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A Commercial Building Plug Load Management System That Uses Internet of Things Technology to Automatically Identify Plugged-In Devices and Their Locations

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***Abstract*—**Plug and process loads (PPLs) account for a large portion of U.S. commercial building energy use. There is a huge potential to reduce whole building consumption by targeting PPLs for energy savings measures or implementing some form of plug load management (PLM). Despite this potential, there has yet to be a widely adopted commercial PLM technology. This paper describes the Automatic Type and Location Identification System (ATLIS), a PLM system framework with automatic and dynamic load detection (ADLD). ADLD gives PLM systems the ability to automatically identify devices as they are plugged into the outlets of a building. The ATLIS framework takes advantage of smart, connected devices to identify device locations in a building, meter and control their power, and communicate this information to a central database. ATLIS includes five primary capabilities: location identification, communication, control, energy metering, and data storage. A laboratory proof of concept (PoC) demonstrated all but the energy metering capability, and these capabilities were validated using a series of system tests. The PoC was able to identify when a device was plugged into an outlet and the location of the device in the building. When a device was moved, the PoC's dashboard and database were automatically updated with the new location. The PoC implemented controls to devices from the system dashboard so that devices maintained correct schedules regardless of where they were plugged in within the building. ATLIS's primary technology application is improved PLM, but other applications include asset management, energy audits, and interoperability for grid-interactive efficient buildings. An ATLIS-based system could also be used to direct power to critical devices, such as ventilators, during a brownout or blackout. Such a framework is an opportunity to make PLM more widespread and reduce the amount of energy consumed by PPLs in current and future commercial buildings.

***Keywords*—**Commercial buildings, grid-interactive efficient buildings, miscellaneous electric loads, plug loads, plug load management.

I. INTRODUCTION

PPLs include all plugged-in and hardwired electronic devices that are not associated with other major building end uses such as heating, cooling, ventilation, and lighting. According to the U.S. Energy Information Administration's Annual Energy Outlook, PPLs account for 47% of the energy consumed in U.S. commercial buildings, and that portion is expected to increase [1]. As a result, there is growing interest in managing PPLs, a challenging proposition given there can be thousands of PPL devices, each serving a unique function, dispersed throughout large commercial buildings. PPL metering and control solutions exist today, though they have not been widely adopted. One such solution, "smart outlets," can be installed at the electrical outlets of a building either as plug-through receptacles or embedded into the outlets themselves. Typically, a smart outlet measures the power consumption of the device that is plugged into it and transmits those data wirelessly to a central dashboard. From this dashboard, building managers can view the data and turn devices on or off by controlling whether electricity can flow to the devices via the smart outlets.

Although there is huge potential to reduce whole building energy consumption by implementing PLM, there has yet to be a widely adopted PLM technology. A challenge with many smart outlet-based systems is that their installation often requires the labor-intensive process of manually recording which device is plugged in to each smart outlet. These systems are not able to identify the location of devices that are moved around in daily use or when spaces are reconfigured. If the smart outlets are not checked regularly after installation, the system can become outdated as devices are moved. If the system is not kept up to date, there is the risk that devices will be controlled in a potentially disruptive or unsafe manner due to outdated control schedules. Additionally, these outdated schedules can cause frustration among occupants because they cannot use their electronic devices when they need them [2].

The principal aim of this work is to explore a PLM technology that would address these challenges, promote PLM system uptake, and clarify how this technology could be implemented in a PLM system. The work was guided by the following research question: How can a PLM system automatically identify the location, energy use, and operating state of every device in a commercial building so that (1) controls can be automatically applied, and (2) labor hours required for setup and maintenance can be minimized?

This paper presents a PLM system framework: the Automatic Type and Location Identification System (ATLIS). This paper describes ATLIS and its capabilities, provides a laboratory PoC, and describes its potential applications in current and

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future commercial building systems.

