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Managing Smart Grids Using Price Responsive Smart Buildings

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Abstract

The market is a tool used to efficiently allocate resources. Energy markets have been used to allocate generation and transmission resources at the level of the transmission and distribution system, with significant innovation on these markets occurring since deregulation in the 1990s. The advent of the Smart Grid and Smart Building have enabled these innovations to be brought to the level of the retail electricity market, where even individual buildings will be able to adjust their consumption based on price signals from the market. This paper gives a review of the development of energy markets and the technologies of the Smart Grid and Smart Building that are enabling their participation in the market at the edge of the grid. The OpenADR communication protocol is examined as a means of communicating price information between the load and the utility. Finally, a hardware-in-the-loop Smart Building test setup is described. This test setup is used to compare the performance of baseline and price responsive controls, with a power reduction of 60% achieved during a period of peak consumption and grid congestion corresponding to a large price surge.

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1. Introduction

A cavalcade of new technologies has produced new opportunities in generation, distribution, and consumption of power which fall under the broad heading of Smart Grid, and in time these technologies have extended into Smart Buildings. These technologies produce potential for reductions in power consumption, or cheaper generation, or reduced grid congestion, among other benefits. In this paper, these new technologies will be combined with energy

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market concepts to demonstrate how these potential benefits can be realized. In particular, this paper will demonstrate how smart buildings and the smart grid can be used to reduce congestion on the grid during periods of peak loading.

The group of technologies that has arisen in the last fifteen years include distributed generation, particularly residential and commercial PV installations, local energy storage, high speed wireless communications networks, distributed and cloud computing, and machine learning-based automation technologies. Distributed generation and energy storage resources have driven a change from centrally controlled and operated power systems to a more diffuse control with bidirectional power flows [1]. This has created the need for high speed communication to collect data and dispense commands. This collection of networks and computational techniques clusters together under the umbrella of the Smart Grid [2]. Ranging from simple technologies, such as smart meters that can enable export to the grid, up to highly complex systems, such as virtual power plants that can coordinate the deployment of resources over a wide geographical area, the Smart Grid provides the framework for control of these new distributed resources.

Smart Buildings combine existing building automation systems with technologies like smart meters and machine learning to provide control of energy consumption within a building [3-4]. Just as the Smart Grid facilitates coordination of distributed generation resources on the edge of the grid, it can also be leveraged to coordinate the operation of Smart Buildings to provide grid services. Programs like demand response, which previously were mostly implemented in large loads like industrial sites, may be extended to small commercial and even residential buildings using the communication infrastructure built for the Smart Grid. The Smart Building can then use technologies like machine learning to find ways to manage its energy via load shedding while minimizing the disruption to the inhabitants of the building.

Electricity markets have long been used to coordinate resources on the grid. They provide coordination for resource scheduling, pricing, transmission capacity reservation, and congestion management [5]. Major innovations since deregulation in the mid-1990's include energy tagging and locational pricing [6]. Such markets have not typically been applied at the retail level, however. Instead, retail customers have a flat rate for electricity. This decouples the consumption of power from the price of power, giving rise to inefficiencies in the use and distribution of power at the point of consumption [7]. The Smart Grid communications framework provides a method to implement these markets at the retail level on the edge of the grid, and research is underway to implement market concepts such as energy tagging at this local level [6, 8].

This paper presents the implementation of a Smart Building that receives the price of electricity over the Smart Grid communication infrastructure. Section 2 will describe the OpenADR communication protocols used to communicate price information. Section 3 will describe the hardware-in-the-loop (HIL) test bed used to implement the Smart Building controls as well as the building, weather, and price models used for the test. Section 4 will present the building energy consumption for the baseline and price-responsive cases.

2. OpenADR and Price Responsive Load Control

OpenADR was developed by the Demand Response Research Center of the Lawrence Berkeley National Laboratory in 2002 [9]. It is intended as a communication interface to send demand response information between the grid and load resources. The standard specifies data models in XML files which are sent over the HTTP or XMPP transport protocols, which can be accessed using a standard internet connection. The standard also specifies cyber security measures.

