Price-based Communications for Load Shedding in Overloaded Panels

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Abstract

Although our national decarbonization goals hinge on load electrification, adding electrical load to a building often incurs slow and expensive infrastructure upgrades for the building and utility. The research field of low-power electrification revolves around adding load while avoiding panel upgrades. Today's emerging solutions involve technology such as smart panels that shed load via disconnecting circuits, which can cause nuisance tripping and may even damage large inductive loads. Instead, we propose the integration of a controller that signals flexible loads to curtail when the net load approaches panel capacity. We explore control algorithms that incorporate price-based and event-based signaling. This paper also documents the development of a bench-scale test bed, which we use to test load-management algorithms and explore the effects of real-world issues such as communications latency. Our experimental results suggest the viability of a hybrid price and event-based load management algorithm and recommend the algorithm for further testing in a building-scale test bed.

Background and Motivation

Load electrification is necessary to achieve our national decarbonization goals. For the commercial sector, this means replacing gas appliances with electric equivalents. In particular, space heating, water heating, and transportation often operate on fossil fuels. While we work on replacing our energy sources to be carbon-free, another part of our decarbonization goals require replacing these appliances with heat pumps, heat pump water heaters, and electric vehicle service equipment in every building.

In many buildings, the electrical panel and utility service feeder do not have the capacity for much additional load, at least in accordance with current electrical codes (Shokrzadeh et al. 2017, Blonsky et al. 2019). Panel upgrades and service upgrades collectively represent a major barrier to national electrification; in the residential sector, they are known to cost homeowners up to $10k and utilities up to $30k (collectively paid by the ratepayers) (Less et al. 2022). As more buildings are electrified, the utility will struggle to upgrade its infrastructure (Wood 2024).

Low power electrification is a field of research that encapsulates a portfolio of solutions for electrification while avoiding a panel/service upgrade. There are many emerging strategies and technologies that aim to address this problem. Researchers are proposing amendments to the National Electric Code (NEC) (NEC 2023), allowing it to be more accommodating of additional electrical load. Panels and upstream transformers are currently sized via simple static calculations that assume worst-case scenarios and load coincidence. However, metered data has often shown such sizing strategies to be overly conservative (Anthony et al. 2013).

Technological solutions include the use of low-power versions of existing electrical loads. For example, replacing a resistive water heater with a heat-pump water heater could reduce peak power rating by 80% (AOSmith CHP-120). In addition, integrating a battery can effectively smooth and shift loads that would otherwise have short high-power peaks. In the residential sector, emerging 120V battery-packaged induction stoves (e.g. Impulse Labs, Channing Copper) showcase the same capabilities as a 30A grid-tied cooking range. Packaging batteries within a plug-load appliance also has the potential to be one of the most affordable ways to add storage to a building (Gerber et al. 2023). Another solution, direct current (DC) microgrids have proven efficiency (Gerber et al. 2018) and cost benefits (Vossos et al. 2018), but may also play a role in load electrification. This strategy proposes a DC subsystem that couples the solar panels, battery storage, and several appliances (e.g. DCbel for EV charging). The subsystem would connect to the rest of the building via a bidirectional gateway inverter, whose capacity can be sized to accommodate panel-capacity constraints. Like battery-packaged appliances, such a system would require adequately charging the battery storage to meet expected load. An extension of the DC concept includes entirely off-grid DC systems, such as a solar carport EV charger (e.g. GismoPower).

Another family of solutions, power sharing and controls, is perhaps one of the more mature in this application space. There are many power sharing devices available today. Smart panels (e.g. Span, Genius, Schneider, Leviton) use relays to programmatically connect or disconnect various circuits. While they do not avoid the panel upgrade, they can ensure the building does not exceed its feeder capacity. Smart sub panels (e.g. Lumin) are applicable to a subset of the building's circuits but are more affordable and easier to install. Smart breakers (e.g. Savant, Eaton) can pop into existing panels and apply programmable control to a smaller set of high-power circuits. Smart sub panels and breakers are intended for load management under resilience scenarios and require the NEC control-system exceptions to be allowable for low-power electrification. Finally, smart splitters (e.g. SimpleSwitch, Dryer Buddy) are used to multiplex a single circuit to have two outputs; they are typically used to power a dryer and EV charger from a single outlet.

