

# Enhancing the Role of Plug Loads in Grid-Interactive Buildings Using Smart Plugs

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## ABSTRACT

Smart plugs are popular Internet of Things devices most prevalent in residential buildings, and more smart plug solutions are emerging for commercial applications. In both residential and commercial buildings, the number of plug loads is growing at an unprecedented rate surpassing other end uses due to the reliance on electronic devices for day-to-day life, productivity, and entertainment. Not all electronic devices have a built-in low power mode when not providing full services. Beyond remote toggling and scheduling of equipment power supply, smart plugs provide an easy way to enable the ever-increasing number of plug loads to play a role in grid-interactive buildings, especially in existing buildings. To realize this, two features are critical: the native energy metering capability and the dispatching mechanism. The energy metering capability determines if and how much a particular load can provide relief to the grid. The dispatching mechanism allows the grid or the building management system to activate the smart plugs to achieve the required load reduction.

This paper presents evaluations of six smart plug products and discusses the current and near-future potential for smart plugs to enable grid-interactive services. The smart plugs' native energy metering performance was tested and quantified under various load levels, electrical conditions, and power and connectivity interruptions. Their ability to be dispatched was also characterized, either directly or through the innate integration mechanisms. Lastly, we measured these smart plugs' internal power consumptions under different normal operating conditions to provide insights into the necessary energy penalty to enable the grid services.

## Introduction

Smart plugs are one of the popular Internet of Things (IoT) devices that provide simple solutions for controlling the ever-increasing number of plug loads in both residential and commercial buildings. Currently, smart plugs are primarily marketed for automation and energy savings. As the concept of grid-interactive efficient buildings (GEBs) takes shape, smart plugs are a promising technology with the potential to enable the traditionally uncontrollable plug loads to contribute to demand flexibility in GEBs. Specifically, the two key capabilities necessary for smart plugs to integrate plug loads into GEBs are being dispatchable and able to natively meter the loads they support.

In the investigation presented in this paper, we evaluated six smart plug models, two of which are marketed primarily for commercial applications and the other four are geared towards residential applications. We first defined the type of smart plugs of interest, including their main features and energy savings potential, and discussed the rationale of selecting these six smart plug models for evaluation. We examined the two key functionalities that allow the smart plugs to support GEBs, namely, the energy metering capability and the dispatch mechanism. A series of different load points and electrical conditions were designed to characterize the accuracy of

the smart plugs' native energy metering capability. A qualitative evaluation was subsequently performed to assess the current dispatching mechanism. We also measured the internal power consumption of the smart plugs under different operating conditions to gain insights into the energy penalty of utilizing them in GEBs. Finally, we identified the missing links and necessary future enhancements to fully unlock the potential for the smart plugs to be an integral part of GEBs.

## **Potential of Smart Plugs**

According to available literature, a smart plug or smart outlet broadly includes a receptacle device that plugs into the existing wall outlet, a panel that is hardwired into the wall to replace the existing wall outlets, and even a power strip that provides multiple receptacles and USB charging ports. In this paper, we define a smart plug to mean a power receptacle device plugged into the existing wall outlet. This type of smart plug offers the simplest installation pathway without requiring additional electrical rewiring. In addition, the smart plugs investigated in this paper are all single receptacle 120VAC devices.

### **Smart Plug Features**

Smart plugs are connected through Wi-Fi, ZigBee, Bluetooth, or other proprietary wireless networking protocols. The key features that are enabled by the connectivity include:

- Toggling the power to the receptacle remotely, thereby turning the equipment plugged into it on or off.
- Programming the power to the receptacle to be turned on or off based on a schedule.
- Grouping one or more smart plugs to be turned on or off together.

A subset of the smart plugs that are more sophisticated have built-in energy metering functionality that monitors and reports real-time power draw as well as cumulative energy use over time. This energy metering capability also enables the smart plugs to provide a safety feature where they can send an alert or turn off the receptacle power autonomously if the measured current or power exceeds a user-specified limit. Such alerts can also be used as a trigger to activate pre-programmed actions of other IoT devices.

All the above features can be accessed, configured, and programmed either through a mobile device or a web interface.

### **Energy Savings Potential**

The savings potential for smart plugs has been reported in both residential and commercial applications although the majority of smart plug products are designed and marketed for residential applications. In newer commercial buildings, automatic receptacle controls, where the control is integrated with the wall outlets, are common as they are required by building energy standards for certain spaces. Nevertheless, smart plugs pose an economical plug load control solution for older buildings, and their energy monitoring and analytics functionalities may still provide valuable insights when deployed to newer buildings.