The OpenADR protocol classifies components as Virtual Top Nodes (VTNs), which initiate demand response requests, and Virtual End Nodes (VENs), which implement those requests. In a typical configuration the VTN might be a server operated by the electric utility and the VEN might be an individual building. The specification does allow hierarchical data flow, so a more complex system might have an aggregator as an intermediary. The aggregator acts as a VEN for the utility server, but is a VTN from the perspective of the individual loads that are aggregated by it.

OpenADR provides a simple version of the standard, OpenADR 2.0a, and a version with a greater number of features, OpenADR 2.0b. One key difference is the type of event signals that can be sent using the protocol. Table 1 provides a list of all of the EiEvent signal types available in the OpenADR standard. OpenADR 2.0a uses only the Simple Levels signal type, which can be used to communicate the start or end of a previously agreed event. The actions required in these events might be pre-programmed, such as turning off a particular set of loads, or could be implemented as pre-agreed energy shedding target.

Table 1. OpenADR EiEvent Signals [9]

Signal Type	Signal Name	Signal Values	Description
Simple Levels	SIMPLE	0,1,2,3	Simple levels used to indicate pre-agreed events have occurred
Price of electricity	ELECTRICITY_PRICE	Any	The cost of electricity expressed in absolute terms, a delta change to the existing price, or a multiple of the existing price
Price of energy	ENERGY_PRICE	Any	The cost of energy expressed in absolute terms, a delta change to the existing price, or a multiple of the existing price
Demand charge	DEMAND_CHARGE	Any	The price of the demand charge fee expressed in absolute terms, a delta change to the existing fee, or a multiple of the existing fee
Customer bid levels	BID_PRICE, BID_LOAD, BID_ENERGY	Any	The price, amount of power, and amount of energy bid by a load as a resource into a market program
Used to dispatch storage resources	CHARGE_STATE	Any, 0 < 1	Used to cause an energy storage resource to charge or discharge, expressed as an absolute amount of energy, a delta change to the state of charge from its current state, or a percentage of full charge that the storage resource should be at.
Used to set the load to specific values of consumption	LOAD_DISPATCH	Any, integer -10 to +10	Used to dispatch a specific amount of a load expressed as an absolute power setpoint, a delta offset from an agreed baseline, a multiple of an agreed baseline, or, if an integer, as discrete levels of the load from -10 to 10.
Used to increase or decrease load consumption when specific value is unknown	LOAD_CONTROL	0 – 100% (0.0 – 1.0), integer value	Instructs the load to operate at some percentage of its maximum consumption when expressed as a percentage, or, when expressed as an integer value, as levels of the load that have some meaning assigned at the load (for instance, as temperature setpoints of a thermostat)

It can be seen that there are a much wider range of possible signals than the simple signals used in OpenADR 2.0a. In this paper, the electricity price signal is used to communicate the cost of electricity to the loads. This enables the loads to make decisions about electricity consumption that are informed by the cost of that consumption. In this way the market should perform its function of efficiently allocating resources.

The purpose of the price responsive control method is to match consumption of electricity with production and minimize congestion in the transmission and distribution networks. On the supply side, the cheapest sources of electricity come from renewable resources, which have zero fuel costs, and from baseline electricity generation stations such as coal and nuclear. When demand exceeds the capacity of these supplies, faster acting generation such as natural gas can be brought online. However, these sources tend to have higher operating costs and are also able to command a premium for their flexibility. This causes the price of electricity to rise. Price may also rise during an outage, such as when bad weather keeps wind and solar sources from producing much energy or a baseline generator is offline for maintenance. In the baseline case, the retail customer sees none of these events. Their rate does not change, so the utility has no choice but to use more expensive energy generation to meet the demand.

Congestion constrains the utility more severely than limited supply, as it is not possible to bring up new network resources on demand. Price can be used as a long term planning signal, with high congestion prices indicating that further network resources should be built, but networks serve as a hard limit on power delivery. There is some capability to use the interconnected nature of the grid to route power around congestion, and in this case the location of power supplies becomes important. In some cases a more expensive power source may be used if it is closer to the load or along a route that is less congested.

Using a price responsive load control gives another alternative to handling supply constraints and congestion. Here, price is used as a signal for these conditions and the load reduces itself in response. This reduces the need to bring online new generation as well as reduces power flow at the site of congestion. It also reduces the load owner's electric bill. In this way the market aligns the private interest with the public interest, improving outcomes for all participants.