While power-sharing devices are readily available today, many are not configured for affordable electrification, and such applications have had confusing and inconsistent approval from code officials and local authorities having jurisdiction. In addition, they prevent overloading the panel or feeder by disconnecting high-power circuits. Such operation results in a nuisance trip for the occupants and repeated interruption may degrade the life span of various high-power loads common in large commercial buildings.

The principle behind demand flexibility is to use power communications to request that loads collectively curtail their power consumption when the net load approaches panel capacity. We propose the use of price-based and event-based communication to allow demand flexibility to act as a low-power electrification solution. This work documents the process of developing and testing our control algorithm as a bench-scale experiment, ending with a discussion of findings and considerations for implementing such a control scheme in a building.

Review of Communication Protocols

A key facet in the decarbonization of the building industry is enabling the transition of the existing building stock to Grid-Integrated Energy Efficient Buildings (GEB). GEBs are characterized by 1) the automated system optimization solutions that provide energy efficiency and demand flexibility and 2) communication between the building, the equipment within, and the utility grid. We discussed how demand flexibility can enable low-cost retrofits to support decarbonization. Communication between the different entities also enables devices to automatically respond to changes in grid conditions.

There are different communication protocols that are commonly used by devices in residential buildings. The ubiquitous nature of Wi-Fi allows devices to communicate over the home's native Wi-Fi network. Devices that communicate over Wi-Fi usually provide a web application programming interface (API) hosted locally on the device or on the device manufacturer's cloud. APIs can be used to communicate with the devices, change their operating status, and read data. Other commonly used protocols include, but are not limited to, Bluetooth Low Energy, Zigbee and Z-Wave. Matter is a new communication protocol that has been released and it was developed by a consortium of connected device manufacturers and attempts to address some of the interoperability challenges that arise due to different communication protocols and different data models (Matter, 2023).

There are also many residential devices in use today that do not have any IP-based networking capabilities. Window air-conditioners, portable heaters, etc. have different modes of operation, but are often controlled via on-device dials or an infrared-based remote control. Such high-power loads can be leveraged for demand flexible strategies such as load shifting and load shedding. These and other devices with no networking ability can only be included as a flexible resource through on/off modulation.

Decarbonization of existing equipment within buildings also requires the devices to react to the needs of the utility grid. Hence, there also needs to be some way to inform the building (and the equipment within the building) of the current grid conditions. Time-of-use (TOU) utility tariffs are a way of conveying the general trends of the grid conditions to the building, where the price is high when the grid is typically under stress. However, these tariffs are not dynamic and do not present an accurate situation of what is happening in the grid at that instant.

There are several strategies that utilities leverage to communicate grid status and its expectation of flexibility from buildings and other devices. The most conventionally used methods are event-based demand-response grid signals, where the building is expected to respond to a signal from the utility by changing the operation of the devices within the building. Some common examples of these signals are load shedding (requesting the building to shed a particular amount of demand), load shifting (requesting the building to increase energy consumption by a particular amount during one time period and reduce energy consumption by another amount during another time period within the same day) and load limiting (do not consume more than a particular amount of power for a specific period of the day).

Some utilities communicate a continuously varying utility-price signal, representing the grid's conditions at every timestep. These dynamic price-based signals can contain 24-hour price forecasts, typically in 5- or 15-minute intervals. Similar to the TOU tariffs, buildings would ideally consume less energy during high-price periods and more energy during the low-price periods.

Over the past few years significant progress has been made in how these signals are communicated. Initially customers who had signed up to receive these "grid signals" would receive email or text alerts roughly a day in advance with information regarding the timing and duration of the event. For example, customers of California's Pacific Gas & Electric utility who signed up for these "Peak Demand Price" programs, would receive cheaper utility tariffs for a year. However, for approximately 15 days in the year, they would be notified of "peak demand" days when the grid was predicted to be under unusually high demand and they were requested to reduce their demand from 2PM-6PM. During these "peak demand" hours of these days, energy costs would be exorbitantly high. However, it was up to the building operator (or owner) to take actions to respond to the notification, and "participate" in the event by turning off certain devices or increasing their air conditioners' setpoints. This requirement of manual interventions resulted in large enrollments in these tariffs, but less participation. Since then, the industry has been making a transition to automated demand response (ADR) where the utility directly communicates with some equipment in the buildings and the equipment automatically makes the necessary adjustments to its operation during the requested periods. OpenADR is a communication protocol that was developed to support communicating these signals and the recent OpenADR 3.0 (OpenADR 2023) supports a Restful web interface. Grid signals can be more than just real-time prices - they can be the real-time greenhouse gas emissions based on how the electricity is being generated; OpenADR 3.0 supports these signals as well. IEEE 2030.5 (IEEE 2023) is another example of a protocol for utilities to manage end-use devices within buildings.