In commercial applications, smart plugs are estimated to result in 50-60% savings in plug loads (King 2017). This savings estimate, however, was based on the broad definition of smart

plugs, including automatically controlled receptacles that take feedback from occupancy sensors. Equipment with the highest savings potential, when controlled by smart plugs, includes packaged terminal AC (PTAC) units, Window AC units, portable space heaters, vending machines, drinking fountains, ice machines, and espresso machines (BOSS Controls 2017; 2022). While not specifically using smart plugs, Metzger et al. (2012) demonstrated average savings of 43% and 52% from a variety of office equipment and appliances in two office buildings by deploying schedule timers, which is the main feature of smart plugs.

In residential applications, Oh (2020) reported energy savings through smart plug deployments to household appliances, including lighting fixtures, air conditioners, electric heaters, home entertainment systems, etc., during a 15-month empirical study in 125 apartments. The same study also observed the highest energy savings potential when smart plugs are used on cooling and heating equipment as well as home audio and video devices.

## **Grid Interaction Potential**

Grid interaction has not been a focus for smart plug deployments. Clark and Valmiki (2016) studied the load profiles of plug loads for a large commercial office building and reported 7.6-55.7% demand reductions from plug load controls depending on the time of day. Although this was implemented using a proprietary plug load energy management system instead of smart plugs, it provides a good indication of the potential for smart plugs, which possess similar capabilities as the system used in the study.

The linchpin of fully unlocking smart plugs' grid interaction potential is their energy metering and dispatching capabilities. As part of the Empower Procurement Product Evaluation Hub sponsored by the California Energy Commission, the grid service capability is identified as one of the critical criteria for evaluating advanced energy efficiency technologies like smart plugs (Product Evaluation Hub 2022). This paper presents the current state of smart plugs' grid interaction capabilities characterized through the Product Evaluation Hub.

## **Enabler for Smart Plugs to Take Part in Grid-interactive Buildings**

The two key enablers we investigated are the energy metering capability and the dispatching mechanism.

The energy metering capability allows the smart plug to discern in real-time how much demand is associated with the equipment it is powering. In the future, the smart plug, with the advent of edge intelligence, could also forecast the demand from the load for the next minutes or hours based on the historical load profile and energy consumption. The demand and energy information of the load is only as accurate as it is measured, and there is currently no standard or recommended best practice on the required level of energy metering accuracy for the actors in the GEBs. Therefore, characterizing the current state of smart plug metering accuracy would provide insights into whether it is a barrier for smart plugs to take part in GEBs.

Being an integral part of GEB, a smart plug needs to be able to establish two-way communication with the GEB controller. In an ideal design, the real-time demand measured by the smart plug is communicated to the GEB controller. Incorporating the demand information and how the particular load is prioritized for curtailment, which can be pre-assigned either at the smart plug or at the GEB controller, the GEB controller can decide at any given moment whether the demand reduction from this load is needed. The smart plug will need to be dispatched by the

GEB controller and cut the power to the equipment it controls when demand reduction is called for.

We examined and characterized six smart plug products. Two of the six products are specifically marketed as a plug load solution for commercial applications. In other words, these smart plugs are not sold as widgets but as solution packages that also includes a dedicated control and management backend hosted either in the cloud or on a local server with an interface provided through a web portal. The other four products are more geared towards residential applications. They are sold as widgets, and a mobile app is a primary way to interact with them although some also provide a web interface. However, these four smart plug products were strategically chosen because they do not require a smart home voice assistant like Amazon Echo, Google Home, or Apple HomePod to be fully functional. Therefore, they can potentially be used in commercial applications. Table 1 provides a summary of the six smart plugs investigated.

Table 1. Key features of the smart plugs examined

| Smart plug                               | C1                                   | C2                                                    | R1                                          | R2                                          | R3                                                    | R4                                          |
|------------------------------------------|--------------------------------------|-------------------------------------------------------|---------------------------------------------|---------------------------------------------|-------------------------------------------------------|---------------------------------------------|
| Primary application                      | Commercial                           | Commercial                                            | Residential                                 | Residential                                 | Residential                                           | Residential                                 |
| Wireless protocol                        | 2.4G Wi-Fi                           | Proprietary                                           | ZigBee HA                                   | 2.4G Wi-Fi                                  | 2.4G Wi-Fi                                            | 2.4G Wi-Fi                                  |
| Uplink connection                        | Wi-Fi router                         | Proprietary gateway                                   | ZigBee HA gateway                           | Wi-Fi router                                | Wi-Fi router                                          | Wi-Fi router                                |
| User interface                           | Web portal & mobile app              | Web portal                                            | Web portal & mobile app                     | Mobile app                                  | Mobile app                                            | Mobile app                                  |
| Local control button functions           | On/off, factory reset                | On/off, network provisioning, factory reset           | On/off, network provisioning, factory reset | On/off, network provisioning, factory reset | On/off, factory reset                                 | On/off, network provisioning, factory reset |
| Available energy and demand measurements | Average power, cumulative energy use | Real-time power, average power, cumulative energy use | Average power, cumulative energy use        | Real-time power, cumulative energy use      | Real-time power, average power, cumulative energy use | Real-time power, cumulative energy use      |

The available energy and demand measurements summarized in the table only include those that are most relevant to the investigation presented in this paper. Most smart plugs provide various other types of related measurements, such as real-time voltage and current, runtime, etc.