3. Smart Building Test Setup

The hardware-in-the-loop test setup for the Smart Building is shown in Fig. 1. The building is modeled in Energy Plus on a PC, with BCVTB used to export measurements and import commands to a BACnet communication network hosted by a Newron doGate industrial PC and building automation server. This device is capable of reading information from a variety of communication protocols, including Modbus, BACnet, KNX, and others. The doGate is also able to save information to an OPC server, where custom applications can be developed using doMooV Smart Services to analyze, manipulate, or act on the data. The doGate is set up to receive electricity price information, which for this example is also stored on the PC in a time-indexed file. In the full set-up the doGate would receive this information from the utility using the OpenADR 2.0b communication protocol.

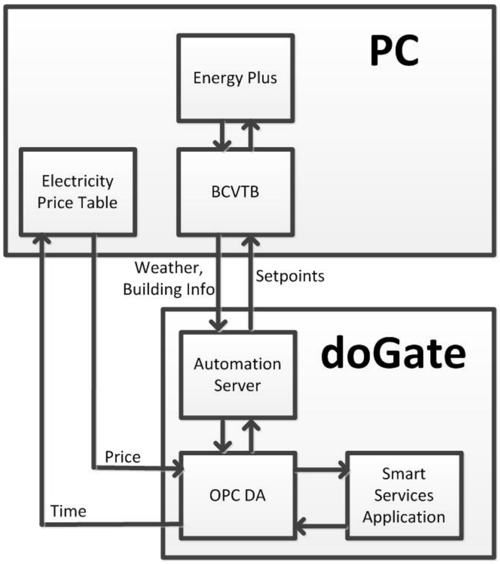

Fig. 1. Smart Building Test Platform

3.1. Building, Weather, and Price Models

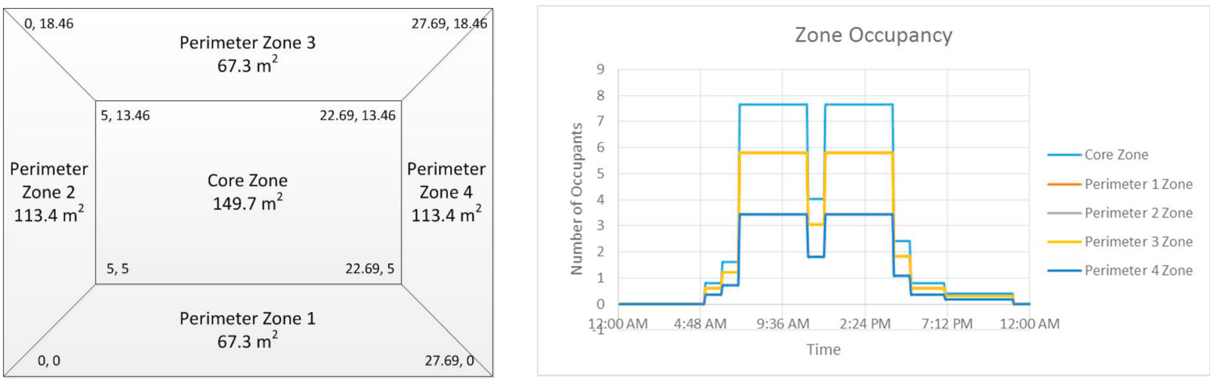

Fig. 2. Energy Plus Building Layout and Occupancy Schedule

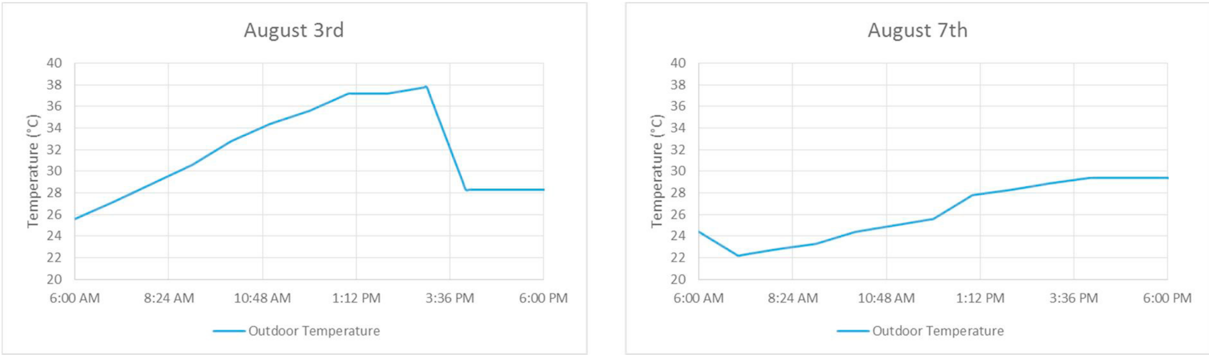

Fig. 3. Houston Outdoor Temperature for August 3rd and August 7th

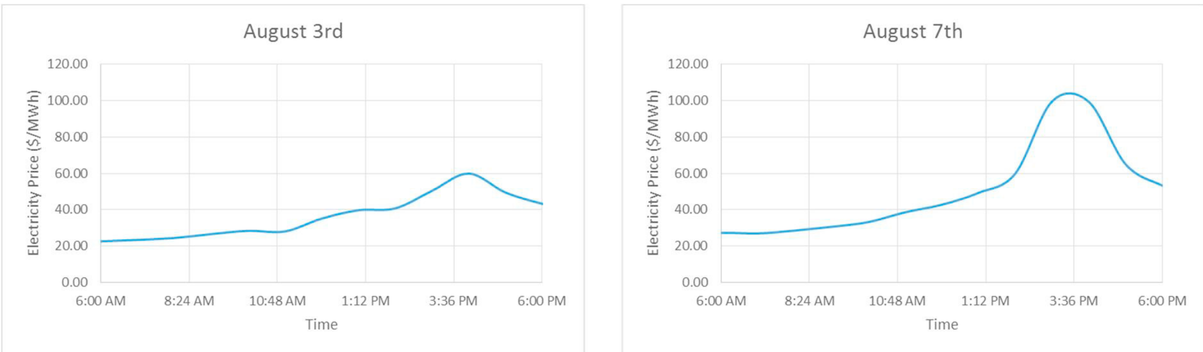

Fig. 4. Houston Electricity Price for August 3rd and August 7th

The building model used for the Smart Building is based on the five zone small office commercial building example model available from the Department of Energy [10]. The Houston climate zone is used, along with the TY3 Houston weather file. A layout of the building is shown in Fig. 2 along with a chart of the zone occupancy. It can be seen that the building has peak occupancy from 6:00 a.m. to 6:00 p.m., so the test focuses on those hours to evaluate building performance.

The building is simulated for the first week of August as this represents peak loading in Houston. The outdoor temperature during work hours for August 3rd and August 7th are shown in Fig. 3. These dates are selected based on the price of electricity on those days. This price is taken from the archived 2015 ERCOT day-ahead market prices [11]. The prices, which are shown in Fig. 4, are in a fairly typical range on August 3rd and have a large spike on August 7th. Such a large price often correlates to grid congestion, such as from a large load consumption in the whole distribution area or from a downed powerline or power plant limiting supply. Examining these two days enables the test to see the difference between normal operations and a day with restricted power availability.

4. Price Responsive Smart Building Performance

The Smart Building was tested using two control methods. In the baseline case, electricity consumption is not under active management. Equipment is used by the occupants to perform work, so its power consumption follows the pattern of occupancy. HVAC energy consumption follows the curve of the outdoor temperature. Electricity consumption rises in the morning as the occupants arrive and begin to use the equipment in the building, then reaches a peak in the afternoon as the temperature rises and the HVAC is used more heavily.