We have looked at the different communication protocols between equipment within a building and between the building and the utility grid. Nordman et al. (2022) previously presented Figure 1 based on the different pathways for price-based signals communication. These methods are applicable to event-based signals as well. In residential buildings, the "building central entity" could be a gateway or a central Home Energy Management System. This entity would be responsible for retrieving the grid signals and either generating control signals directly for the loads or transmitting the grid signals to devices that can interpret them. The price signals can also be retrieved by a third party (such as a device manufacturer's cloud or an external control optimization software) that will process the grid signal and send the corresponding actuation command to the devices.

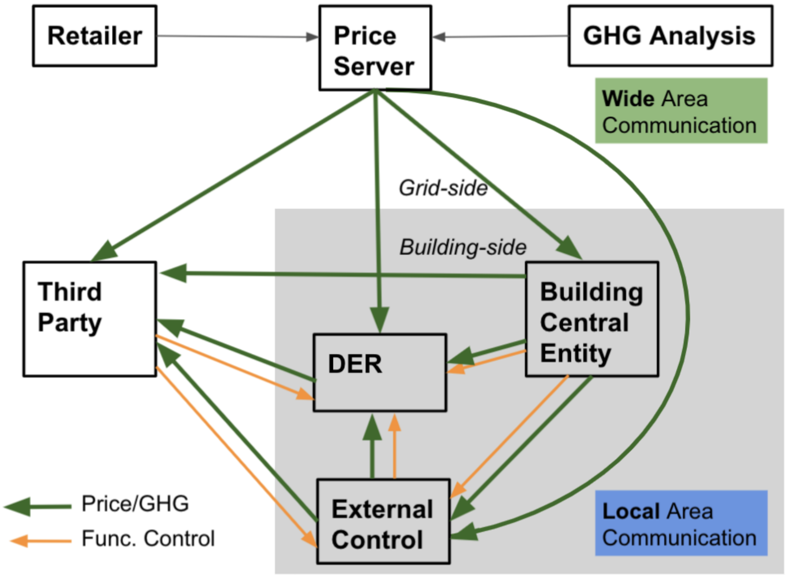

Figure 1. Price-based grid coordination system architecture. *Source*: Nordman et al. 2022.

We studied the combined use of event-based and price-based communication for managing flexible loads in the context of maintaining panel capacity. Localized price-based signals are ideal for daily normal operation due to their universality and ability to incorporate price data from the grid. Localized event-based signals have been incorporated to accommodate extenuating circumstances (such as an immediate load-shed when the total load approaches panel capacity). Such functionality, however, requires more customized load management based on the device type.

Experimental Test Bed

We developed an experimental test bed to evaluate load-management algorithms and study the ability for a centralized controller or gateway to shed or curtail loads that are representative of commercially available high-power networked appliances. The test bed serves to validate the ability of flexible-load algorithms to maintain panel capacity. Even when algorithms work perfectly in simulation, a scaled-down experimental validation can reveal issues brought about by real-world implementation. The full system control loop crosses between electrical and digital domains, and such multi-domain systems are very hard to accurately model. For example, the Wi-Fi communications introduce delay into the system that may reduce closed-loop controller speed and even introduce oscillations. As such, a scaled-down experimental test bed is invaluable as a light-weight means of revealing a number of real-world issues.

The experimental platform consists of a panel prototype and an assortment of connected loads. The panel prototype is rated for 15A and plugs into a wall outlet. The sum of connected loads is intentionally greater than 15A, emulating an overloaded panel. The experiment is a scaled-down test bed that can represent a building's main or sub-panel for the purposes of algorithm demonstration. Figure 2 shows the power flow through various parts of the prototype panel. Within the panel, power flows through the 15A main breaker and a current sensor to the panel's bus bar. The current sensor measures the input current and reports it to the panel's controller. The bus bar is connected to six outlet circuits, each of which has a relay to accommodate experiments that involve emergency load interruption. In this experiment, we attempt to keep the current load under 10A.