II. Background

ADLD has been identified as a technology with the potential to significantly reduce the labor required to manage PLM systems [3]. With ADLD, the PLM system automatically identifies devices as they are plugged into the outlets of a building. Trenbath et al. [4] describe two approaches to ADLD, namely *implicit identification*, where device identities are inferred based on their measured electrical consumption patterns, and *explicit identification*, where device identities are communicated directly. The explicit identification method can identify devices with certainty, which is important when applying controls to a building with a broad range of devices.

Trenbath et al. [4] reviewed eight publications that included research studies and patents related to explicit identification. They found that the most common approach to explicit identification included a tag on the device plug that identifies the device and a tag reader at the outlet that can read the device's identity when it is plugged in [5]-[8]. In most instances, the outlets could communicate device identities to a central management system. For the tags and readers, the most frequently used technology was radio frequency identification (RFID). Other approaches include short distance communication protocols such as near field communication, which is a subset of RFID technology that would allow for dynamic information communication, and direct electrical connections that pass information from a device to an outlet. Although these ADLD technologies are conceptualized, none of the explicit identification technologies are available for commercial building applications.

Another relevant area of recent technology development is the Internet of Things (IoT). IoT, the ability of devices to send and receive data via the internet [9], has redefined what it means for a device to be "modern." Ten years ago, a television was simply a visual display for a cable box and a refrigerator was a chest in which to keep food cold. Today, smart (IoT-connected) televisions can stream content and browse the internet directly, and smart refrigerators can place online orders automatically. The IoT is growing rapidly, allowing more devices to be monitored and controlled remotely [10].

In the residential building sector, there are commercialized smart home management systems that connect to IoT devices such as lighting, thermostats, appliances, and even plug loads. Homeowners can control their devices from a central command system such as Google Home™ [11], Apple HomeKit® [12], or Amazon Alexa© [13]. These capabilities have not yet been translated to commercial building energy management systems.

The lack of a full-scale IoT-connected commercial building PLM system is largely due to complexities that arise when attempting to scale up residential systems. Compared to residential buildings, commercial buildings typically have orders of magnitude more occupants with varying needs and expectations for comfort, lighting level, and service level of electronic equipment. Additionally, commercial buildings contain many more devices and device types that need to be managed. Therefore, building-wide energy management rules are more difficult to implement within commercial buildings.

A critical consideration in any PLM system is energy metering. Current systems use external meters at the device or circuit level in the form of smart outlets and submeters. However, with the growth of IoT and smart devices, this metering can be done by the devices themselves. Nordman et al. [14] investigated device energy reporting by exploring how 12 different devices could self-report their energy consumption. Some of the devices were equipped with energy metering hardware whereas others already measured power consumption internally and were modified with software to access that information. With some devices already capable of energy metering and with ongoing work to develop small profile meters such as PowerBlade [15], self-reporting devices are becoming far more feasible.

This IoT growth is an opportunity to develop commercial building PLM solutions that take advantage of the devices themselves becoming smarter. A smart device could not only self-report its energy consumption [14], but also record other important information such as device health as well as offering access to advanced controls. For example, they could access different device energy states—standby, for instance—and allow a device to determine the safest way for it to enter a specified state. To illustrate, when instructed to power down at the end of the day, a projector could follow its own process to ensure that it powers down safely. This increase in communicated information could also be valuable for asset management. For example, information technology, audiovisual, and sourcing professionals could gain a clearer understanding of how devices are used and be able to make better-informed decisions when purchasing new equipment.

III. System Framework Overview

ATLIS is a commercial building PLM system framework that uses smart, IoT-connected devices to manage device energy use. During system installation, RFID tags will be placed at every outlet, and the outlet locations will be logged in the system. Additionally, each device will have an RFID reader at its plug to read the outlet tags. When a device is plugged in to an outlet, it automatically registers itself in the system. If the device is moved and plugged into a different outlet, the system registers the new location of the device and maintains whatever controls were associated with the device. For example, if a coffee maker is moved to a different outlet in an office kitchen, its associated controls will follow the device and it will maintain regular operation, regardless of what had been previously plugged in to that outlet. Building operators and managers can apply controls to the devices via a system dashboard.

