Energy Efficiency (2024) 17:96
https://doi.org/10.1007/s12053-024-10272-3

ORIGINAL ARTICLE

Pathways to commercial building plug and process load efficiency and control

Amy Van Sant · Omkar Ghatpande · Robin Tuttle · Kim Trenbath

Received: 3 May 2024 / Accepted: 7 October 2024

Abstract To accomplish net-zero carbon emissions in the built environment by 2050, we must equitably decarbonize commercial buildings, including reducing plug and process loads (PPLs). PPLs are plug-in or hardwired electric and gas loads that are not associated with major building end uses like lighting and HVAC. Research shows PPL energy reduction strategies and control technologies have the potential to save energy. But even when implemented, these savings have rarely been achieved and there has not been widespread uptake in U.S. commercial buildings. We investigate why these technologies and strategies have not seen widespread adoption and identify behavior and technology pathways to increase PPL reduction in U.S. commercial buildings. We examined behaviors of commercial building stakeholders through 44 interviews and cross-referenced qualitative analysis findings with in-depth technical knowledge of existing PPL control technologies and reduction strategies.

PPL control implementation must be paired with management strategies, such as occupant engagement and training, to achieve optimal savings, and best practices should be disseminated across the industry. We found that increasing access to cost and energy savings data will promote uptake of PPL control technologies and allow designers to better incorporate PPLs into building design. Improving access to funding for PPL energy efficiency projects and addressing the split-incentive problem will increase adoption of PPL efficiency and control. Code bodies should continue to include PPL monitoring and reduction measures in energy codes. Key building stakeholders, including cybersecurity and information technology teams, should be involved in PPL monitoring and reduction strategy processes for successful implementation.

A. Van Sant (✉) · O. Ghatpande · R. Tuttle · K. Trenbath
National Renewable Energy Laboratory, 15013 Denver West Parkway, Golden, CO 80401, USA
e-mail: Amy.VanSant@nrel.gov

Keywords Plug and process loads · Miscellaneous electric loads · Energy efficiency · Commercial buildings · Adoption pathways · Behavioral influences

Introduction

Commercial buildings accounted for approximately 18% of total energy consumption in the U.S. in 2022 (U.S. Energy Information Administration, 2024) and 16% of national greenhouse gas (GHG) emissions (U.S. Energy Information Administration, 2023), making them pivotal in addressing the global climate crisis. Plug and process loads (PPLs), or miscellaneous loads, are plug-in and hardwired electric and gas loads in a commercial building that are not associated with another major building end use, such as lighting, water heating, or heating, ventilation, and air conditioning (HVAC). This end use includes devices like computers and printers, and larger loads like kitchen equipment, vertical transportation, and medical imaging equipment. Other common terms used to describe a subset of the end use include plug loads and miscellaneous electric loads (MELs). Both of these terms refer to electric

Published online: 14 November 2024

loads only: plug loads include all plug-in electric loads, while MELs encompass all electric plug-in and hard-wired loads not associated with another major building end use.

On average, PPLs constitute 28% of whole-commercial building energy consumption, and that figure is expected to increase as more PPL devices and equipment are added to buildings while other end uses continue to become more energy efficient (U.S. Energy Information Administration, 2023). This end use encompasses a diverse range of occupant-dependent equipment and device types, most of which are integral to the daily operations of commercial buildings.

Historically, HVAC and lighting have been the primary targets for energy reduction by commercial building energy managers, as these end uses have had high consumption, and there are a variety of commercialized HVAC and lighting efficiency and control technologies available on the market. Energy consumption of PPLs, however, has not been as widely and thoroughly addressed through efficiency and control measures despite the potential for significant savings that could be achieved by powering non-critical PPLs off during unoccupied hours. PPL efficiency and control refers to the management, minimization, and optimization of PPL energy consumption in a commercial building through energy efficiency improvements, such as installation of efficient devices, and implementation of control technologies that power PPL devices down or reduce their power draw when not in use.

In a commercial building, PPLs are a challenging end use to manage as there are hundreds to thousands of occupant-dependent individual PPLs ranging from small energy consumers, such as coffee makers, to high energy equipment, such as elevators. The scale of PPLs makes individual control difficult to implement and manage. Additionally, one-size-fits-all control technologies and reduction strategies are often not appropriate for PPLs due to the breadth of device types captured within the end use. Some research also suggests that improperly implementing reduction strategies and control technologies on devices and equipment that occupants regularly interact with can result in unsuccessful deployment (Kandt & Langner, 2019). However, little has been studied or documented about the factors that influence PPL efficiency and control adoption in U.S. commercial buildings.

In this study, we examine the current state of the market, and identify drivers, barriers, and pathways to more widespread PPL efficiency and control uptake to provide valuable insights for commercial building stakeholders, such as building owners, facility managers, policy makers, and researchers by answering the following research questions:

1. What is the current state of PPL efficiency and control?
   (a) What or who is driving the implementation?
   (b) What strategies are currently being implemented to reduce PPL energy consumption?
2. What are the drivers and barriers to current PPL efficiency and control strategies?
3. Moving forward, what are the recommendations for commercial building stakeholders to achieve PPL reduction?

In the Background section, we discuss past and present PPL control technologies and reduction strategies, followed by a literature review. In the Methodology section, we detail the stakeholder interview process and the qualitative data analysis that was conducted to highlight the major drivers and barriers, which are then discussed in the Results sections. The Discussion section describes pathways to PPL efficiency and control in commercial buildings.

Background

PPL reduction strategies and control technologies

There are many methods that commercial building owners and operators can employ to manage PPLs. This section provides a high-level overview of the historical and present PPL reduction strategies and control technologies.

Reduction strategies

Reduction strategies refer to the occupant-enacted, deliberate reduction or shutdown of non-essential PPLs when not in use, such as during the building's unoccupied hours. Strategies in this category include occupant awareness programs, such as training sessions and informational campaigns to educate occupants about the energy impact of PPLs. Communication and signage reminding occupants to turn off PPLs when not in use are often part of these programs, as well as PPL champions that organize and promote PPL energy-saving initiatives. Often, these programs are tied to the implementation of a PPL control technology (Jenkins et al., 2019). Also in this category are gamification and incentive programs that recognize occupants for energy-saving behaviors, which have been shown to be effective at reducing energy consumption and developing energy stewards (Hafer et al., 2018).

Another strategy involves procuring and installing energy-efficient PPLs. As devices and equipment become inherently more efficient through manufacturer-implemented improvements, replacing PPLs at the end of their life with more efficient models presents an opportunity for savings. Many PPLs now come equipped with low-power modes or sleep settings. Ensuring these features are enabled during installation or commissioning can further enhance energy savings.

Control technologies

There are several types of PPL control technologies, also referred to as plug load management (PLM) or plug load control (PLC) technologies, all of which cut power to PPL devices automatically to reduce standby energy consumption. Advanced power strips (APSs) are separate power strips that can be controlled manually or with sensors to shut off power to specific PPLs (Fig. 1). There are many APS providers and varieties that come with different capabilities to meet different needs. For example, depending on the APS purchased, there may be wireless transmission and energy monitoring capability (Earle & Sparn, 2012). This technology is most effective for controlling specific devices, rather than the whole building, and allows the linking of multiple appliances under the same control.

There are two technologies used as PLM systems. The first are smart outlets, which are plugged into existing outlets and measure plug load energy usage (Fig. 2). They wirelessly transmit data and can be controlled to turn power on or off. This technology is effective for automatically controlling devices based on a schedule and understanding full building and device-specific energy usage and behavior. Often, data can be accessed via an online dashboard or smartphone application. Additionally, some smart outlet systems use machine learning algorithms that can predict schedules (Trenbath et al., 2020), while others can apply controls based on occupancy sensor data. There are buttons built directly into smart outlets that allow the in-room user to instantaneously override the control and turn on power delivery through the outlet.

Fig. 1 Advanced Power Strip. *Photo by Werner Slocum, NREL 46058*

Automatic receptacle controls (ARCs) are also used as PLM systems, and they automatically turn off power to receptacles using signals from occupancy sensors, control schedules, or other building systems (Fig. 3). This technology meets energy code requirements specified in ASHRAE Standard 90.1, the International Energy Conservation Code (IECC), and California Title 24. They are best suited for plug-in devices that only need to be operational when the building is occupied. Like smart outlets, there are often buttons built directly into ARCs for users to override control and turn on power through the receptacle. Manufacturers offer multiple ARC configurations for controlling either one or both outlets in a duplex ARC.

Integration of PPL control systems with other building controls may provide increased energy savings compared to PLC alone, and a few of these PPL integration projects have emerged over the past 3-5 years.

Fig. 2 Smart outlet. *Photo from WattIQ*

Fig. 3 Automatic receptacle control. *Photo from Legrand.*

PPL control technologies are often good candidates for integration with lighting control systems because they can leverage occupancy sensor data that is already employed by the lighting control system (Davalos et al., 2020; Integrated Controls for Plug Loads and Lighting Systems, 2022). Integration of PPL control technologies with the building automation system (BAS) is even less common. This technology is actively being researched, with demonstration of integration between smart outlets and BAS at a university campus showing 66% energy savings (Chia et al., 2023).

To date, most PLC technologies cut off the power supply to PPLs at the outlet to save energy. However, not all devices are suitable for on/off controls provided by these technologies. This is due to several factors, such as the need to maintain network connection or the risk of component damage if powered off at the outlet. For PPLs where on/off controls are not suitable, sleep settings can be a viable option for achieving energy savings.