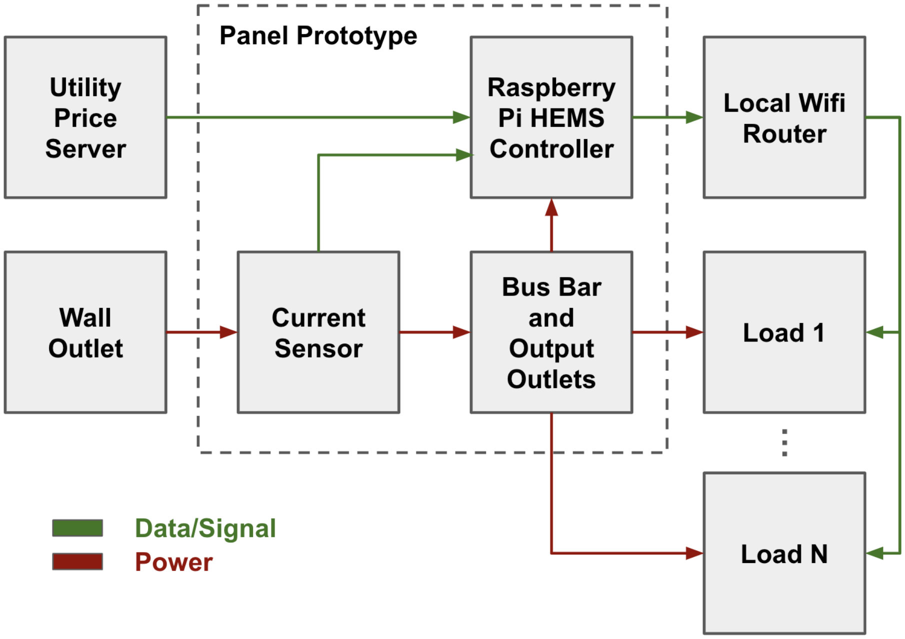

Figure 2. Hardware diagram and power flow of the panel prototype.

In this experiment, we attach several loads, some of which can be controlled over Wi-Fi. The loads are:

- Two 250W flood lights, modified for Wi-Fi: these lights have a 0-10V input signal that can be used to dim/brighten them. A 0V signal corresponds to minimum brightness and a 10V signal triggers maximum brightness.
- A 900W infrared (IR) space heater, controlled by a customized Wi-Fi IR transmitter: can be turned on/off over the network
- An AC electronic load: no communication interface. The only way for the panel to control this load was to stop the power supply to the load (enabled using a relay). However, this load was generated using a Chroma programmable load[1] and we were able to manually control the current it was drawing. We used this load to represent a home's uncontrollable base demand.

Software Architecture

Figure 3 shows the communication architecture between the different device interfaces. We used a publish/subscribe architecture (implemented using the MQTT messaging protocol[2]) where the panel controller would receive the grid signals. In this case, we used the CalFlexHub research price server (CalFlexHub, 2023) to obtain a price forecast, which is broadcast on the message bus to the "panel/price" topic. Each device had an associated software driver that would receive the prices and other signals from the panel and translate that into control signals for the device. Any driver subscribed to the "panel/price" topic would get a price forecast and update its operation accordingly. The panel also continuously measures the total aggregate current consumption of its connected devices. As the total current approaches a certain threshold, the panel increases the local price until the total current falls sufficiently. Beyond this threshold price-based control is insufficient, and the panel controller broadcasts emergency event signals, possibly disconnecting the relays to avoid tripping the main breaker.

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[1] https://www.chromausa.com/product/programmable-ac-electronic-load-63800/

