference to the Research Areas listed in Section 3.2 of the above draft:
    c. Are there any missing research areas for building cybersecurity? If so, please describe.
    d. Which research areas should BTO prioritize? Please justify in detail.
    e. In your opinion, should any of the listed near-term and long-term research areas be omitted from this discussion? Please justify in detail.
9. Please provide feedback on how Chapter 3 may identify/address equity considerations to ensure the benefits of R&D investments in building cybersecurity reach disadvantaged and historically underserved communities.

Category 4: Interoperability

10. In reference to the Technical and Adoption Barriers listed in Section 4.1 of the above draft:
    a. Are there any missing technical and adoption barriers to achieving semantic interoperability in building systems? If so, please describe.
    b. Have any of the listed barriers already been sufficiently addressed through current state-of-the-art? If so, please describe.
11. In reference to the Research Areas listed in Section 4.2 of the above draft:
    a. Are there any missing research areas for semantic interoperability? If so, please describe.
    b. Which research areas should BTO prioritize? Please justify in detail.
    c. In your opinion, should any of the listed research areas be omitted from this discussion? Please justify in detail.

12. Please provide feedback on how Chapter 4 may identify/address equity considerations to ensure the benefits of R&D investments in building interoperability reach disadvantaged and historically underserved communities.

Category 5: **Other**

13. Is there any other feedback on the draft RDO or broader issue you would like to provide? As much as possible, please provide factual information with citations.
14. Do you have recommendations on additional studies, data, or research that could inform BTO strategy around EMCS? If so, please describe.

Request for Information Response Guidelines

Responses to this RFI must be submitted electronically to **emcs_rfi@ee.doe.gov** no later than **11:59 pm (ET) on July 18, 2022**. Responses must be provided as attachments to an e-mail. It is recommended that attachments with file sizes exceeding 25MB be compressed (i.e., zipped) to ensure message delivery. Responses must be provided as a Microsoft Word (.docx) attachment to the e-mail, and no more than six pages in length, 12-point font, 1-inch margins. Only electronic responses will be accepted.

Please identify your answers by responding to a specific question or topic if applicable. Respondents may answer as many or as few questions as they wish.

EERE will not respond to individual submissions or publish publicly a compendium of responses. A response to this RFI will not be viewed as a binding commitment to develop or pursue the project or ideas discussed.

Respondents are requested to provide the following information at the start of their response to this RFI:

- Company / institution name;
- Company / institution contact;
- Contact's address, phone number, and e-mail address.