Literature review

PPL efficiency and control adoption

There have been limited studies conducted on the adoption of PPL efficiency and control. Tekler et al. conducted focus groups and online surveys to investigate adoption of PLM systems in office buildings (Tekler et al., 2021). Among the concerns expressed in the study, participants were worried that an automated PLM system would be difficult to use, may turn off their plug loads when they are in use, and may affect their current workflow. Study participants selected intuitive, easy-to-use, and easy-to-integrate with other management systems as the attributes of an ideal PLM system.

Occupant behavior and engagement have been identified as key factors for PLM system adoption in several studies. A PLM system field study published by Kandt and Langner found that building occupants became frustrated with the PLM system due to schedule controls that were incompatible with their device needs and unplugged the PLM devices to override controls, leading to decreased energy savings and unfavorable payback. The researchers cited operations staff engagement with both the PLM system and building occupants as a key contributor to the success of PLM system implementation (Kandt & Langner, 2019). Hafer et al. implemented a PLM system with active occupant engagement technology to enable participants to view their consumption, remotely control devices, set schedules, and engage in a game (Hafer et al., 2018). The results showed 21% savings in average daily consumption, and demonstrated that occupant engagement was an effective strategy when paired with a PLM system.

There are limited, formal studies that investigate or document the influence of occupant behavior on PPL efficiency and control adoption. Anecdotally, speaking with building owners and operators we have learned that occupant pushback has historically been a significant barrier to adoption of control technologies and reduction strategies. There is more literature available (see Section "Commercial building energy efficiency adoption") on the impact of occupant behavior on technology adoption in commercial buildings, in general. Though they do not explicitly investigate or describe PPL efficiency and control, their findings may be applicable to PPL adoption.

Commercial building energy efficiency adoption

As noted in the previous section, few studies have explored the adoption of PPL efficiency and control measures. This section examines the factors influencing the adoption of efficiency practices and technologies in commercial buildings, which may also affect PPL efficiency and control implementation.

As is the case with PPLs, occupant behavior is also a factor in non-PPL efficiency and control technology adoption, as well as in commercial building energy efficiency in general. Zhang et al. estimated the whole-building energy-saving potential of occupant behavior in commercial buildings to be 5-30% (Zhang et al., 2018). Like PPLs, eco-feedback and gamification can be effective methods to influence occupant behavior to achieve greater energy efficiency (Paone & Bacher, 2018). Technology design can be a factor in adoption as non-intuitive design can impede occupants' ability to use the technology, as was the case for thermostats in an office field study (Karjalainen & Koistinen, 2007). Additionally, so-called "robust" design techniques make commercial building energy consumption less sensitive to occupant behavior, and do not require building occupants to understand how the building's systems work to use them properly. An energy simulation study by Karjalainen showed that a "careless user" consumes 75-79% less energy in buildings with robust design solutions compared to ordinary design solutions. They also argued that the design of energy-efficient buildings could benefit from using a realistic view of occupant behavior (i.e., reducing the burden on occupants to understand building operations or take energy-saving actions) (Karjalainen, 2016). Furthermore, there is a need for occupant data, including behavior and patterns, to inform building design and modeling (Ahn & Park, 2016; Delzendeh et al., 2017).

Several other studies have investigated the non-occupant behavior factors impacting energy efficiency technology adoption in commercial buildings. Hanus et al. found that owners and managers prioritize corporate social responsibility (CSR) when making energy efficiency decisions, whereas experts, such as consultants, do not emphasize CSR and are more concerned with costs, such as energy and labor costs, and retaining tenants (Hanus et al., 2018). Papagiannidis and Marikyan found that labor force skills, the readiness of organizational structure, and compatibility of existing technological infrastructure with smart devices impact smart technology adoption. In addition, they found that a company's culture can influence whether they make changes toward more intelligent buildings, and that company management may believe smart technologies pose security, financial, or other threats (Papagiannidis & Marikyan, 2020). Hanus et al. identified four key non-technical barriers to energy efficiency investment decision-making in data centers: low energy efficiency saliency in information technology (IT) staff, technical risk aversion, lack of knowledge, and time discounting. Proposed interventions to address these barriers include increasing awareness of energy-efficient products, technologies, and services; establishing an energy efficiency champion; and demonstrating a multitude of benefits from energy efficiency measures (Hanus et al., 2023). Andrews and Krogmann found newer, larger, more energy-intensive, owner-occupied buildings to be those most likely to adopt energy-efficient heating, cooling, window, and lighting technologies because they can afford installation costs (Andrews & Krogmann, 2009). They cite the split-incentive problem as a key factor affecting adoption–rental buildings are less likely to adopt energy–efficient technologies. The split-incentive problem (also referred to as the principal-agent problem) in commercial buildings refers to a relationship between landlord and tenant in traditional leasing agreements in which capital improvements that yield energy savings result in one party paying for the improvements while the other party receives the benefit of reduced utility costs. This is a well-documented, international problem in both the commercial and residential sectors, and there are numerous proposed solutions, including green lease structures, regulatory solutions like minimum performance standards or green building codes, disclosure of energy performance during the buying and leasing process, building sub-metering, and financial incentives designed for renters (Bird & Hernández, 2012; Joint Research Centre (European Commission) et al., 2017; Miller, 2010; White et al., 2020).

Policy plays an important role in the adoption of building energy efficiency practices and technologies, though policy decisions are out of scope of this paper. Ensuring a well-functioning policy mix is especially important (Rosenow et al., 2016). There are generally three categories for policies: mandatory, voluntary, and economic incentives. Each has its own challenges: mandatory policies require resources to enforce, voluntary policies are highly dependent on the enthusiasm of stakeholders to be effective, and economic incentives require consistent funding (Shen et al., 2016). Björklund et al. identified policy opportunities for the transition to energy-efficient and zero-carbon buildings in the European Union (EU), finding that voluntary policy instruments should be complemented by mandatory instruments to promote policy uptake. Furthermore, new policy instruments tend to be developed most commonly at the regional/local level, and there is limited diffusion and coordination between governance levels, thus limiting sharing of best practices within multilevel systems (Björklund et al., 2023). Additionally, Mills found that a more focused and coherent policy strategy may improve the adoption of residential heat pump water heaters in the U.S. (Mills, 2022).

Building energy codes, like ASHRAE 90.1, IECC and Title 24, also play an important role in the adoption of energy efficiency practices and technologies. Schwartz and Krarti found code requirements to be among the common characteristics for highly adopted sustainable energy technologies in the U.S. residential building sector (Schwartz & Krarti, 2022). Codes have also been found to drive product innovation (Vaughan & Turner, 2013) and can increase energy-efficient products available on the market.

Adoption theories

There are several formal theories that describe the adoption of new behaviors and technologies. Rogers' Diffusion of Innovation (DOI) theory explains how an idea or product diffuses over time, and establishes five adopter categories: Innovators, early adopters, early majority, late majority, and laggards.When promoting an innovation or product, it is important to consider your audience with regards to these adopter categories. Rogers' DOI also proposes five characteristics that make a technology more or less readily adoptable: Relative advantage, compatibility, complexity, trialability, and observability (Rogers Everett, 1962). These characteristics have been used to explain the adoption of many energy efficiency technology measures, and researchers have published additions to Rogers' key characteristics (Outcault et al., 2022).

The Unified Theory of Acceptance and Use of Technology (UTAUT) explains behavior related to stakeholder expectation and buy-in of new technologies with four key constructs (Venkatesh et al., 2003):

- Performance expectancy: The extent to which a person expects that utilizing the system will improve their work performance.
- Effort expectancy: How simple or easy an individual finds using the system.
- Social influence: The extent to which a person feels that significant individuals in their life think they should adopt the new system.
- Facilitating conditions: The belief that the organizational and technical resources necessary to support the system's use are in place.

Cowan and Daim found parallels between UTAUT and the adoption of energy-efficient lighting (LED) technology. Namely, future energy price expectancies, actual savings results, and ease of energy savings, as well as social influences such as perceptions of environmental friendliness, policies, incentives and educational programs are key factors influencing adoption (Cowan & Daim, 2013).

Although there is no existing literature on the application of Rogers' DOI or the UTAUT to PPL technology adoption, these theories have been utilized for other energy efficiency measures and could similarly be applied to PPLs.

Methodology

We addressed the research questions using qualitative research methods including semi-structured interviews, as well as coding and categorizing of the response narratives. The codes and categories plus our technical PPL expertise led to the conclusions presented in this paper. We used grounded theory to analyze the data (Glaser & Strauss, 1967) and collected data using two methods: 1) individual interviews with commercial building stakeholders, and 2) a workshop with members of the smart buildings industry. We developed a detailed questionnaire (Appendix A and Appendix B) before data collection to maintain consistency during interviews and the workshop. Study participants were divided into eight categories based on their background and their interactions with commercial buildings, as listed in Table 1. The participants were not required to have any PPL background knowledge to be invited to an interview or the workshop. The reasoning is that most participants will regularly work or visit commercial buildings with PPLs, and therefore can affect the amount of their building's PPL energy consumption.