## Energy Metering Accuracy

As pointed out previously, the ability to meter and report the load plugged into it is essential for a smart plug to take part in GEBs. A 120 VAC smart plug is typically rated at 15 A and is expected to support equipment with a current draw anywhere between 0 and 15 A at any given moment. Therefore, we tested the six selected smart plugs at different load points and electrical conditions to characterize their metering accuracy. In addition, we tested the smart

plugs' ability to accurately and continuously meter and report energy data after recovering from network or power disruptions.

## Load Performance Test

The smart plugs were tested at different load points as well as electrical conditions, both on the supply side and the load side, that deviate from the nominal operating condition.

**Test conditions and test method.** The load points and electrical conditions tested are shown in Table 2.

Table 2. Smart plug load performance test points

| Test condition                  |      | Supply voltage | Supply frequency | Power factor | Test load |
|---------------------------------|------|----------------|------------------|--------------|-----------|
| Low load range                  | (1)  | 120 V          | 60.0 Hz          | 1.00         | 0.015 A   |
|                                 | (2)  | 120 V          | 60.0 Hz          | 1.00         | 0.025 A   |
|                                 | (3)  | 120 V          | 60.0 Hz          | 1.00         | 0.05 A    |
|                                 | (4)  | 120 V          | 60.0 Hz          | 1.00         | 0.15 A    |
| Common load range               | (5)  | 120 V          | 60.0 Hz          | 1.00         | 0.25 A    |
|                                 | (6)  | 120 V          | 60.0 Hz          | 1.00         | 0.5 A     |
|                                 | (7)  | 120 V          | 60.0 Hz          | 1.00         | 1.0 A     |
|                                 | (8)  | 120 V          | 60.0 Hz          | 1.00         | 1.5 A     |
|                                 | (9)  | 120 V          | 60.0 Hz          | 1.00         | 2.5 A     |
|                                 | (10) | 120 V          | 60.0 Hz          | 1.00         | 5.0 A     |
|                                 | (11) | 120 V          | 60.0 Hz          | 1.00         | 7.5 A     |
|                                 | (12) | 120 V          | 60.0 Hz          | 1.00         | 10.0 A    |
| Electrical condition variations | (13) | 108 V          | 60.0 Hz          | 1.00         | 5.0 A     |
|                                 | (14) | 132 V          | 60.0 Hz          | 1.00         | 5.0 A     |
|                                 | (15) | 120 V          | 58.8 Hz          | 1.00         | 5.0 A     |
|                                 | (16) | 120 V          | 61.2 Hz          | 1.00         | 5.0 A     |
|                                 | (17) | 120 V          | 60.0 Hz          | 0.5 lag      | 5.0 A     |
|                                 | (18) | 120 V          | 60.0 Hz          | 0.886 lead   | 5.0 A     |
|                                 | (19) | 120 V          | 60.0 Hz          | N/A          | 5.0 A     |

The test load used for test condition (19) has a non-sinusoidal pulse current waveform, and the waveform was created to draw 5.0 A current. The power factor was a result of the load circuit design.

The test conditions were selected based on the tests for 2 A and 10 A current class electricity meters in the ANSI C12.20 Standard (ANSI 2015). We classified the test conditions into three categories:

- Test conditions (1) to (4) are the low load range representing equipment activities that draw very low current, such as charging Bluetooth earbuds or a laptop in sleep mode. This range is likely to be less critical in the context of GEBs as the potential contribution to demand flexibility will be negligible.
- Test conditions (5) to (12) are the common load range, in which most equipment is likely to operate.

- Test conditions (13) to (19) represent various electrical conditions that deviate from the nominal operating condition in terms of the supply voltage (13 and 14), supply frequency (15 and 16), load power factor (17 and 18), and load waveform (19).

The test method is similar to an earlier study that evaluated the metering errors of two residential-marketed smart plugs and three commercial-marketed power strips (Waghale et al. 2020). We tested three units for each of the six smart plug models. Each test condition in Table 2 was applied to a test unit for five minutes or more, depending on the energy reporting interval available for the smart plug model. The energy measurements reported by the test unit were compared to those taken simultaneously by a reference meter to determine the measurement error. The reference meter had a certified accuracy of 0.5% in the load range of 0.01-15 A with a NIST (National Institute of Standards and Technology) traceable calibration.

**Test results.** Figure 1 is the box and whisker plot of the measurement errors aggregated across the three units tested for each of the six smart plug models when operated within the common load range, i.e., test conditions (5) to (12).