The ATLIS framework includes five main capabilities: location identification, communication, control, energy metering, and data storage. The ATLIS framework is unique in that it takes advantage of smart, IoT-connected devices to handle four of these five capabilities through the devices themselves, with data storage handled externally (energy use data are stored in a database, not on the devices). Another unique capability of an ATLIS-based system is that once set up

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in a commercial building, the system will automatically identify specific plug-in devices and know their locations so that the device's unique control schedule can be applied no matter where it is in the building.

The ATLIS framework consists of six key elements: an RFID tag at the outlet; an RFID reader on the device plug; smart, IoT-connected devices; a central control hub; a system dashboard; and a database. Fig. 1 provides a high-level diagram of the ATLIS workflow including the capabilities handled by each element. The device pulls the RFID tag ID number from the RFID reader on its plug to determine its location when it is plugged into an outlet. This information, along with the device type, energy consumption, and operating state, is passed from the device to the system dashboard and database through a central control hub. The system dashboard allows users to visualize real-time and historical data and administer controls. Control signals are sent through the central control hub to the corresponding device to implement the control. The central control hub coordinates processes, communication, and controls on the ATLIS framework and can communicate wirelessly with devices.

The following sections provide greater detail on each of the five capabilities of the ATLIS framework.

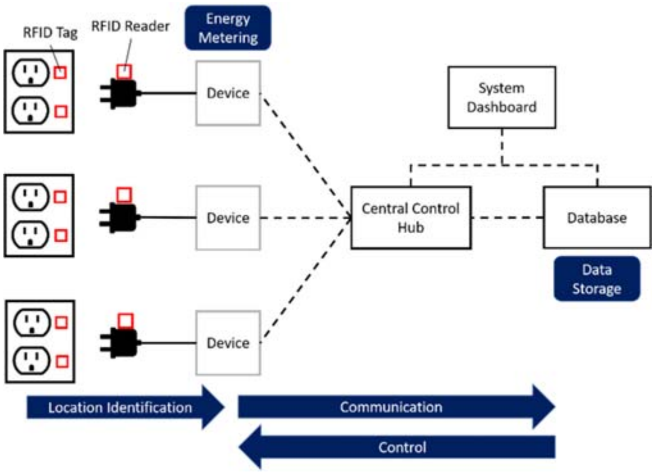

Fig. 1 Diagram of the ATLIS framework workflow. The PLM system has the RFID tag numbers saved so that it can associate them with a location in the building

A. Capabilities

i. Location Identification

The ATLIS framework uses RFID technology to keep track of where devices are plugged into a building. Each outlet contains a passive RFID tag, either added to the outlets when the system is installed or embedded directly into the outlet wall plate. Each RFID tag has a unique identification (UID) number that is transmitted upon scanning. During the PLM system installation, each tag is scanned, associating the UID numbers with specific locations and circuits in the building. Devices have RFID readers at their plug to read the tag. When plugged in, the reader reads the UID number, the device passes it to the central control hub, and the system then knows which outlet the device is plugged into and its location within the building. A device ID number is assigned to each device when it is initially plugged in. Device controls are also attached to this ID number. This ID number follows the device as it is moved throughout the building, which allows for up-to-date measurement data and control implementation. Although this methodology still requires up-front labor in establishing the location corresponding to each UID, the setup time can be reduced because the system will automatically register which devices are plugged in to each outlet. Additionally, the system will adapt as devices are moved around or spaces are reconfigured in the building. This will keep device locations within the PLM system updated and save significant maintenance time in the long term.

ii. Communication

As more internet-connected devices come on the market, the opportunity to have the devices communicate to a central control hub becomes more accessible. The ATLIS framework's communication capability is handled by the devices, the central control hub, and the system dashboard. Enabling the devices to communicate directly, rather than via smart outlets, allows for communication of both static (e.g., device type, brand, model) and dynamic (e.g., power, operating state, location) information. This information can be far more granular than in implicit systems, which often can only identify general device types for larger loads and relatively simple operating states. Using the devices to communicate also removes the uncertainty often associated with implicit systems in determining this information. Improving both the granularity and accuracy of the information passed to the PLM system allows for more effective asset management and control.