The first method was one-on-one, virtual interviews where we gathered participants from various commercial building stakeholder categories. We recruited interview participants using an online form that we distributed to commercial building stakeholders via exist-

Table 1 Interview and workshop participant categories

Category	Definition	Interview Participant Count	Workshop Participant Count	Total Participant Count
Building Occupant	Occupants of office buildings	3	0	3
Building Owner	Owners of one or more commercial buildings	4	4	8
Consultant	Consultant in the commercial building industry	0	1	1
Design Engineer	Mechanical or electrical engineers working for a commercial building design firm	4	2	6
Facility Manager	Facility managers for one or more commercial buildings	4	5	9
Lighting Industry	Lighting manufacturer, lighting manufacturer representative, lighting industry expert	4	0	4
Sustainability Manager	Sustainability managers for municipality	2	0	2
Technology Company	Building energy management technology company	1	10	11
Total		22	22	44

ing email distribution lists, colleague contacts, and professional social media (LinkedIn) posts. The form required name and email, along with optional details like their organization's primary category, job role at their organization, and whether they were concerned about PPL efficiency and control. We received 32 form submissions and selected 22 participants based on achieving an even distribution by participant category.

We interviewed each participant using a semi-structured interview approach. At the beginning of each interview, we provided some context, including background of the study, but did not provide any information on PPL reduction strategies to reduce bias. For each category, we asked the participants the same questions, and we noted their responses. Participants responded about their current and prior experiences with PPLs, how they make energy efficiency decisions, whether they monitor PPLs, and what they see as drivers and barriers for PPL efficiency and control (see Appendix A for full list of interview questions). We asked follow-up questions if the interviewee provided content that we, as researchers, determined additional information was necessary. Most of these follow-up questions were about occupant behaviors, building or leadership policies, and organization-specific questions. The interviews lasted about 30 minutes and included two research team members: one to ask the questions, and the other to take notes.

In the second method, we collected data through a workshop with members of a smart buildings industry group. This workshop was open to all members of the group and 22 members participated. We provided the workshop participants with a brief introduction to PPLs and summarized the study to ensure all participants had a basic understanding of the role and scope of PPLs in their commercial building. To help with comprehensive data collection, we randomly separated workshop participants into three breakout groups with 7-9 participants each. Each breakout group also had two members of the research team, one to facilitate discussion and the other to take notes. We used Google Jamboards to pose a set of 7 questions to each group (see Appendix B), and participants responded to questions using sticky notes on the Jamboards. The notetakers recorded additional discussion, feedback and insights from participants.

We analyzed data collected through both the interview process and the workshop using similar methods. The response "phrases" were tabulated from notes taken by the research team and sticky note contents from the workshop Jamboards. The stakeholder category and the corresponding question accompanied each phrase; the responders name was excluded during analysis. For categorization, we then took an iter-

Table 2 Barrier and driver theme definitions

Theme	Definition
Awareness	Familiarity with PPLs, its energy use, and reduction strategies.
Company Goals	The company has established sustainability, energy efficiency, or energy/ emissions reduction goals related to PPLs, the individual building, or building portfolio.
Data	Availability of information for use by building stakeholders to make decisions.
Deferred Responsibility	None of the parties involved are willing to make energy efficiency decisions, leading to nothing being done.
Funding	Availability of monetary resources with which to make energy efficiency or control upgrades.
Occupant Behavior	Actions and habits of occupants influence the usage patterns of PPLs and can impact control and reduction strategy implementation and success.
Regulations	Established guidelines, rules, or directives imposed by authorities to govern and standardize practices related to the energy efficiency and controls of PPLs.

ative approach to assign a "theme" to each of the participant's responses in order to analyze them all together (Glaser & Strauss, 1967). The first iteration of the themes was specific and relied on wording of the phrase such as "Energy codes are single motivator in product offering." Based on this first iteration, the team grouped the response phrases into wider subjects to reveal broader themes. In this step, the example theme provided earlier became "Regulations: Codes." Finally, all the responses were split into theme and sub-theme where the theme captures the broader topic of the phrase, and the sub-theme captures the specific aspect of the topic. In this iteration, phrases were also categorized as either a barrier or driver to capture which the speaker was identifying. Tables 2 and 3 show the theme and sub-theme definitions we developed as part of the analysis process.

Results

Current state of the market

Current drivers of PPL efficiency and control implementation

Several factors currently drive implementation of PPL efficiency and control. Most common was energy-efficient procurement strategies. One facility manager participant said that all vending machines in their facility were required to be ENERGY STAR-certified: "Most of vending is third-party contract. These must be ENERGY STAR." Another participant said all new equipment is required to be energy efficient: "If new equipment is procured, ENERGY STAR or efficient equipment is procured." Several participants mentioned that PPLs are becoming a higher priority for reduction: "Other low-hanging fruit getting done makes PPL more important," and "As buildings become more efficient, PPLs are larger part of our energy pie. [We] will eventually need to reduce PPLs as we drive down future energy [and] GHGs."

Based on participant feedback, it is also common for commercial buildings to be sub-metered: "[We] sub-meter loads as best as possible to evaluate better technologies for control or load reduction." One building owner participant has required sub-metering on their tenant spaces specifically for PPL monitoring: "[We] have implemented sub-metering as a tenant requirement to allow for visibility of plug loads." Another participant identified monitoring loads as an area of improvement: "[Our loads] are not monitored. This would be an area of improvement." Several participants also noted they are not currently monitoring their PPLs but did not make any indication as to whether they would in the future.

When it comes to "who" is driving the implementation, one design engineer participant said it is the client/building owner: "[The] client has a goal in mind, and we work with them to get to that goal." Another said it depends, and that design engineers play a role by providing energy-efficient options: "[The] client/owner decides, in some cases [the] architect. Designers suggest energy-efficient options to explore for projects." Another said, "The brokers really drive the decision. If [the client] needs to position the building on the market, they always ask the brokers in terms of what we are seeing on the market."

Table 3 Barrier and driver sub-theme definitions

Theme	Sub-theme	Definition
Awareness	All stakeholders	All commercial building stakeholders, including occupants and decision-makers.
	Decision-makers	Commercial building facility managers, sustainability managers or owners.
	Occupants	Commercial building employees, occupants, tenants, or residents.
Company Goals	EE procurement	The company has energy-efficient procurement goals or policies for new PPL devices and equipment.
	Emission targets	The company has carbon and emissions reduction targets for its building(s).
	ESG	The company has established environmental, social, and governance (ESG) goals.
	General energy goals	The company has general energy reduction goals for its building(s).
	LEED	The company is committed to meet the LEED standards for its building(s).
	SDG	The company has established sustainable development goals (SDG).
	Stakeholder support	Building stakeholders whose support ensure successful implementation of PPL reduction projects.
Data	Financial	Availability of data that can be used to make financial decisions (e.g., cost savings, ROI, payback).
	Technical	Availability of data that can be used to make technical feasibility decisions (e.g., metered/measured data), to implement the technologies, and to inform building design. Even if data is collected, it still needs to be analyzed to be useful and make decisions.
Deferred Responsibility	Building owners' responsibility	Non-building owner participant mentions building owners are responsible for energy efficiency decisions in commercial buildings.
	Commissioning responsibility	Participant mentions commissioning agents as being responsible for energy efficiency decisions.
	Communication	Participant mentions communication affects energy efficiency decisions.
	Leadership's responsibility	Participant mentions company leadership as being responsible for energy efficiency decisions.
	Manufacturers' responsibility	Non-manufacturer participant mentions PPL manufacturers are responsible for energy efficiency decisions.
	MEP industry responsibility	Non-MEP (mechanical, industrial, and plumbing) industry participant mentions the MEP industry are responsible for energy efficiency decisions.
	Procurements' responsibility	Non-procurement team participant mentions a company's procurement team are responsible for energy efficiency decisions.
Funding	Capital	Availability of funding from the building owner required to undertake efficiency upgrades.
	Equitable	Income level impacts ability and willingness to undertake efficiency upgrades.
	Incentives	Availability of third-party funding sources, such as government (federal, state, city) or utility incentives for efficiency upgrades.
	Split-incentive	Split incentives between commercial building owner and tenant due to common lease structures.

Table 3 continued

Occupant Behavior	Invasion of space	Occupants with private spaces within the building, such as private offices, push back against PPL metering, controls, and/or reduction strategies because they find them to be intrusive.
	Occupant buy-in	Occupants do not support or actively participate in PPL metering, controls, and/or reduction strategies that have been implemented in their building.
	Occupant dissatisfaction with technology	Occupants are dissatisfied with some or all features of a PPL control technology.
Regulations	Code implementation or scope	Implementation or scope of PPL building energy codes prevents implementation of PPL energy reduction strategies and/or control technologies.
	Codes	Building energy codes impact implementation of PPL energy reduction strategies and/or control technologies.
	Ordinances	Local ordinances impact implementation of PPL energy reduction strategies and/or control technologies.
	Voluntary regulations	Benchmarks, specifications, and standards impact implementation of PPL energy reduction strategies and/or control technologies.

Implemented strategies to reduce PPL energy consumption

Study participants are currently reducing PPL energy consumption via plug load control (PLC) and occupant engagement. PLC technologies mentioned include schedule-based and occupancy-based control ARCs, and smart outlets. Several participants have used or are currently using time clock-based controls: "[Using] time clock [automatic receptacle control] (ARC) is the majority [of PPL control processes]," and "Select building receptacles are on a time clock." Others have experience using occupancy-based PLC: "[We use] occupancy-based power strips," and "Computer monitor and task lamp plug loads [are] controlled by occupancy sensors." One participant said that in addition to occupancy-based control, they have used smart plugs: "Experience with smart plugs and have some plug loads in our building that are connected to occupancy sensors." One facility manager participant has experience with integrated PLC: "BAS controls and lighting controls that control plug loads with occupancy sensors."