[2] https://mqtt.org/

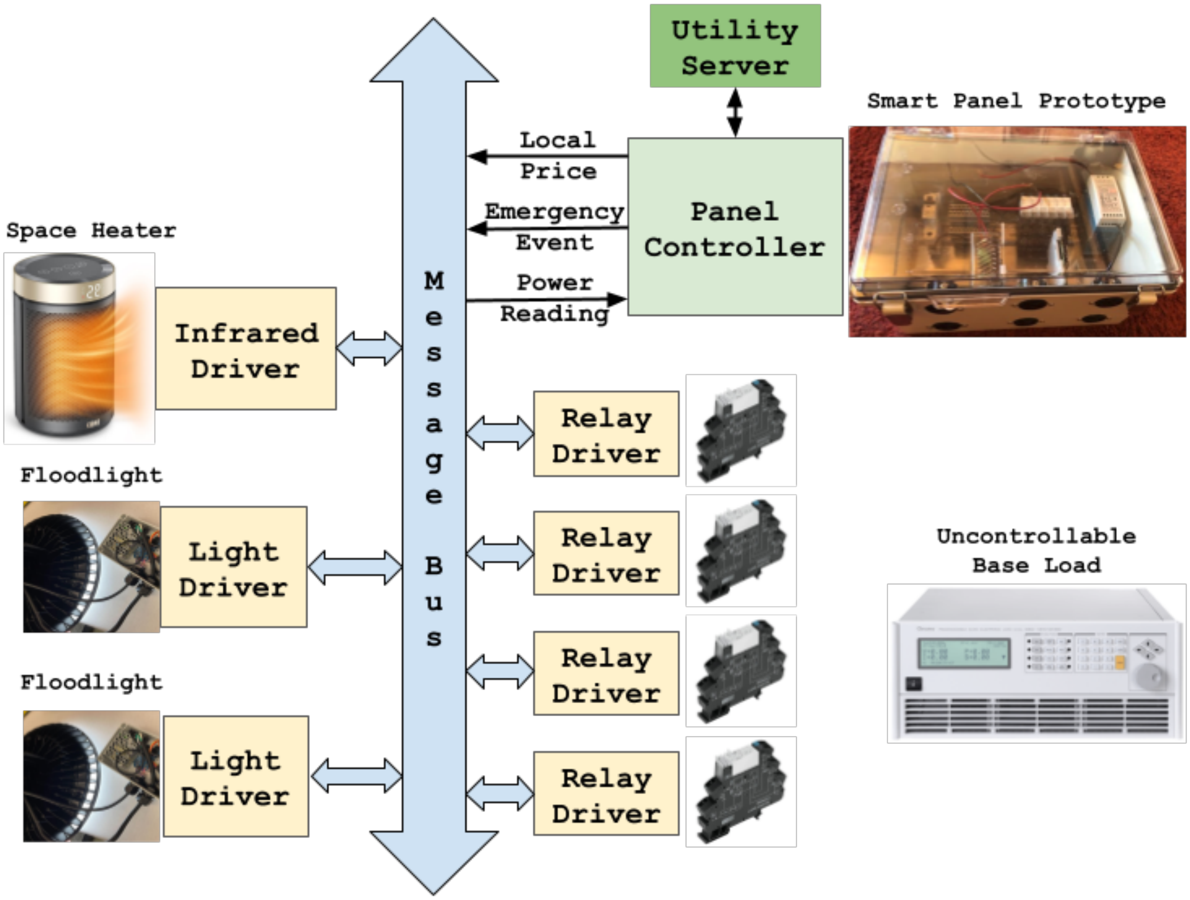

Figure 3. Software diagram and communications flow of the experimental test bed.

For the experiment, our sample control algorithm sets the local price based on the following rules:

- If the input current is greater than 10A, set the local price to $10 (essentially set it to a very high value)
- If the input current is between 5A and 10A, set the local price to a value that is linearly interpolated between the CalFlexHub server's current and daily maximum prices
- Increases in local price happen instantaneously
- Decreases in local price occur at $0.03 per second: if we were to reduce prices immediately, the demand would increase suddenly, triggering another price increase. Hence, we decrease the rate at which the price reduces to avoid oscillations.

Experimental Results

For each experiment, we collect data on power, operation, and current at 1-second increments. For any price-based algorithms, we collect and report the price input from the server and local price output to the loads. The loads report their received local price and operation mode data (e.g. LED dimming). They also estimate and report their power consumption based on modeled power-operation curves. Finally, we collect hardware information on the input current and status of each relay.

Our trial validation experiment shows how the price-based load-management algorithm responds in several simulated scenarios. First, we simulate a slow step increase in panel load, manually added with the electronic load. This tests how accurately the system settles to a steady state. The second simulation involves a rapid increase in panel load, representing a shock to the system, analogous to suddenly turning on a resistive tankless water heater. This test is intended for measuring the speed of response, and revealing any overshoot or oscillatory behavior that may occur.

Our results for both simulations are shown in Figure 4, where the local price responds to the panel's aggregate input current and the light dimming output responds to the local price. With incremental (1 A) steps of load added to the system, the lights properly dimmed to 64% and the current was just around 5.7 A (as you can see around the 100s mark). Without the lights curtailing, the current would've increased to around 7 A, given 3 incremental 1A increase in the base load. After bringing the system back to the original state, we performed a shock test by suddenly increasing the base current by 5 A. This represents a high current consuming load turning on. This resulted in the lights initially dimming to 22%, but normalizing at 40% in steady state. In either case, the prototype's internal main breaker did not trip. Steady-state oscillations can be observed, though are limited relative to the local-price decrement step size of $0.03 per second.