Within the ATLIS framework, devices communicate with the central control hub, which includes wireless communication capabilities such as a wireless router. At regular intervals (e.g., every 15 seconds), each plugged-in device sends an update to the central control hub. The device will send its dynamic and static data to be displayed on the dashboard and stored in the database.

The proposed communication process assumes devices are plugged into an alternating current (AC) wall outlet, which requires information to be transmitted wirelessly. However, wired alternatives exist, such as universal serial bus (USB) and power over ethernet (PoE). These technologies transmit both power and data in the same connection. PoE is a common technology for powering network equipment and voice over internet protocol phones, and it is being expanded to power more types of devices at higher voltages [16], [17]. Additionally, many consumer electronics—mobile phones, cameras, and laptops, for example—are powered via USB connections. These devices typically have power supplies that convert from the AC building distribution electricity to direct current (DC) for the USB connection. Many wall outlets are available today that have a USB connection embedded directly in the outlet [18], [19]. With growing interest in the potential benefits of DC distribution within buildings [20] and with increasing standardization of USB connections for devices, it is likely that these power delivery methods will become more

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common in buildings. Future work could investigate how PoE and USB could be integrated into an ATLIS-based system and how their data transfer capabilities could benefit the system.

iii. Control

As the IoT becomes more prevalent, more devices will be controllable and more operating states will be accessible by sending control signals directly to devices. Like communication, this capability is handled by the system dashboard, central control hub, and the devices themselves. Rather than controlling the flow of electricity to a device using a smart outlet, an ATLIS-based system can instruct a device to enter a specific operating state, such as low-power mode. Controls are administered as schedules or commands entered by the user into the dashboard, and then aggregated and communicated to the devices through the central control hub. The controls could also be triggered by sensors within a space, such as occupancy sensors. This method of administering controls reduces the conflict between energy savings and occupant disruption that often plagues binary (on/off) controls [2]. It also allows more devices to be safely controlled, including ones to which binary controls cannot normally be applied. Going back to the example mentioned in the background section, projectors are typically excluded from PLM systems because abruptly cutting a projector's power can damage it. With an ATLIS-based system, a projector could automatically receive signals to begin its shutdown process and power itself down safely.

iv. Energy Metering

One of the primary functions of a PLM system is to meter energy consumption of a plugged-in device. Device power consumption can be used to identify PPLs with unnecessarily high energy use and those that are good candidates for controls. Within the ATLIS framework, this capability is handled by the devices themselves. Some electronic devices already have the ability to self-meter, such as mobile (battery) devices, PoE devices, and power strips [14]. More devices are expected to be self-metering as the IoT grows. An ATLIS-based system will take advantage of this self-metering functionality and IoT communications to report device energy use to the system dashboard and database.

v. Data Storage

Access to historical data is incredibly valuable for users of PLM systems to gain insights into device health, occupancy trends, and asset management as well as to improve PPL controls. In the ATLIS framework, data communicated from plug-in devices to the central control hub (both dynamic and static) are stored in a database to capture these insights. Visual presentation of these data via the system dashboard will help system users easily identify trends and other important information, such as when a device is reaching end-of-life.

B. Summary

ATLIS enables greater PLM system automation. Placing four of the five main PLM capabilities within devices themselves allows for safer and less disruptive controls and improved granularity in asset management. This, along with the system's ability to identify device location, reduces much of the setup time required for a PLM system and could eliminate almost all maintenance time, offering a more user-friendly system.

IV. METHODS

A PLM system that uses the ATLIS framework automatically identifies device location, records the energy use and state of every device, and controls the device's state (e.g., on, off, standby). A small-scale laboratory PoC was developed to demonstrate the unproven capabilities listed in the previous section. Table I lists these capabilities and the elements required for each. The methods were focused on the capabilities that do not yet have scaled solutions; four of the five capabilities were therefore included in the PoC. Energy metering is not the distinguishing capability of ATLIS because extensive research has been conducted on device energy metering and self-reporting [14], [15]. As a result, it was excluded from the PoC development.