Several participants have engaged building occupants to promote energy efficiency: "[We have conducted an] educational campaign for residents like fridge magnets – guidance and social media blast for energy efficiency." Another building owner participant mentioned educating occupants about a PLC system in the buildings: "A net-zero energy building has a system [where] if computer is not docked, the [occupants] do not have power to the desk plug loads and task lighting. Information was distributed through the property manager association to tenants."

While study participants cited load monitoring as a current driver for PPL efficiency and control, the data is primarily being collected for all building end uses through sub-metering: "[I have] experience with sub-meters and pulling those into analytics software but rarely is it just plug loads." For participants sub-metering their building(s) at the end-use level, some are not currently using this information to make decisions: "[We have been] increasing our sub-metering to get a better idea of usage and cost of end-use loads, but not currently doing a whole lot to manage and control these devices." However, a minority of the participants are utilizing sub-metered data: "[We] sub-metered PPLs for buildings including IT rooms, data centers, lab equipment, data equipment, etc., [and] conducted studies to analyze tenant versus landlord loads."

Drivers

Figure 4 shows the count of drivers by theme and sub-theme, and Table 4 shows the most common driver themes and sub-themes by participant category. Regulations, Company Goals, and Funding were the driver themes most mentioned by study participants.

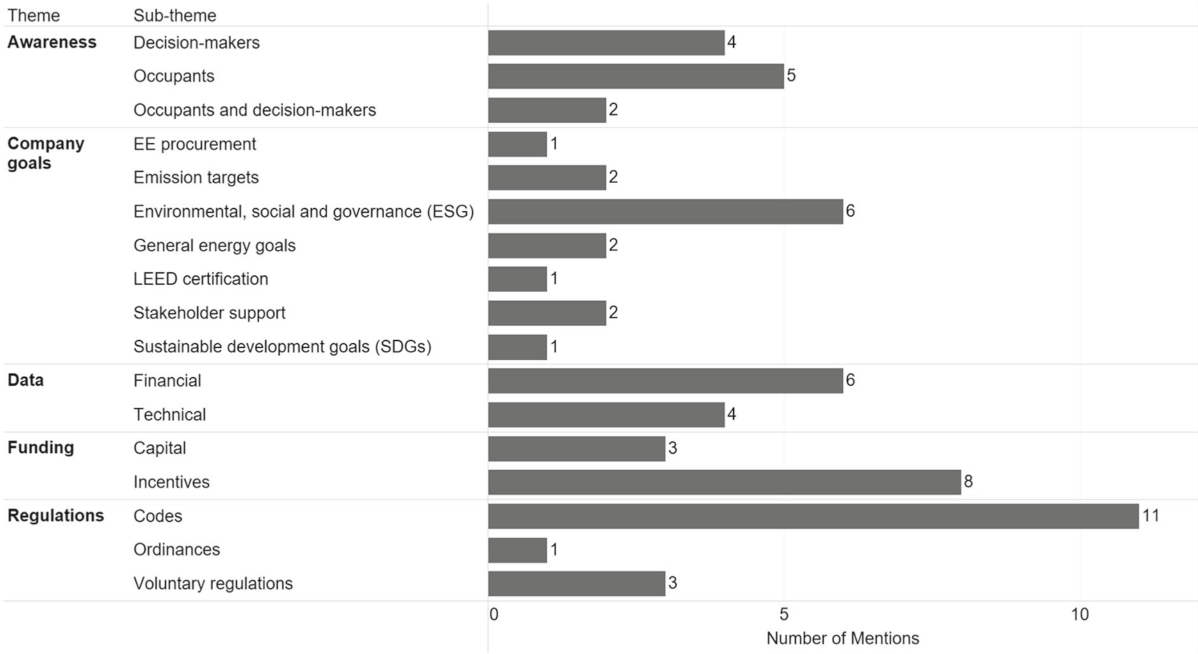

Fig. 4 Number of driver theme and sub-theme mentions

Design engineers, lighting manufacturers, and technology companies all mentioned Energy Codes under the Regulations theme as a driver most often. One participant said, "The only way [PPL efficiency and control] will work is owner standards or legislation, with the responsibility on the business that owns the equipment." Another said, "Our building code provides easier approval when efficiency equipment is added."

Lighting manufacturer representatives mentioned Company Goals most frequently as a driver. The sub-theme Environmental, Social, and Governance (ESG) was mentioned by study participants. When asked about their company's approach to energy efficiency, one building owner participant said, "Reason is to reach various ESG and energy savings targets. ESG is major driver for business, promised to go carbon neutral / net zero by 2040." Another study participant said, "[They are] heartened by the fact that ESG is becoming a big thing. [There are] cities like New York and Washington D.C. that are focused on the performance of the building." Company energy goals and emissions targets were briefly touched on by

Table 4 Most common driver themes and sub-themes by participant category

Participant Category	Theme	Sub-theme
Design Engineer	Regulations	Codes
Building Owner	Funding	Capital/Incentives
Sustainability Manager	Data	Technical
Lighting Designer	Awareness	Decision-Makers
Facility Manager	Data	Financial
	Regulations	Ordinances/Codes
Building Occupant	Awareness	Occupants
Lighting Manufacturer	Regulations	Codes
Technology Company	Regulations	Codes
Lighting Manufacturer Rep.	Company goals	General Energy Goals

some participants: “New construction – 50% of people are very energy conscious and don’t push back on PLC requirement,” “Organizations that are environmentally conscious tend to have better luck with [PLC] systems,” and “Carbon targets [are] more prevalent.” Other driver sub-themes under Company Goals were focused on energy-efficient equipment procurement. These responses indicate that having focused and clear company goals drives many efficiency-related decisions, including PPLs.

Funding was the third most common theme identified as a driver by participants, with Incentives being the most frequently referenced sub-theme. When asked to describe the impact of commercial building codes and incentives on their PPL approach, one building owner participant said, “CRE [commercial real estate industry] is still focused on ‘meeting’ not ‘exceeding,’ so if PPL becomes a baseline requirement or if the incentives reduce cost sufficiently, it will become a higher priority.” When prompted with the same question, a facility manager participant said, “It is tough with existing buildings that were built under older codes. If we had better incentives, [PLC] would be attractive.” This speaks to the challenges associated with implementing PPL control retrofits and offers incentives as a driver toward greater implementation. Capital funding was another sub-theme under the Funding driver. One building owner participant said, “Cost of install is the single driver.”

Awareness was another prominent theme, with building occupants and lighting designers citing it as a driver most often. Participants mentioned educating occupants as a key driver: “Educating people would be effective”; “Marketing would encourage the end users, [such as] building owners to use plug load [controls].” Another participant said that occupant awareness is key for any plug load control to be used as designed for maximum savings: “[There was a] big corporate user with a big presence that installed their own solution, and had their own signs and reminders to power down, primarily when occupants went on vacation.”

Sustainability managers and facility managers are both driven by Technical and Financial Data, respectively. When asked what drives energy efficiency decisions, a sustainability manager participant said, “Being able to demonstrate energy savings. The financial case for investment is essential.” A design engineer participant explained the importance of return-on-investment (ROI) data for PLC technology, and that there is a maximum ROI that will be considered: “Having data is important. ... As long as the ROI is no more than 2-3 years, the client will consider the technology.” A technology company participant mentioned studies that make the financial case for PPL control technologies as a driver: “[A] credible study of energy effect extrapolated to [the] national level would be very helpful in education. Quantifying effect would be great.” Technical data was identified by multiple participants as a driver. When asked how they would reduce PPL energy consumption in their building, a sustainability manager participant highlighted the importance of understanding PPL base load, saying simply, “Sub-meter, sub-meter, sub-meter!” A technology company participant spoke to the impact that awareness of PPL consumption could have: “When you have [to] perform an energy balance and see 30% or more for plug loads, it starts a conversation.”

Barriers

Figure 5 shows the count of barriers by theme and sub-theme, and Table 5 shows the most common barrier themes and sub-themes by participant category. The barrier themes most mentioned by study participants were Awareness, Data, Funding, and Company Goals. Lack of awareness of PPLs was most mentioned by building occupants, lighting manufacturers and representatives, and sustainability managers. One study participant cited the culture around energy savings as a key barrier: “There was not an energy saving culture. Few people were thinking about it.” This indicates that lack of awareness of the importance of energy savings is affecting the success of PPL efficiency and control implementation.