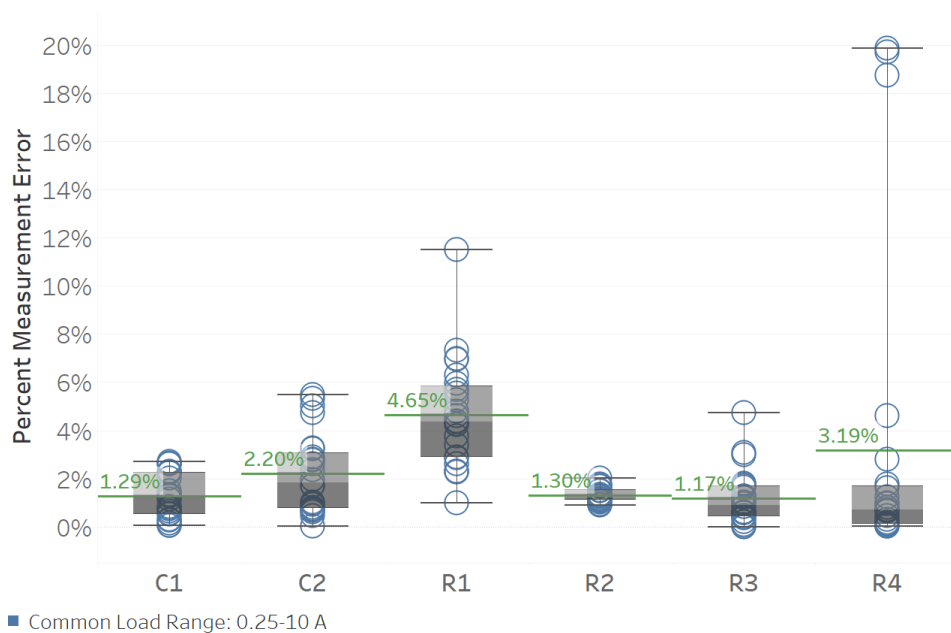


Figure 1. Smart plug energy metering measurement errors within common load range.

For each smart plug model, the blue circles represent the measurement errors at different load points, and the green line signifies the average measurement error over the three test units and all load points. The average measurement errors are all within 5%, ranging from 1.17% to 4.65%, with smart plug model R3 being the lowest and smart plug model R1 being the highest. Smart plug model R1 not only has the highest average error but also exhibits the highest degree of deviation across all the load points. Smart plug model R2 has the most consistent measurement errors across all load points followed by smart plug model C1. Smart plug model R4 has three significantly high measurement errors, around 20%, and these all occurred at the 7.5 A load point, i.e., test condition (11), for each of the three test units.

When considering all test conditions, the average measurement errors of all smart plugs increase as shown in Figure 2. The average measurement errors range from 1.95% to 9.37%, with smart plug model C1 being the best performer while smart plug model C2 being the worst. Except for smart plug models C1 and R2, all other models exhibit a high degree of errors when measuring at a very low current range, i.e., test conditions (1) to (4). The limitations on how each smart plug records and reports energy data, as detailed in the following section, could have also contributed to the errors. As discussed previously, this might not be an issue since the equipment is likely to have a very limited opportunity to contribution to GEBs when operating at such low power conditions.

Compared to the performance under various loading conditions, all smart plug models are reasonably resilient to variations in electrical conditions, i.e. test conditions (13) to (19). Variations in power factor, specifically the power factor of 0.5 lagging in test condition (17), caused the highest measurement errors for all smart plugs. Lowered supply voltage, test condition (13), also caused high measurement errors for several smart plugs.

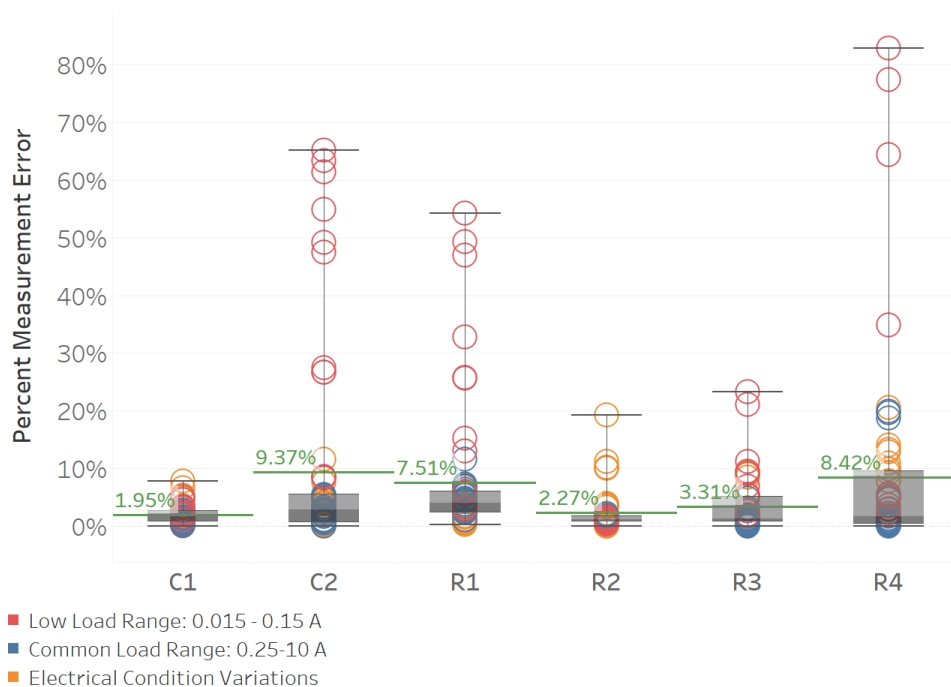


Figure 2. Smart plug energy metering measurement errors under all test conditions.