The PoC was subjected to a series of tests to validate the PLM system capabilities included in the PoC and demonstrate ATLIS' application in a realistic environment.

This section provides a description of the laboratory PoC and PoC test plan.

TABLE I
CAPABILITIES AND ELEMENTS OF ATLIS

	Capabilities				
ATLIS Elements	Location Identification	Communication	Control	Energy Metering	Data Storage
RFID Tag	X				
RFID Reader/Writer	X				
Device	X	X	X	X	
Dashboard		X	X		
Database					X
Central Control Hub		X	X		
Proved in PoC?	Yes	Yes	Yes	No	Yes

A. Laboratory PoC

A laboratory PoC was built in the Systems Performance Laboratory in the Energy Systems Integration Facility at the National Renewable Energy Laboratory. A rapid prototyping approach was used in which Arduino microcontrollers [21] ("Arduinos") emulated real devices. Although the Arduinos do not look like a typical plug-in device, they can report fabricated information (device category, type, brand, model, year, location, status, power, current, and voltage) to the main dashboard as if they were real devices. This allowed for fast development of the PoC and provided full control over all parts of the system.

RFID readers were connected to each Arduino and read in the UID numbers of the RFID tags. The Arduinos included a push button to control their operating state and an LED indicator; both are characteristics of real devices.

For the PoC, Wi-Fi was used to communicate device information to a central dashboard on a laptop computer. Communication protocols that could be considered for a scaled-up version include Wi-Fi, Zigbee [22], Z-Wave [23], and Bluetooth [24].

i. *PoC Components*

There were nine main physical components to the PoC, arranged as in Fig. 2. The Arduino, mini push button, and LED indicator light made up the "device." The push button simulated the power control button/switch on a real device, and the LED changed colors corresponding to the device's operating state. The laptop ran a Python script to pull information from the Arduino to display on the dashboard (a graphical user interface shown in Fig. 3) and post to the database. The dashboard also allowed users to administer controls to the devices. A Wi-Fi router acted as the central control hub and facilitated all communications between the devices and laptop.

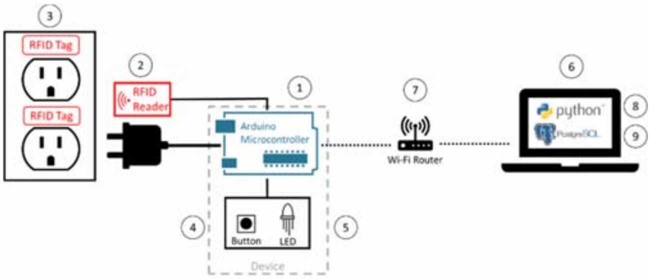


Fig. 2 Diagram of the PoC system for a single device, including its nine main physical components. The Arduino, button, and LED together are what emulate the "device"

Each Arduino was programmed with logic to automatically connect to the Wi-Fi network. Once connected, it began an iterative process in which it checked whether it had received any commands from the dashboard. The dashboard also underwent an iterative process in which it pinged the internet protocol (IP) addresses of each Arduino connected to the network every 20 seconds and updated the dashboard table with the latest data. Although this method of communication functioned well for a laboratory PoC, a scaled solution would use a more streamlined approach such as an established communication protocol by which the devices will communicate with the central control hub.

B. *Test Plan*

The PoC was tested to validate its capabilities and demonstrate ATLIS as a functioning PLM system that can automatically identify device location and communicate energy use and device operating state so that controls can be automatically applied. This included a series of tests to demonstrate the PoC's capabilities and its behavior in situations that PPL devices are commonly in.