When asked whether their building monitors PPL energy use, a facility manager participant said, “[We used] Trickle Star smart plugs – [there was] confusion on how to set up the control. [Occupants] need one-on-one help. Occupants were in charge of the setup. Once [they] learned, occupants were OK,” demonstrating that occupants were able to successfully interact with PPL control technology once they learned how the system worked. To a similar effect, another participant said, “End users are pushing back. [I] don’t think they understand what’s happening in the control situation. They are concerned their loads will be turned off when they are expecting them to continue to function.” A participant in the building occupant category

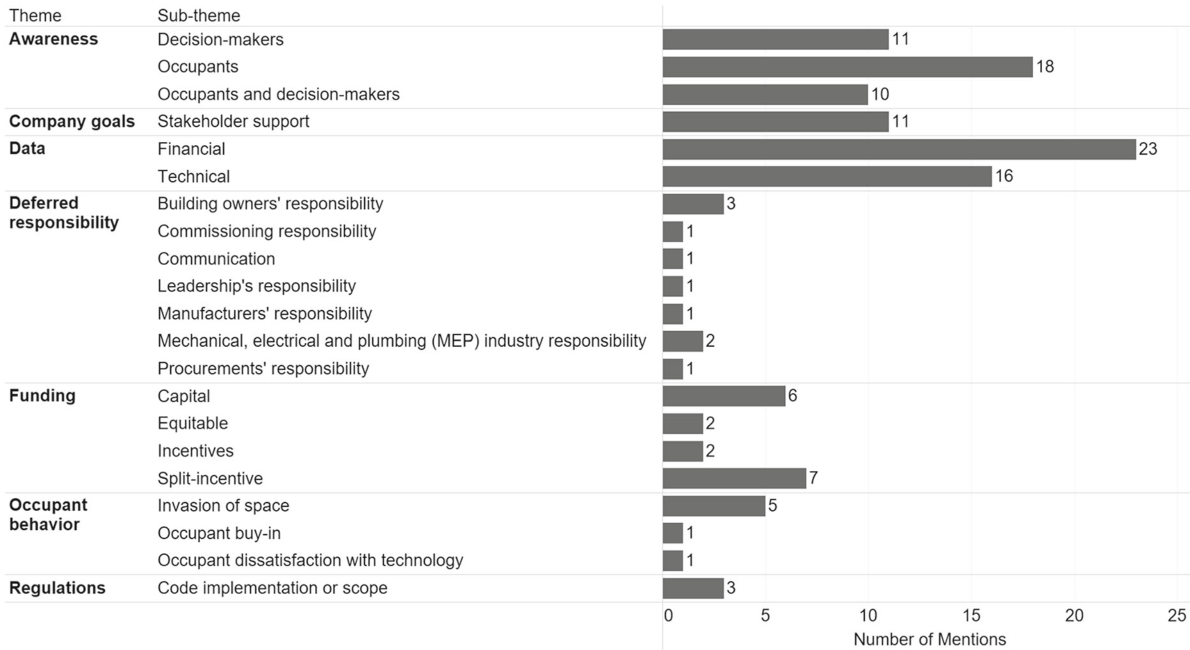

Fig. 5 Number of barrier theme and sub-theme mentions

recalls confusion when a PLC system was installed in their building, saying, "No information was provided when plug load [control] was installed. It was fairly easy to use but some occupants were annoyed and did not use plug load control." Occupant awareness can be helpful to avoid occupants circumventing control technologies, an issue cited by multiple study participants. One participant said, "People can buy extension cords and connect to hot [on] plugs. Could be [an] occupant issue as there is a work-around and they think their loads are important to run continuously." Another participant simply stated "Another issue is that PLC is so easy to circumvent" when referring to power strips as the method by which occupants circumvent the technology.

Design engineers, sustainability managers, lighting designers, and facility managers all cited lack of data, whether Technical or Financial, as a barrier to PPL efficiency and control adoption most frequently. Technical data is data used to make technical decisions, such as for

Table 5 Most common barrier themes and sub-themes by participant category

Participant Category	Theme	Sub-theme
Design Engineer	Data	Technical
Building Owner	Funding	Split-Incentive
	Data	Technical/Financial
Sustainability Manager	Awareness	Decision-Makers
	Data	Technical
Lighting Designer	Data	Financial
Facility Manager	Data	Financial
Building Occupant	Awareness	Occupants
Lighting Manufacturer	Awareness	All Stakeholders
Technology Company	Deferred Responsibility	Building Owners' Responsibility
	Occupant Behavior	Invasion of Space
Lighting Manufacturer Rep.	Awareness	Occupants/All Stakeholders

building design or prioritizing energy efficiency measures in an existing building. One design engineer noted that lack of PPL technical data can lead to other building systems being overdesigned: “[Design engineers] assume some plug load value, some of the information is overdesigned (for example, old CRT [cathode-ray tube] monitor). [We] need [a] study to find latest/recent and accurate design data. Most design engineers won’t spend the time digging for a better number.” Another design engineer echoed the overdesign sentiment and added the importance of understanding the relationship between peak PPL energy consumption compared to the design value: “Understanding real world data related to peak numbers to design number. [An] energy model is based on a number for plug load which is a big guess currently. [We are] 100% conservatively overdesigning the building.” The lack of technical data for this application can have significant implications on whole-building energy consumption through overdesigning of HVAC systems to meet a higher internal load. A lack of technical data to promote awareness of PPL energy consumption was also cited as a barrier: “Lack of data. [I] found that 30% energy use is surprising. [I] imagined that PPL is a smaller share compared to heating and cooling processes.”

Financial data is energy savings and ROI for PPL control systems. One participant said, “[There is] no data to back up the PLC actual energy savings.” Another echoed this point but was a bit more specific: “[I am] unable to find peer-reviewed data on the measured savings over, say, a full year. Very little data? So how does one calculate ROI?” One study participant noted that while there may be some data available to suggest that PLC saves energy, this is not sufficient for savings calculations for specific design or retrofit projects: “There is enough documentation to give an idea that there is energy savings potential from PLC. Not enough documentation to show that PLC will have savings with their specific project.” The last two quotes indicate that it is not enough to have energy savings data for PLC. It is the breadth and scale of this data that is important, both duration (for at least one year) and variation so design engineers can evaluate savings potential for their specific project.

Funding was the third most common barrier theme, and was the most common barrier for building owners, with Split-Incentive coming up most frequently. This sub-theme references the well-documented split-incentive problem in traditional commercial building leases where one party has the capacity to make capital/energy efficiency improvements to the building, and the other pays the utility bills and therefore receives any energy savings benefits. One study participant explains this problem exactly: “Owners see no benefit from energy efficiency projects. All the savings are passed to the tenants.” When asked about their barriers to PPL efficiency and control implementation, a technology company participant simply stated, “Split incentives between landlords and tenants.”

The Stakeholder support sub-theme under Company Goals was mentioned commonly. Quotes in this theme and sub-theme refer to barriers from lack of support of key building stakeholders, with the majority referring to IT departments and their impact on enabling low-power or sleep settings. One facility manager explained, “Given one of the top action items is computer and server rooms. [I] tried to get traction on this with IT, but there was zero interest,” adding “[I] would like IT to implement some energy efficiency measures such as putting computing equipment to sleep automatically. Right now, laptops are able to go to a black screen, but they don’t sleep or hibernate. If [I] try auto-set sleep, IT would ‘correct’ this [meaning turn the auto-sleep off].” A building owner said, “IT has control of putting computers and monitors to sleep and the network policies override individual settings.” Other study participants cited difficulties with getting multiple stakeholders aligned: “Too many hand-offs and involvement of multiple parties.” Another said, “[The] Sustainability Team would talk to building sites about traditional replacements, but for PPLs [they] would need to talk to Architecture Team and Technology Team. It’s a different subset of ownership with PPL decisions,” indicating that communication among different teams can be a challenge and barrier to PPL efficiency and control implementation.

Other common barriers mentioned by technology company study participants were Deferred Responsibility and Invasion of Space. Deferred responsibility refers to a lack of willingness of the parties involved in energy efficiency decisions to take ownership, leading to nothing being done. There are a variety of parties that are thought to have responsibility for PPL energy efficiency decisions per the study participants. Most common are building owners. One participant cited building owners’ expertise as a reason they play a role in energy efficiency: “Businesses who lease space use [the] space as a tool to do their business [and] don’t think about energy. They look to the owners as experts in operation." Another technology company participant said, "We feed data and analyses to the customer and their engineer(s), leaving the decisions to them."

Several study participants cited Invasion of Space as a key barrier to PPL controls. These participants said things like, "Frustration from occupants, especially private offices, feel like their space is being taken over from their control," and "People don't want their equipment messed with." According to these participants, occupants with private offices were especially likely to push back against the implementation of PPL control systems because they felt like the office space was their own.

Discussion

This qualitative study highlights the major factors affecting PPL energy efficiency and control adoption in U.S. commercial buildings. The job function of the participant directly relates to the drivers and barriers mentioned for wider adoption of PPL controls. In the Results section, we analyzed the driver and barrier mentions by participants using theme and sub-theme categorization. This analysis resulted in five pathways toward greater adoption of PPL efficiency and control, derived from the interviews and workshop: Case studies, Funding, Data, Codes, and Company goals. We discuss these pathways in the following subsections.

Pathways

Case studies

Uncertainty of savings was identified as a barrier to commercial building energy efficiency adoption by Hanus et al. (2018). This was also a significant barrier to PPL efficiency and control adoption we identified by speaking with study participants. One of the major pathways to address the barrier associated with the lack of available financial data is to conduct rigorous and widespread technology evaluations in real commercial buildings. Once installed, operated, and monitored, independent evaluators or measurement and verification (M&V) specialists should analyze the resulting data from these PPL technologies. Guidelines and M&V frameworks such as those from the International Performance Measurement and Verification Protocol (IPMVP) should be applied to accurately determine energy consumption and savings. To address the next set of awareness barriers and promote effective PPL efficiency solutions, evaluators should disseminate the assessed technical and financial data, operational best practices, and lessons learned. Conducting training sessions, imparting knowledge gained through successful case studies (written and webinar format), simple commissioning how-to guides, and control technology campaigns for various organizations can lead to awareness among the occupants and decision-makers.