## Disruption Recovery Test

Energy metering is a native hardware functionality that does not rely on connectivity, which is only required when reporting out the energy measurement data. This test set is designed to examine whether the smart plug is indeed capable of continuously and correctly measuring the energy use of the equipment plugged into it as long as it is powered.

**Test conditions and test method.** The three test conditions are described in Table 3. Test conditions (1) and (2) verify the smart plug's ability to take energy measurements during long-term and intermittent connectivity loss, respectively. Test condition (3) introduces a long-term power outage to examine whether the smart plug can continue to accumulate energy usage from

the measurement immediately before the power loss. The test method and test setup are the same as those of the load performance test, and three units of each smart plug model were tested.

Table 3. Smart plug disruption recovery test conditions

| Test condition | Disruption types                | Description                                                                                |
|----------------|---------------------------------|--------------------------------------------------------------------------------------------|
| (1)            | Long-term network disruption    | Interrupt the uplink connectivity for 30 minutes.                                          |
| (2)            | Intermittent network disruption | Interrupt the uplink connectivity for 1 minute and restored for 5 minutes. Repeat 5 times. |
| (3)            | Long-term power disruption      | Interrupt the power supply for 20 minutes and restore for 10 minutes.                      |

The power supply and test load used in the test conditions are the same as test condition (10) in Table 2. The power supply was set at 120 V at 60 Hz, and the test load was set at 5.0 A with a power factor of 1.0.

**Test results.** The test results are shown in Figure 3, and the measurement error is capped at 20% in the plot. For each test condition, the measurement error is the average across the three units tested per smart plug model. Some of the data points are not shown in the figure because they have a value higher than 20% and are thus out of range.

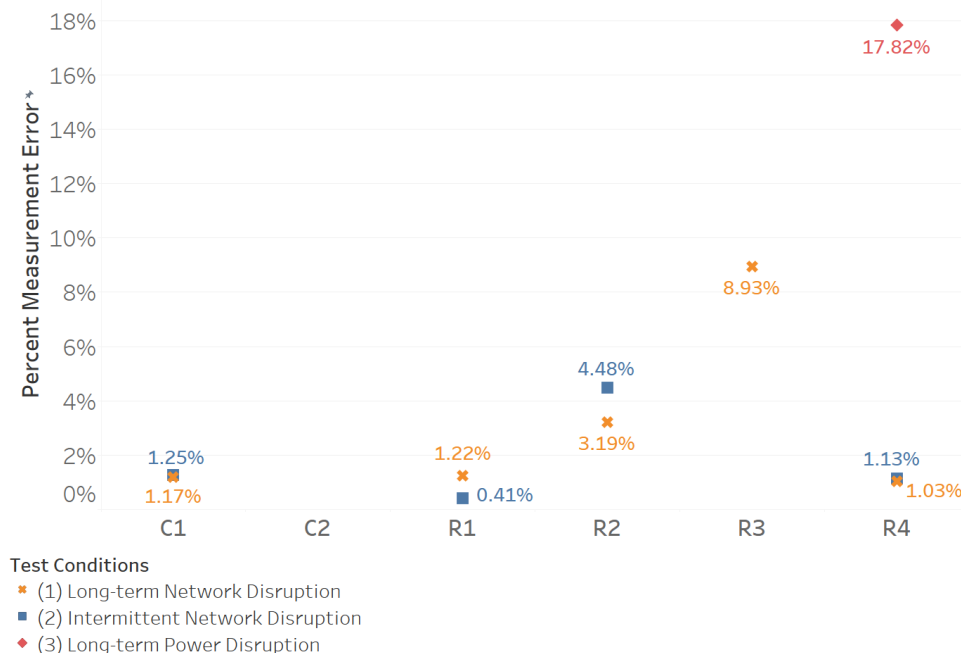


Figure 3. Smart plug disruption recovery energy metering measurement errors.

Smart plug models C1, R1, R2, and R4 appear to be able to continue energy metering with reasonable measurement errors that are less than 5% when facing both long-term and intermittent network interruptions. Smart plug models C2 and R3, on the other hand, failed to maintain a reasonable measurement error as evident in Figure 3, where some or all of the measurement errors fall outside of the 20% upper bound of the chart. The energy reports for these two products are available through their cloud backend, and it may be that energy use is accumulated at the cloud instead of locally at the smart plugs. This would cause energy

accumulation to fail when the loss of connectivity prevented the measurements from being transmitted to the cloud.