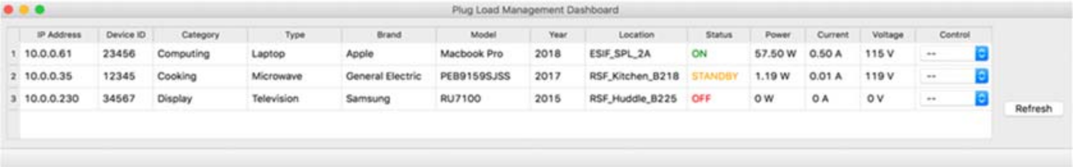
Five devices were emulated during testing. Five outlets, each with an RFID tag, were used to simulate outlets in different locations throughout a simulated building.

System tests were used to validate several PLM system capabilities, including location identification, communication, and control. These tests were conducted by administering controls from the PLM system dashboard and powering the devices on and off using the button control on the Arduino. These tests also included unplugging all devices, a whole-system power down from the dashboard, powering on a single device from the dashboard, and moving devices from one outlet to another.

C. *Results and Discussion*

The PoC should register devices plugged into outlets with RFID tags and display this information on a dashboard. Table II shows seven tests used to demonstrate these capabilities and indicates whether the PoC passed the test with the expected outcome.

The PoC performed all system tests with the expected outcomes, demonstrating that device location and operating state can be tracked accurately. The tests showcased the PoC's capabilities, such as administering controls to specific devices from the dashboard, tracking changes in device operating states, and registering devices when they are plugged in. The PoC also showcased ATLIS' novel capability: location identification. When two devices were unplugged and plugged into new outlets in system test No. 7, the PoC registered this change and showed the devices' current locations on the dashboard automatically. The PoC recognized the change in location within the demonstrated 20-second data collection period. This is much less time than it would take a building manager to manually record this change and rearrange the setup accordingly on conventional PLM systems. ATLIS' ability to automatically identify a device in its new location has the potential to not only save an immense amount of time in maintaining a PLM system, but also to automatically apply device controls to save energy.



	IP Address	Device ID	Category	Type	Brand	Model	Year	Location	Status	Power	Current	Voltage	Control
1	10.0.0.61	23456	Computing	Laptop	Apple	Macbook Pro	2018	ESIF_SPL_2A	ON	57.50 W	0.50 A	115 V	--
2	10.0.0.35	12345	Cooking	Microwave	General Electric	PEB9159SJSS	2017	RSF_Kitchen_B218	STANDBY	1.19 W	0.01 A	119 V	--
3	10.0.0.230	34567	Display	Television	Samsung	RU7100	2015	RSF_Huddle_B225	OFF	0 W	0 A	0 V	--

Fig. 3 Example of the dashboard operating with three connected devices

TABLE II
PASS/FAIL SYSTEM TESTS DEMONSTRATING THE POC'S CAPABILITIES

No.	Test Summary	Capability Represented	Expected Outcome	Pass?
1	Disconnect all devices	Communication	No devices register on the dashboard	Yes
2	Plug all devices in; all devices powered on from their power buttons	Location identification, communication	All devices appear on the dashboard with the correct location and show ON in the "Status" column	Yes
3	Whole-system power down from the dashboard controls	Control	All devices show OFF in the "Status" column	Yes
4	Whole-system power up from the dashboard controls	Control	All devices show ON in the "Status" column	Yes
5	Power down single device	Control	The device that has been powered down shows OFF in the "Status" column	Yes
6	Power up single device	Control	The device that has been powered up shows ON in the "Status" column	Yes
7	Two devices change outlet locations	Location identification	Both devices show the appropriate location in the "Location" column	Yes

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V. SYSTEM FRAMEWORK APPLICATIONS

A system that uses the ATLIS framework has many applications beyond reducing PPL energy consumption. This section discusses some of these additional technology applications that have the potential to be the most impactful.

A. Grid-Interactive Efficient Buildings

Grid-interactive efficient buildings (GEBs) use smart technologies like advanced controls, sensors, and data analytics to continuously optimize their use of renewable energy generated at the building site. They can systematically perform demand-side management, including load shedding, load shifting, load modulation, and electricity generation. As their name suggests, they also incorporate advanced energy efficiency measures [25].