Several studies we reviewed found occupant awareness and engagement to be a key factor in PPL energy reduction (Hafer et al., 2018; Kandt & Langner, 2019; Tekler et al., 2021; Zhang et al., 2018). From our interviews and the workshop, we found that because PPLs are a highly occupant-dependent end use, mere PPL control technology installation in a commercial building is not effective and requires decision-makers and occupants to learn how to work effectively with the technology to achieve maximum benefit. The performance expectancy and effort expectancy are not being communicated to the occupants. Including material for engaging and educating occupants in the case studies could address this barrier and result in successful implementation.

We did not find the type and features of the PPL control technologies to be a major factor in adoption – technology features were only mentioned once in the interviews. This emphasizes the importance of occupant awareness and engagement with the control technologies for uptake.

Increasing the number of available case studies on PPL efficiency and control implementations, as well as disseminating best practices, is essential to overcoming key barriers in the commercial building industry. By showcasing real-world examples and providing transparent data, these case studies can help reduce uncertainty around savings, enhance awareness, and promote broader adoption of PPL technologies across diverse building types.

Funding

Increasing funding opportunities, such as incentives and rebate programs, is critical to enabling the widespread adoption of PPL efficiency and control measures in commercial buildings. Multiple studies found availability of funding to be a significant factor for the implementation of commercial building efficiency technologies (Andrews & Krogmann, 2009; Hanus et al., 2018). In this study, we spoke with commercial building owners and occupants who mentioned there being a lack of funding for PPL control technology implementation. The split-incentive problem was a barrier identified by Andrews and Krogmann (2009) and Hanus et al. (2023). Participants in our study pointed to the split-incentive problem as a barrier to PPL efficiency and control adoption, as well. The split-incentive problem is a known issue in traditional commercial building lease structures that affects energy efficiency projects. A lot is being done to address the split-incentive problem, including green leases, and these efforts will help remove barriers for PPL efficiency and control implementation in commercial buildings. Green leasing, also known as energy-aligned, energy-efficient, or high-performance leasing, is the practice of equitably realigning the costs and benefits of energy and water efficiency investments for landlords and tenants (White et al., 2020).

Furthermore, increasing the availability of PPL-related incentives, including packaged incentives with other energy efficiency measures and rebate programs could help commercial buildings overcome these funding barriers, as well as promote implementations with favorable payback. This, in turn, will increase the number of available case studies.

Data

Literature shows there is a need for commercial building occupant data to inform and improve building design and modeling (Ahn & Park, 2016; Delzendeh et al., 2017). Beyond that, our study reveals that design and modeling will also benefit from comprehensive PPL baseline consumption data, and will be important for addressing the current data gaps that hinder the adoption of PPL efficiency and control measures. Several participants cited lack of available data as a barrier to PPL efficiency and control uptake. Participants mentioned that scarcity of quality and revised technical data available to designers and facility/sustainability managers often leads to excessive and overdesigned infrastructure. A rigorous compilation of updated PPL baseline and peak consumption for the U.S. commercial building stock could lead to the generation of the technical data needed for designers and building energy modelers. This accurate PPL load data can also help efficient design of other building end uses like HVAC and lighting.

Codes

Study participants focused on inclusion of PPL monitoring and reduction measures in commercial building energy codes as an important factor for driving widespread adoption of PPL control technologies and ensuring long-term energy efficiency in the sector. Participants mentioned codes and regulations as key drivers of getting various PPL control technologies into commercial buildings. While Hanus et al. also identified energy codes as a crucial factor for adoption of commercial building technologies, this insight is relatively novel in the context of PPL literature (Hanus et al., 2018).

Additionally, successful case studies with favorable financial performance will encourage code bodies to continue to include effective PPL monitoring and controls in energy codes.

Company goals

Company goals were mentioned as a key contributor to the success of PLM system implementation in commercial buildings, and companies should continue to establish goals related to energy efficiency and emissions reductions, such as ESG goals, SDGs, and emissions targets. Some study participants mentioned PPL efficiency and control implementation as being the responsibility of another stakeholder group, and that lack of implementation is the result of lack of action by the other stakeholders. This deferred responsibility can be influenced by gaining buy-in from key stakeholders and critical implementors (e.g., a building's cybersecurity and IT teams, electricians) through things like company goals. Additionally, establishing a PPL champion to initiate the PPL control and reduction procurement and implementation process can help get the necessary stakeholders on board.

Organizations with ESG goals, SDGs, and emissions targets and/or strong culture around environmental stewardship may be early adopters of PPL efficiency and control technologies and strategies. These buildings may be best suited to generate initial case studies that can help members of the early majority and late majority adopter categories make the business case for implementation. Additionally, effectively communicating these goals to employees and building occupants can create the social influence needed to promote proper engagement with the technology or strategy.

Limitations and future work

This study has limitations that should be acknowledged. First, the number of participants involved in the research was limited, which may affect the generalizability of the findings. A larger sample size would provide more robust insights into the effectiveness and adoption of PPL efficiency measures across diverse commercial buildings.

Second, the study included input from three building occupants, and did not include input from other several key stakeholder groups, such as utilities, codes and standards organizations, and community organizations. The absence of these perspectives may have resulted in an incomplete understanding of how PPL efficiency and control measures can be adopted and supported across various sectors.

Additionally, the study is subject to self-selection bias, as participants were not randomly selected but rather opted into the research voluntarily. This may have resulted in a participant pool that is more engaged or informed about energy efficiency measures than the broader population, potentially skewing the findings toward more favorable views on PPL technologies and policies.

Lastly, our study concentrated on the adoption of PPL efficiency and control measures in U.S. commercial buildings. In other regions, variations in infrastructure, occupant behavior, and PLM practices may lead to different outcomes, potentially limiting the applicability of our findings in an international context. This work could be expanded by including a more diverse participant base, and considering adoption pathways outside of the U.S.

Conclusion

In this study, we examined the current state of the market, and identified drivers, barriers, and pathways to more widespread PPL efficiency and control uptake. Based on the interviews with 44 commercial building stakeholders, we present the following pathways for achieving increased PPL efficiency and control uptake:

- Case studies: Increasing available PPL efficiency and control implementation case studies and disseminating best practices across the commercial building industry.
- Funding: Increasing funding opportunities to implement PPL efficiency and control, such as incentives and rebate programs.
- Data: Compiling PPL baseline consumption data en masse for the whole U.S. commercial building stock.
- Codes: Continuing to include PPL monitoring and reduction measures in commercial building energy codes.
- Company goals: Promoting adoption of company goals, including but not limited to, ESG, SDG, and emissions targets.

Although some outcomes may seem intuitive or expected, the study's focus on PPL efficiency and control remains an underresearched area. By documenting these findings, we highlight new insights into how various pathways can facilitate broader adoption of PPL technologies. This is crucial for advancing the field and providing actionable recommendations for stakeholders.

The study does have limitations, including a relatively small sample size, limited input from key stakeholder groups, and self-selection bias which may affect the generalizability of the findings. Furthermore, the focus on U.S. commercial buildings may limit the applicability of the results in other regions with different infrastructure and practices.

Future research should aim to include a broader and more diverse participant base, incorporate perspectives from additional stakeholder groups, and explore adoption pathways in different international contexts. Expanding this work will contribute to a more comprehensive understanding of PPL efficiency and control adoption and support the development of strategies to achieve energy efficiency and emissions reduction goals on a global scale.

Appendix A Interview Questions

Italicized text indicates a follow-up question.

A.1 Building Occupant

1. Please describe your company and your role at your company.
   What type of building do you work in?
2. Are you thinking about your impact to the building's energy use? Why, or why not?
3. What kinds of plug and process loads do you interact with in your building?
4. How might you, as an occupant, influence a building's plug and process load energy use?
5. How would you reduce the energy use of plug and process loads in your building?
6. Are you making any of these choices now? Why, or why not?
7. What is currently encouraging you, or what would encourage you, to reduce a building's plug and process load energy?
8. What is preventing you from reducing a building's plug and process load energy?
9. Is there any other information that you would like us to know?

A.2 Building Owner

1. Please describe your role in your company.
   Please describe the company you work for - size, location, clients.
   How long have you been in this role?
2. What is your approach to energy efficiency in your building(s)?
   What is your company's approach to energy efficiency in your buildings?
3. What are your company's goals related to energy efficiency?
   How are you planning on achieving these goals?
4. What strategies are you implementing to reduce your energy bill?
5. What kinds of plug and process loads do you have in your building(s), and do you monitor their energy use?
6. How would you reduce the energy use of your plug and process loads?
7. Are you implementing any of these strategies now? Why, or why not?
8. Do you have plans to implement any other strategies in the future? Why, or why not?
9. What is encouraging, or what would encourage, you to reduce your building's plug and process load energy?
10. What is preventing you from reducing your building's plug and process load energy?
11. Are there any other projects you're aware of or other people we should talk to in this space?
12. Is there any other information that you would like us to know?