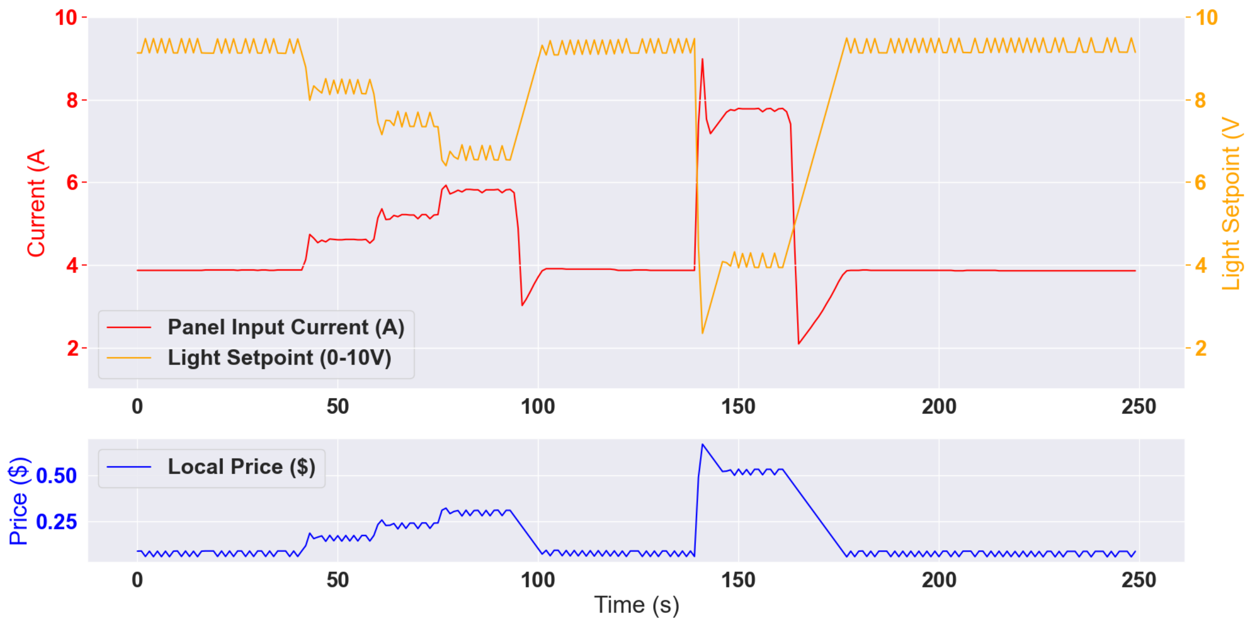

Figure 4. Demonstration of a functional price algorithm for the panel prototype. The chart illustrates how the lights respond to steps in load (50s-100s) and a load shock (145s).

Overall, the price-based control algorithm was able to properly dim the lights to offset increases in the aggregate load. With our trial control algorithm, the speed of response was satisfactory, and oscillations were minimal. The system shock test caused minor undershoot, which was recovered within a couple seconds.

The algorithm can be improved in several ways. Such improvements and optimizations will likely depend on what types of loads are present. In buildings with more panel-capacity buffer, the lights' depth of dimming can be reduced, thus maintaining most of their output to the occupants. In buildings with quick and flexible loads, the local-price decrement step size can be increased to improve the speed of system-shock recovery. And finally, a variable step size would allow for better steady-state settling.

Conclusions

Panel and service upgrade requirements pose a major barrier to building decarbonization. Many emerging low-power electrification solutions maintain panel capacity by interrupting power to loads. We propose an alternative solution that uses event-based and price-based control to curtail loads. To validate our sample control algorithm, we develop an experimental test bed that communicates with its attached loads over MQTT. Our experimental results indicate that such an algorithm may well be viable in real buildings.

The next phase of the project involves applying the algorithm to a smart-home test bed. There will be many challenges involved in controlling larger loads such as heat pumps and electric vehicle chargers. Once these loads are integrated into the control system, we expect to tweak many aspects of the algorithm as well, such as decrement step size and overall behavior. From the smart home test, we intend to gain insight on the technical and regulatory issues that may occur from implementing such a control system in commercial buildings.

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