An ATLIS-based system supports GEBs by enabling efficient, centralized control of PPLs in a building. One of the system's greatest assets is its inventory of devices and device locations in a building. This inventory could allow the system to automatically identify which devices are "approved" for curtailing and send control signals to those devices at times when the building should curtail energy use. Future PPL research could include an investigation of how PPLs can respond to grid demands [26]-[30]. Work in this area has been relatively limited because PPLs are one of the most challenging end uses to manage due to their distributed and diverse nature.

i. Interoperability

As systems in buildings are becoming smarter and more connected, improving interoperability—the ability of PLM systems that use the ATLIS framework to communicate with other building systems with a common understanding of control signals—has emerged as an important topic among building experts. Interoperability with systems for controlling other building end uses such as lighting or heating, ventilating, and air conditioning (HVAC) could make the PLM system more effective in future buildings in general and is critical for successfully transitioning to GEBs.

Although interoperability has been largely achieved at the technical (i.e., data transfer) level (transmission control protocol [TCP]//IP, BACnet [31]), achieving GEB functionality and instantaneous connectivity across multiple building systems requires advances in semantic interoperability. Semantic interoperability is the shared understanding among different platforms, systems, and software of what a given building data point "means," in terms of defining characteristics such as its location, timing, units, quantities, and relationship with other points. This contextual information can be captured and represented by a structured set of descriptive metadata. This structuring can be done at a sufficiently high level of abstraction to encompass the needs of multiple industries and allow integration across the energy system [32].

The ATLIS framework could convey semantics using existing open-source standardized taxonomies developed by semantic interoperability initiatives such as Project Haystack [33], Brick Schema [34], and ASHRAE 223P [35]. An ATLIS-based system includes a database of RFID tags along with the location of the corresponding electric receptacles within the building (e.g., level or floor number, conference room name) and identification of the corresponding electric circuit and feeding panels. This valuable location and circuit information as well as device information (device type, make, model, typical usage pattern, state, emergency category) would also be provided in a format that complies with the chosen interoperability standard. However, there is still much work to be done to develop PPL taxonomies and integrate them into control schemas and overarching semantic interoperability protocols [36], [37] before full semantic interoperability becomes a reality.

ii. Building Load Forecasting

A system that uses the ATLIS framework could provide highly detailed power and energy consumption data by device type, which in turn could be used by the electric utility sector for improved grid transmission and distribution, and to address peak demand challenges. Day-ahead and long-term load forecasting could be made more accurate through insights from an ATLIS-based system.

iii. Nonbinary Plug and Process Load Control

Current PLM systems control power from an outlet with the only option being on (power) or off (no power). These binary PPL control options present a challenge in determining whether a device is required to be on, how much inconvenience or risk turning off a device will cause occupants, and the amount the load will be reduced by turning the device off. Because the ATLIS framework communicates nonbinary PPL controls directly to devices, they could be put into lower power states, saving energy while minimizing inconvenience to occupants. These nonbinary PPL controls allow for better response to grid signals.

B. Virtual Emergency Circuits

Typically, commercial buildings with backup generators have dedicated, hardwired circuits for powering critical equipment when the main power fails. These hardwired circuits, required because the generators lack sufficient capacity to power all the equipment in the building, can be expensive to change when buildings are reconfigured. An ATLIS-based PLM system, however, makes it feasible to create virtual emergency circuits in which designated devices are permitted to be on during an emergency scenario and all other devices are kept off. This strategy would allow the building's PPLs to be limited so the backup generator could supply backup power to critical loads without the need for a separate hardwired circuit. For example, power could be directed to important devices such as ventilators during a brownout or blackout.

In addition to backup generators, distributed generation in the form of renewable energy could be used to provide the necessary power during grid-independent operation. When a building is in this grid-independent or island mode, it is sometimes necessary to disconnect nonessential loads. These systems would benefit even more from an ATLIS-based PLM system because of the intermittency of renewable energy.