After suffering from a 20-minute power loss in test condition (3), none of the smart plugs demonstrated the ability to correctly accumulate energy from the measurement immediately before the outage. The reason for this is unclear. However, the recent energy measurements are likely stored in the smart plug's volatile memory before being transmitted to the cloud at the set interval, and the power loss would wipe out everything stored in the volatile memory.

## **Test Limitations**

The energy metering data from the tests described in this section were collected using the reporting and exporting functionalities available natively in the smart plugs. Consequently, the test results could potentially be constrained by their reporting interval and resolution.

The energy monitoring feature of the smart plugs is designed to provide the users with energy usage insights on an hourly, daily, or weekly basis, and these types of long-term energy information are not suitable for testing purposes. The highest available temporal granularity for the energy data varies depending on the specific smart plug model. Some smart plugs can report energy measurements at a much shorter interval, such as 5 minutes, and some can provide on-demand energy measurement readouts through their web or mobile user interface. We had to adapt the test method to each smart plug's energy reporting capability, which could inadvertently cause measurement errors. For example, when using the on-demand energy reporting function provided by some smart plugs, we had to manually press the button on their user interface at the start and end of each test condition. There could be a slight mismatch between the timing when the on-demand energy measurement readout request button was clicked and the timing when the reference meter started and ended logging the test load energy use. Also, when the on-demand energy measurement readout was requested, there could be a slight delay for the command to propagate wirelessly from the web or mobile user interface to the smart plug.

The unit and resolution in which energy measurements are reported could also impact the pertinence of the energy measurement errors. Some smart plugs report energy in kilowatt-hours, and the energy readings are reported with only two digits below the decimal point. In this case, the test duration for each test condition would have to be extended for the accumulated energy use to be meaningfully significant, especially when testing at the low current range. Even with the extended test duration, the limited number of significant digits could still introduce additional measurement errors.

## **Internal Power Consumption**

While smart plugs are a promising technology to enable plug loads to play a role in GEBs, they do consume energy themselves to provide connectivity as well as all the control and monitoring capabilities. As rightfully pointed out by Hendrickson (2019), smart plugs use energy to save energy. Understanding that the smart plugs in this context are meant not only for saving energy but also for providing building demand flexibility, we should place a higher value on the energy used by them. That said, there is no existing standard or certification program specifying an efficiency level for smart plugs, and the internal power consumption is not listed on the spec sheet, marketing material, user manual, or packaging for the products we evaluated.

To better understand and characterize the internal power consumption of smart plugs, we measured the power consumption of the six selected smart plug models. Without any load

plugged into the smart plugs, their power consumptions under four operating conditions as detailed in Table 4 were determined in accordance with the IEC 62301 standard for standby power measurement (IEC 2011). Three units of each smart plug model were tested.

Table 4. Smart plug internal power consumption test conditions

| Test condition | Switch state | Connectivity state            |
|----------------|--------------|-------------------------------|
| (1)            | Off          | Searching for connectivity    |
| (2)            | Off          | Connected to a stable network |
| (3)            | On           | Searching for connectivity    |
| (4)            | On           | Connected to a stable network |

Switch state represents whether the receptacle of the smart plug is powered on and ready to supply power when equipment is plugged into it.

Figure 4 shows the internal power consumption averaged across the three units tested for each smart plug model and each test condition. The internal power consumption varies depending on the smart plug model.