A.3 Design Engineer

1. Please describe your role at your company.
   Please describe the company you work for - size, location, clients.
   How long have you been in this role?
2. What types of buildings does your company design?
3. To what extent do you consider energy efficiency in your design process?
4. Who decides how important energy efficiency is to a project? The client, design engineer, design company, etc.
   Do the designers try to encourage the client to pursue higher energy efficiency?
   Is the client presented with information or data to help them make these decisions?
5. To what extent do you consider plug and process loads in your design process?
   Has this changed throughout your career? If so, why has it changed?
6. What plug and process load reduction strategies or technologies have been implemented in the buildings you have designed?
   What feedback have you received from the building(s) about these strategies and technologies?
7. What is encouraging, or what would encourage, design engineers to reduce a building's plug and process load energy?
8. What is preventing design engineers from reducing a building's plug and process load energy?
9. Are there other projects you're aware of or other people we should talk to who are working in this space?
10. Is there any other information that you would like us to know?

A.4 Facility Manager

1. Please describe your company and your role at your company.
   Please describe the company you work for - size, location, clients.
   How long have you been in this role?
2. What are your company's goals related to energy efficiency?
   How are you planning on achieving these goals?
3. What is your approach to energy efficiency in your building(s)?
4. What strategies are you implementing to reduce your energy bill?
5. What kinds of plug and process loads do you have in your building(s), and do you monitor their energy use?
6. How would you reduce the energy use of your plug and process loads?
7. Are you implementing any of these strategies now? Why, or why not?
8. Do you have plans to implement any other strategies in the future? Why, or why not?
9. What is encouraging, or what would encourage, you to reduce your building's plug and process load energy?
10. What is preventing you from reducing your building's plug and process load energy?
11. Are there any other projects you're aware of or other people we should talk to in this space?
12. Is there any other information that you would like us to know?

A.5 Lighting Designer

1. Please describe your company and your role at your company.
   Please describe the company you work for - size, location, clients.
   Who are your clients (design firms, building owners, etc.)?
   How long have you been in this role?
2. What types of buildings does your company design for?
   Do you primarily provide designs for retrofits or new construction?
3. What lighting technologies do you include in your designs?
   What considerations do you make when selecting a technology for a particular project?
4. What plug load management technologies do you include in your designs?
   If none currently, do you have plans to add PLM technologies? Why or why not?
   What feedback have you received from your clients about these technologies?
5. Have you designed integrated lighting and plug load control systems?
   Who decided to pursue the integration? The client, the design engineer, the design firm, etc.
   Can you tell us about your experience with this design?
6. Have clients shown interest in plug load control systems?
7. Are there plug load management system projects you're aware of or other people we should talk to who are working in this space?
8. Is there any other information that you would like us to know?

A.6 Lighting Technology Company

1. Please describe your company and your role at your company.
   Please describe the company you work for - size, location, clients.
   How long have you been in this role?
2. What lighting control products do you sell?
   Which products are most popular?
3. How many buildings are your products in around the country?
4. What do you consider when developing new products?
   What customers do you consider when developing new products?
5. What plug load control products do you sell?
   If none currently, do you have plans to add PLC products? Why or why not?
6. What is your experience with plug load control systems?
   Have your lighting control products been integrated with plug load control systems?
7. What are the drivers of plug load control technology adoption?

8. What is preventing adoption of plug load control technologies?
9. Are there plug load management system projects you're aware of or other people we should talk to who are working in this space?
10. Is there any other information that you would like us to know?

A.7 Sustainability Manager

1. Please describe your role in your company.
Please describe the company you work for - size, location, clients.
How long have you been in this role?
2. What is your approach to energy efficiency in your building(s)?
What is your company's approach to energy efficiency in your buildings?
3. What are your company's goals related to energy efficiency?
How are you planning on achieving these goals?
4. What strategies are you implementing to reduce your energy bill?
5. What kinds of plug and process loads do you have in your building(s), and do you monitor their energy use?
6. How would you reduce the energy use of your plug and process loads?
7. Are you implementing any of these strategies now? Why, or why not?
8. Do you have plans to implement any other strategies in the future? Why, or why not?
9. What is encouraging, or what would encourage, you to reduce your building's plug and process load energy?
10. What is preventing you from reducing your building's plug and process load energy?
11. Are there any other projects you're aware of or other people we should talk to in this space?
12. Is there any other information that you would like us to know?

A.8 Sustainability Program Manager

1. Please describe your organization and your role at your organization.
Please describe the organization you work for - size, location, clients. How long have you been in this role?
2. What are your organization's goals related to energy efficiency?
How are you planning on achieving these goals?
3. What buildings do you oversee as part of your program?
How many buildings? What types of buildings?
4. What is your organization's approach to energy efficiency in these building(s)?
5. What plug and process load energy efficiency policies are implemented in these building(s)?
6. Do you have plans to implement plug and process load energy efficiency policies in the future? Why, or why not?
7. What is encouraging, or would encourage, you to target plug and process load energy reductions in your building(s)?
8. What is preventing you from targeting plug and process load energy reductions in your building(s)?
9. Are there any other projects you're aware of or other people we should talk to in this space?
10. Is there any other information that you would like us to know?

A.9 Technology Company

1. Please describe your role at your company.
Please describe the company you work for - size, location, clients.
How long have you been in this role?
2. What plug load management products do you sell?
3. How many buildings are your products in around the country?
4. What building types are your products in?
5. Are there certain building types that your products are best suited for?
6. What customers do you consider when developing your products?
7. To what extent do you consider small to medium buildings and/or disadvantaged communities in your product development process?
8. Can you describe the system procurement and installation process?
About how long does the process take?
9. What feedback, if any, have you received from building owners or facility managers about your products?

10. Are there plug load management system projects you're aware of or other people we should talk to who are working in this space?
11. Is there any other information that you would like us to know?

Appendix B Workshop Questions

1. What is your experience with commercial building plug and process loads (PPLs)?

2a What are your approaches for managing commercial building PPLs?

2b What are your industry peers doing to manage commercial building PPLs?

3 What is your experience with the following aspects of commercial building PPLs? Post a sticky note with your name under the category(ies) that apply to you and briefly describe your experience.

   (a) Monitoring
   (b) Management Policies
   (c) Control Technology
   (d) Energy Efficient Procurement

4 How do you decide the priorities on energy-efficient retrofits in your facility? Where are PPLs on your list of priorities?

5 What have been the barriers and drivers for commercial building PPL efficiency and control for you?

6 What feedback have you received from your stakeholders about PPL control technologies and management strategies?

7 Describe the impacts of commercial building codes and incentives on your PPL approach.

Acknowledgements The authors would like to thank the study participants for their time and thoughtful responses. Thank you also to the National Renewable Energy Laboratory (NREL) communications center for their editing and publishing support.

Author contributions Research contributions of the authors are as follows: Conceptualization, A.V., K.T.; Investigation, A.V., O.G., R.T., K.T.; Methodology, A.V., O.G., R.T., K.T.; Formal Analysis, A.V., O.G.; Visualization, A.V., O.G.; Writing—Original Draft, A.V., O.G.; Writing—Review and Editing, R.T., K.T. All authors have read and agreed to the published version of the manuscript.

Funding Information Open access funding provided by National Renewable Energy Laboratory Library. This work was authored by the National Renewable Energy Laboratory, operated by Alliance for Sustainable Energy, LLC, for the U.S. Department of Energy (DOE) under Contract No. DE-AC36- 08GO28308. Funding provided by the U.S. Department of Energy Office of Energy Efficiency and Renewable Energy Building Technologies Office. The views expressed in the article do not necessarily represent the views of the DOE or the U.S. Government. The U.S. Government retains and the publisher, by accepting the article for publication, acknowledges that the U.S. Government retains a nonexclusive, paid-up, irrevocable, worldwide license to publish or reproduce the published form of this work, or allow others to do so, for U.S. Government purposes.

Availability of Data and Materials No data is available for this work.

Code Availability No code was developed for this work.

Declarations

Competing Interests The authors have no competing interests to declare that are relevant to the content of this article.

Ethics Approval Ethics approval was not required for this study. This was not human subjects research.

Consent to Participate This research was not human subjects research.

Consent for Publication This research was not human subjects research.

References

Ahn, K.-U., & Park, C.-S. (2016). Correlation between occupants and energy consumption. *Energy and Buildings, 116*, 420–433. https://doi.org/10.1016/j.enbuild.2016.01.010. Accessed 18 March 2024

Andrews, C. J., & Krogmann, U. (2009). Explaining the adoption of energy-efficient technologies in U.S. commercial buildings. *Energy and Buildings 41*(3), 287–294. https://doi.org/10.1016/j.enbuild.2008.09.009. Accessed 26 Sept 2023

Bird, S., & Hernández, D. (2012). Policy options for the split incentive: Increasing energy efficiency for low-income renters. *Energy policy, 48*, 506–514. https://doi.org/10.1016/j.enpol.2012.05.053. Accessed 18 March 2024

Björklund, M., Malmborg, F., & Nordensvärd, J. (2023). Lessons learnt from 20+ years of research on multilevel governance of energy-efficient and zero-carbon buildings in the European Union. *Energy Efficiency, 16*(8), 98. https://doi.org/10.1007/s12053-023-10178-6. Accessed 18 March 2024

Chia, K., LeBar, A., Agarwal, V., Lee, M., Ikedo, J., Wolf, J., Trenbath, K., & Kleissl, J. (2023). Integration of a Smart Outlet-Based Plug Load Management System with a Building Automation System. In: *2023 IEEE PES Grid Edge Technologies Conference & Exposition (Grid Edge)*, (pp. 1–5) https://doi.org/10.1109/GridEdge54130.2023.10102749. https://ieeexplore.ieee.org/document/10102749 Accessed 18 Jan 2024