Regardless of supply choices, energy storage is a very important element for grid-independent operating modes. The ATLIS framework enables accurate, detailed PPL load profiles that make optimal dispatch of batteries and other energy storage devices more convenient. Some forms of optimal dispatch could use forecasted PPL load profiles along with weather forecasts to trigger charge versus discharge modes for energy storage. In addition, a system that uses the ATLIS framework would communicate whether a PPL includes an embedded battery, so that power could be temporarily interrupted when in grid-independent mode or to facilitate ancillary services such as demand response.

C. Automated Inventory-Automated Audits

For energy audits, counting and identifying PPLs in buildings is a tedious and time-consuming step. Through the ATLIS framework, the PPL inventory process could be highly automated. For example, energy audit software could connect with an ATLIS-based system to perform a building-wide scan and gather necessary information about the building's PPLs. This energy audit software could also include a database of best-in-class PPLs for energy efficiency and GEB capability. Through a system that uses the ATLIS framework, the software could conveniently compare them with the existing PPLs in the relevant building and ultimately make recommendations for PPL upgrades and improvements.

D. Better-Informed Building Design

The ATLIS framework could provide highly detailed power and energy consumption data by device type. This would solve a major challenge, as building designers today do not have sufficient information about PPLs to optimally design electrical and HVAC systems to address the waste heat from PPLs. An ATLIS-based PLM system could be instrumental in developing libraries of PPL load profiles, categorized by device type and space type. These libraries could include representative load profiles for each category of PPL and help designers develop building plans that accurately represent PPLs.

E. Asset Management

Asset management aims to maximize the value for a building owner or organization by managing its assets. These assets can be devices and appliances within the building or the building space itself. Building managers can track performance and use of the building's assets to ensure devices are performing as they should and meeting their energy ratings, to inform equipment purchases, and to provide insights into how and to what capacity building spaces are being used. For instance, device energy profiles could be used to determine when a device requires maintenance or replacing. This information can reduce wasted energy by improving device energy performance.

In large commercial buildings, asset management is especially time-consuming, and therefore costly, as there can be thousands of devices to be managed within the building [38]. The ATLIS framework can make this process more manageable by enabling the system user to determine quickly and easily how devices are being used and where they are in the building.

VI. CONCLUSIONS

ATLIS is a PLM system framework that automatically identifies the location, energy use, and operating state of every connected, plug-in device in a commercial building. It takes advantage of the influx of smart, IoT-connected devices into the market to improve PLM controls for increased energy savings and enhanced device safety through updated controls. RFID technology (or PoE and USB connections) enables an ATLIS-based PLM system to track device locations as devices are moved, which will reduce the labor hours required for PLM system setup and maintenance and ultimately reduce building energy consumption.

The automation of PLM systems is an opportunity to encourage PLM integration with other building control systems. Automated PLM systems will require less manual management and therefore will be easier to operate with other systems. Integration will capture the whole picture of building energy use and enable improved building operation. This integration is a step toward the interoperability required for achieving GEBs. However, the ATLIS framework's benefits go beyond energy savings. The system's automation and detailed PPL inventory opens the door for virtual emergency circuits, automated energy audits, better-informed building design, and improved asset management—all areas of future work.

This research proved four of the five main capabilities of the ATLIS framework in a laboratory PoC. All laboratory tests were successful. Future laboratory work includes a more advanced buildout of the ATLIS framework so that it is scalable and robust.

The ATLIS framework relies heavily on device manufacturers incorporating energy metering and communication protocols into their smart, IoT-connected devices and building owners installing the infrastructure required for such a system (e.g., RFID tags at the outlets). Collaboration between manufacturers will also be necessary to ensure that devices are interoperable. Additionally, consumers and market demand will play a key role in encouraging manufacturers to pursue this type of technology.

It is to be hoped that this paper acts as a catalyst for all entities to work toward making ATLIS-based PLM systems a reality. There is significant potential for energy savings and other nonenergy benefits through PLM, and the ATLIS framework is a way to realize those benefits.

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