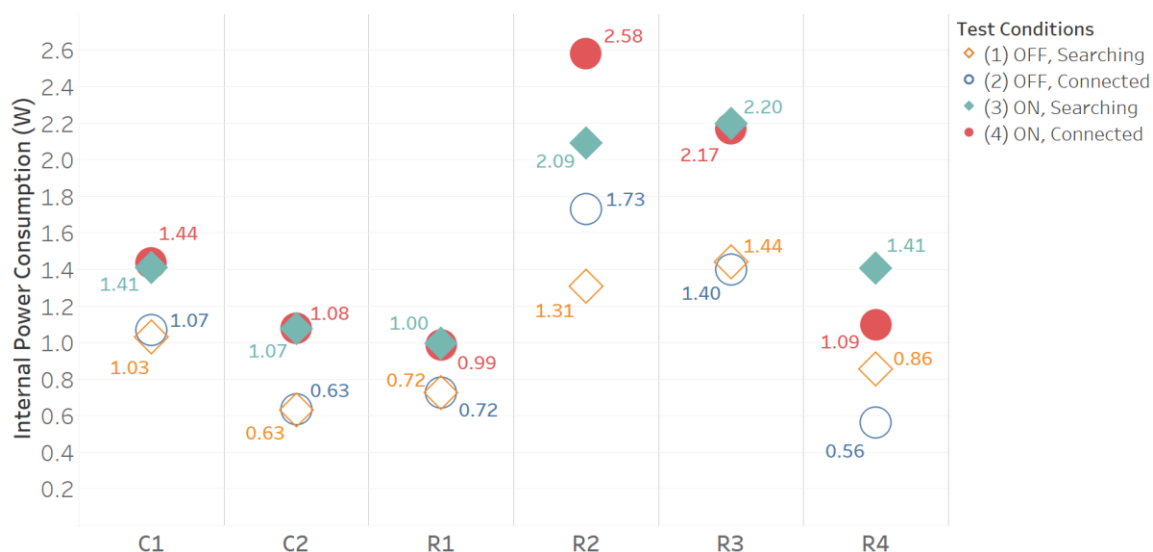


Figure 4. Smart plug internal power consumption.

It seems intuitive that the internal power consumption is lower when the power to the receptacle of the smart plug is turned off. Except for smart plug model R2, the smart plugs' power consumption is either lower when connected to a stable network or similar regardless of stable network connectivity. It is not clear why smart plug model R2 exhibits noticeably higher power consumption with a stable network connection; perhaps it communicates with its cloud backend more frequently, and therefore, commands higher power.

## Dispatching Assessment

Smart plugs, for both commercial and residential applications, are currently designed and marketed for automation and saving energy rather than contributing to a building's demand

flexibility. Therefore, an explicit dispatching mechanism for smart plugs to take part in GEBs is understandably lacking. In this qualitative assessment, we examined the features related to dispatching that already exist in smart plugs as well as the functionalities that could be repurposed or improved to better enable integration with GEBs.

## **Load Flexibility Indication**

Smart plug model C2 is the only product evaluated that provides an explicit input on its web interface, in the form of a virtual toggle switch, for the users to indicate whether the equipment plugged into each smart plug is a non-critical load. The power to the equipment flagged as non-critical loads will be cut off by the smart plug when dispatched, and the instruction from the GEB controller to turn off non-critical loads may be issued through the integration between the smart plug cloud backend and the GEB controller.

All smart plug models, including C2, have the capability of grouping multiple smart plugs to be controlled together. This feature is commonly used to group smart plugs either in the same geographical context, such as the same room, or of the same service types, like drinking fountains. Lacking an explicit indication for non-critical loads whose services can be temporarily halted, the grouping feature of smart plugs may be utilized as an alternative. This way, all non-critical loads are assigned to a dedicated group, and the power these smart plugs supply may be turned off when called for.

Another consideration is whether it will be helpful to have a more granular indication of how critical the load is. For example, in the implementation of smart plug model C2, the non-critical load indication is binary, i.e., a load is either critical or non-critical, and the power to all non-critical loads will be cut indiscriminately and simultaneously when triggered. There may be a future scenario where the loads are prioritized in tiers such that their services can be temporarily interrupted based on the level of demand reduction the GEB controller is aiming for. This is ideally achieved by extending the non-critical load indication, like smart plug model C2 implementation, to a tiered load criticality assignment, but it may also be accomplished by utilizing multiple smart plug groups, one for each criticality tier.

Opportunities of non-critical flexible loads are more likely to be found in common areas than in personal space for both residential and commercial applications. This is based on both the equipment load reduction potential (BOSS Controls 2017; 2022) and occupant control autonomy. Appliances in common areas typically have higher power consumption in nature and are also likely to exhibit more sporadic usage pattern, thus making them good candidates of non-critical and flexible loads. While certain equipment in personal spaces, such as space heaters, also have high power consumption, it is more prone to be overridden by the occupant when flexibility is needed and removing control from the occupants might jeopardize further adoptions of smart plugs.

An ultimate future scenario is that the smart plug has the ability to detect its location within the facility as well as the type of load it controls and automatically prioritize the load's demand flexibility. Langner and Trenbath (2019) identified several existing technologies and ideas that could facilitate automatic and dynamic load detection. While such autonomy is a ways off, the innovative business model of smart plug vendors and the pervasion of machine learning may pave the way to this eventual reality. Several smart plug vendors are pivoting from a widget business to providing plug load management solutions and services. This means that they will be more closely involved with the customers in planning, deploying, configuring and monitoring the smart plugs on an on-going basis, and therefore, the location of each smart plug and the type of

load it controls are likely to be more identifiable. With the pervasion of machine learning, particularly edge intelligence on IoT devices, future smart plugs can potentially be better equipped to identify the load they control and profile the usage pattern in an autonomous fashion.

Our understanding is that these emerging plug load management solutions and services are currently focusing on energy efficiency with little to no emphasis on demand flexibility. Therefore, increasing the provider's awareness of demand flexibility and GEB value proposition is also key to accelerating smart plug integration into GEBs.