Cowan, K., & Daim, T. (2013). Adoption of Energy Efficiency Technologies: A Review of Behavioral Theories for the Case of LED Lighting. In: T. Daim, T. Oliver, & J. Kim (Eds.), *Research and Technology Management in the Electricity Industry: Methods, Tools And Case Studies*, (pp. 229–248). Springer, London. https://doi.org/10.1007/978-1-4471-5097-8_10. Accessed 2024-03-26

Davalos, P., Albright, M., Yoder, B., Miller, J., Rose, R., & Sanders, D. (2020). Intelligent Building Management with Holistic Digital Lighting. Technical Report EW-201720, ESTCP. https://apps.dtic.mil/sti/pdfs/AD1135270.pdf Accessed 18 Jan 2024

Delzendeh, E., Wu, S., Lee, A., & Zhou, Y. (2017). The impact of occupants' behaviours on building energy analysis: A research review. *Renewable and Sustainable Energy Reviews, 80*, 1061–1071. https://doi.org/10.1016/j.rser.2017.05.264. Accessed 18 March 2024

Earle, L., & Sparn, B. (2012). Results of Laboratory Testing of Advanced Power Strips. Technical Report NREL/CP–5500-55162, 1219753, 5913 https://doi.org/10.2172/1219753 . https://www.osti.gov/servlets/purl/1219753/ Accessed 18 Jan 2024

U.S. Energy Information Administration. (2023). U.S. Energy Information Administration Annual Energy Outlook, Table 18. https://www.eia.gov/outlooks/aeo/data/browser/#/?id=17-AEO2023&cases=ref2023&sourcekey=0 Accessed 17 Jan 2024.

U.S. Energy Information Administration. (2024). Monthly Energy Review January 2024: Energy Consumption: Residential, Commercial, and Industrial Sectors https://www.eia.gov/totalenergy/data/monthly/pdf/sec2_4.pdf Accessed 30 Jan 2024.

U.S. Energy Information Administration. (2023). Use of energy in commercial buildings. https://www.eia.gov/energyexplained/use-of-energy/commercial-buildings.php Accessed 30 Sept 2023.

Glaser, B. G., & Strauss, A. L. (1967). *The Discovery of Grounded Theory: Strategies for Qualitative Research*. New York, NY: Aldine de Gruyter.

Hafer, M., Howley, W., Chang, M., Ho, K., Tsau, J., & Razavi, H. (2018). Occupant engagement leads to substantial energy savings for plug loads. *2017 IEEE Conference on Technologies for Sustainability, SusTech 2017 2018-Janua*, 1–6. https://doi.org/10.1109/SusTech.2017.8333475

Hanus, N., Newkirk, A., & Stratton, H. (2023). Organizational and psychological measures for data center energy efficiency: barriers and mitigation strategies. *Energy Efficiency, 16*(1), 1. https://doi.org/10.1007/s12053-022-10078-1. Accessed 18 March 2024

Hanus, N., Wong-Parodi, G., Small, M. J., & Grossmann, I. (2018). The role of psychology and social influences in energy efficiency adoption. *Energy Efficiency, 11*(2), 371–391. https://doi.org/10.1007/s12053-017-9568-6. Accessed 19 Dec 2023

Integrated Controls for Plug Loads and Lighting Systems. (2022). Technical Report PNNL-32670 https://betterbuildingssolutioncenter.energy.gov/sites/default/files/attachments/ILC_Case_Studies_MnDOT.pdf

Jenkins, C., Young, R., Tsau, J., Razavi, H., Kaplan, J., & Ibeziako, M. A. O. (2019). Effective management of plug loads in commercial buildings with occupant engagement and centralized controls. *Energy and Buildings, 201*, 194–201. https://doi.org/10.1016/j.enbuild.2019.06.030. Publisher: Elsevier Ltd

Joint Research Centre (European Commission), Castellazzi, L., Bertoldi, P., & Economidou, M. (2017). Overcoming the Split Incentive Barrier in the Building Sector: Unlocking the Energy Efficiency Potential in the Rental & Multifamily Sectors. Publications Office of the European Union, ??? https://data.europa.eu/doi/10.2790/912494 Accessed 26 March 2024

Kandt, A. J., & Langner, M. R. (2019). Plug Load Management System Field Study. Technical report, Golden, CO (United States). https://doi.org/10.2172/1495720. https://www.nrel.gov/docs/fy19osti/72028.pdf

Karjalainen, S. (2016). Should we design buildings that are less sensitive to occupant behaviour? A simulation study of effects of behaviour and design on office energy consumption. *Energy Efficiency, 9*(6), 1257–1270. https://doi.org/10.1007/s12053-015-9422-7. Accessed 18 March 2024

Karjalainen, S., & Koistinen, O. (2007). User problems with individual temperature control in offices. *Building and Environment, 42*(8), 2880–2887. https://doi.org/10.1016/j.buildenv.2006.10.031. Accessed 18 March 2024

Miller, S. R. (2010). Commercial Green Leasing in the Era of Climate Change: Practical Solutions for Balancing Risks, Burdens, and Incentives. *Environmental Law Reporter News & Analysis, 40*, 10487.

Mills, E. (2022). Market spoiling and ineffectual policy have impeded the adoption of heat pump water heating for US buildings and industry. *Energy Efficiency, 15*(4), 23. https://doi.org/10.1007/s12053-022-10029-w. Accessed 18 March 2024

Outcault, S., Sanguinetti, A., & Nelson, L. (2022). Technology characteristics that influence adoption of residential distributed energy resources: Adapting Rogers' framework. *Energy Policy, 168*, 113153. https://doi.org/10.1016/j.enpol.2022.113153. Accessed 26 March 2024

Paone, A., & Bacher, J.-P. (2018). The Impact of Building Occupant Behavior on Energy Efficiency and Methods to Influence It: A Review of the State of the Art. *Energies, 11*(4), 953. https://doi.org/10.3390/en11040953. Number: 4 Publisher: Multidisciplinary Digital Publishing Institute. Accessed 18 March 2024

Papagiannidis, S., & Marikyan, D. (2020). Smart offices: A productivity and well-being perspective. *International Journal* *of Information Management, 51*, 102027. https://doi.org/10.1016/j.ijinfomgt.2019.10.012. Accessed 26 Sept 2023

Rogers Everett, M. (1962). *Diffusion of Innovations*. New York, NY: Free Press.

Rosenow, J., Fawcett, T., Eyre, N., & Oikonomou, V. (2016). Energy efficiency and the policy mix. *Building Research & Information, 44*(5–6), 562–574. https://doi.org/10.1080/09613218.2016.1138803. Publisher: Routledge_eprint: Accessed 18 March 2024

Schwartz, E. K., & Krarti, M. (2022). Review of Adoption Status of Sustainable Energy Technologies in the US Residential Building Sector. *Energies, 15*(6), 2027. https://doi.org/10.3390/en15062027. Number: 6 Publisher: Multidisciplinary Digital Publishing Institute. Accessed 26 March 2024

Shen, L., He, B., Jiao, L., Song, X., & Zhang, X. (2016). Research on the development of main policy instruments for improving building energy-efficiency. *Journal of Cleaner Production, 112*, 1789–1803. https://doi.org/10.1016/j.jclepro.2015.06.108. Accessed 18 March 2024

Tekler, Z. D., Low, R., Choo, K. T. W., & Blessing, L. (2021). User Perceptions and Adoption of Plug Load Management Systems in the Workplace. In: *Extended Abstracts of the 2021 CHI Conference on Human Factors in Computing Systems*, (pp. 1–6). ACM, Yokohama Japan. https://doi.org/10.1145/3411763.3451726. https://dl.acm.org/doi/10.1145/3411763.3451726 Accessed 26 Sept 2023

Trenbath, K., Doherty, B., Vrabel, K., & Burke, C. (2020). Emerging Technologies for Improved Plug Load Management Systems: Learning Behavior Algorithms and Automatic and Dynamic Load Detection. In: *Summer Study on Energy Efficiency in Buildings*. https://betterbuildingssolutioncenter.energy.gov/sites/default/files/attachments/ACEEE_2020_Plug_Load_Mgmt_Paper.pdf

Vaughan, E., & Turner, J. (2013). The Value and Impact of Building Codes. Technical report, Environmental and Energy Study Institute https://www.eesi.org/papers/view/the-value-and-impact-of-building-codes Accessed 26 March 2024

Venkatesh, V., Morris, M. G., Davis, G. B., & Davis, F. D. (2003). User Acceptance of Information Technology: Toward a Unified View. *MIS Quarterly, 27*(3), 425–478. https://doi.org/10.2307/30036540. Publisher: Management Information Systems Research Center, University of Minnesota. Accessed 26 March 2024

White, A., Kirby, A., Debelius, H., Duncan, J., & Gahagan, R. (2020). New Leasing Languages - How Green Leasing Programs Can Help Overcome the Split Incentive. In: *Summer Study on Energy Efficiency in Buildings*. https://www.imt.org/wp-content/uploads/2020/08/ACEEE-Summer-Study-2020-Final-Paper.pdf

Zhang, Y., Bai, X., Mills, F. P., & Pezzey, J. C. V. (2018). Rethinking the role of occupant behavior in building energy performance: A review. *Energy and Buildings, 172*, 279–294. https://doi.org/10.1016/j.enbuild.2018.05.017. Accessed 26 Sept 2023