## **Dispatching mechanism**

In commercial settings, dispatching the dedicated smart plug group should come from the GEB controller through the application programming interface (API) provided by the smart plug cloud backend. GEB solution providers, such as those selected by General Services Administration Proofing Ground Program for evaluation (GSA 2020), may be readily utilizing API or other methods to integrate plug load controllers. Other plug load control systems, such as those using in-wall outlets, may be more mature in providing the API or other means for integrating with building automation systems (BAS) and energy management and information systems (EMIS). However, at the time of this writing, there is very limited information on which smart plug manufacturers have made an API available for integration and what smart plug functionalities are accessible through the API.

In residential applications, dispatching may be orchestrated by the home energy management system (HEMS), such as a smart home hub or voice assistant, which may by itself be the GEB controller or serve as an interface to the GEB controller. Most HEMS are already capable of dispatching the smart plugs through voice command, a pre-programmed schedule, or a geofencing trigger. The missing link currently is the lack of intelligence built into the HEMS for making dispatching decisions based on the real-time building load conditions.

At the current technology maturity, enabling seamless smart plug dispatching for GEB is likely to still require a significant level of integration and programming by professionals in both commercial and residential applications. An early GEB validation study confirmed that such integration is not a “do it yourself” project, and there are still product ecosystem compatibility challenges (Mayernik 2020).

## **Missing Links**

The evaluation of energy metering and dispatching capabilities has revealed the following missing links that prevent smart plugs from being easily and seamlessly integrated into GEBs.

- Lack of a standardized mechanism for sharing energy data with other systems
- Lack of indications for load criticality
- Lack of a standardized dispatching mechanism

The energy measurements are available from the smart plugs mostly as on-screen displays or Excel/CSV exports. This was sufficient for the purpose of examining energy metering accuracy. However, real-time and historical energy data are also critical information for the GEB controller to track and control building demand, and on-screen display or Excel/CSV files do not facilitate data sharing between the smart plugs and the GEB controller. Among the

tested smart plugs, only smart plug model R1 seems to provide an API for accessing energy data from an external machine in real time. If other smart plug models evaluated also have an API available, such information is proprietary and was not available to the authors through the public channel. And programming the GEB controller to request the smart plug energy data through the API is a nontrivial task.

As discussed in the previous section, for most smart plugs, there is not a dedicated variable for indicating which load is suitable for being temporarily turned off to contribute to the building demand flexibility. While this can be circumvented using the grouping feature existing in almost all smart plugs, a dedicated indication would be much more convenient and straightforward. For example, smart plugs in the same room are grouped together, but only some of the loads within this group are non-critical. In this case, using the grouping feature as an alternative would significantly complicate the group configuration. Furthermore, a load may only be critical during certain times of the day or certain days of the week and non-critical at other times. This is also not a scenario the grouping alternative can sufficiently handle.

The dispatching assessment pointed out that there is currently not a clear mechanism for the GEB controller to dispatch the smart plugs. The most viable integration approach between smart plugs and the GEB controller is through the API provided by the smart plug cloud backend. This is the same trend as many other end-use systems, such as lighting, for integrating among building systems. Only a few smart plug products provide an API that can be utilized for integration; however, the API does not provide any specific functions to facilitate integration into GEBs.

## Conclusions

In this paper, we presented the evaluation of energy metering accuracy and a qualitative assessment of the dispatching mechanism, the two key enablers for smart plugs to become an integral part of GEBs. The smart plugs tested have shown reasonable accuracy in their native energy metering functionality when operating within the common load range, and the measurement errors are less than 5%. The smart plugs are also generally resilient to variations in electrical conditions, both on the supply side and the load side. The measurement error increases when the smart plugs are only subjected to a light load that is 0.15 A or lower; nonetheless, the higher error will likely be inconsequential since the opportunity of contributing to demand flexibility for GEBs is limited at such a light load. Four of the six smart plug models tested demonstrated the ability to continuously and accurately meter cumulative energy use in the face of long-term and intermittent connectivity disruption. After recovering from a long-term power outage, none of the smart plugs managed to correctly continue energy accumulation from the measurement prior to the power loss.

While the smart plugs that power non-critical loads can be grouped together and temporarily turned off when needed, the grouping functionality is not designed and optimized for supporting GEBs. There is currently not an established mechanism for a GEB controller to dispatch the smart plugs either in commercial or residential applications.

In summary, smart plugs may be configured and programmed in a roundabout way to integrate into GEBs; however, such integration is far from ideal and requires substantial effort. The missing elements include standardized energy data sharing, load criticality indications, and a standardized dispatching mechanism. Fundamentally, taking part in GEBs has not been a known and important use case for smart plugs, and consequently, relevant considerations are not accounted for in designing their functionalities and capabilities. We anticipate that as the concept

of GEB matures with more successful implementations, these missing links will be addressed, and smart plugs will play a key role in facilitating plug loads to contribute to demand flexibility in GEBs.

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