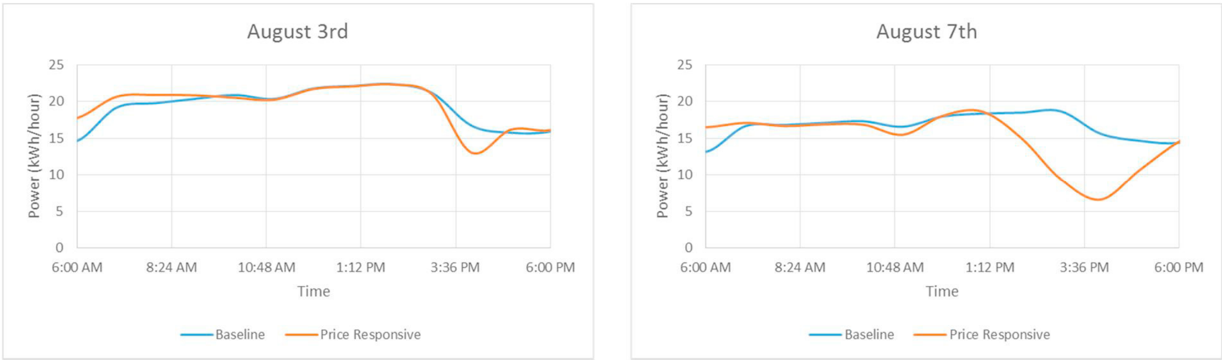

Fig. 5. Smart Building Electricity Consumption

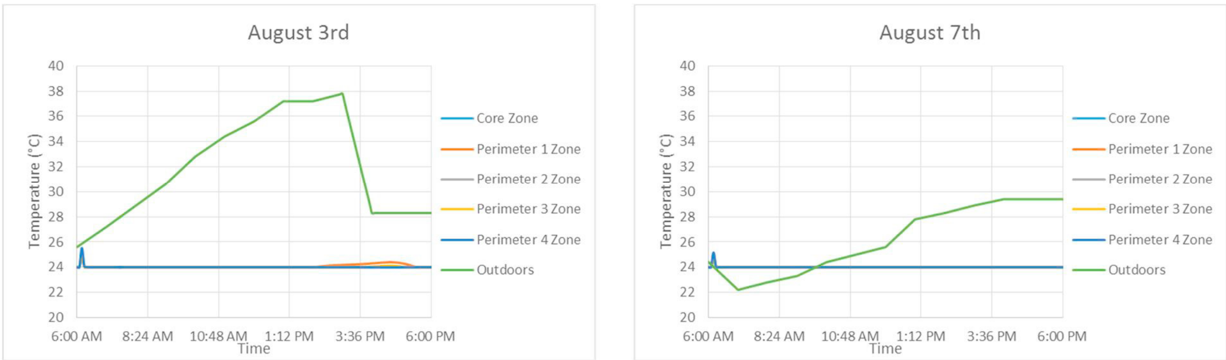

Fig. 6. Smart Building Zone Temperature under Baseline Control

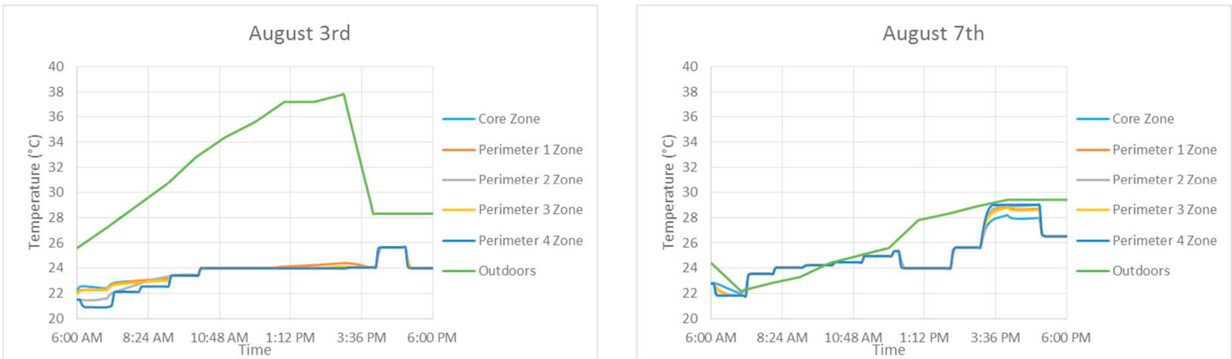

Fig. 7. Smart Building Zone Temperature under Price Responsive Control

The second control method makes some of the electrical loads responsive to price. The loads are constrained by comfort and productivity, but within those limits the loads change as the price increases in order to consume less energy. In some cases the loads may consume more electricity if the price is cheap. This load control can be implemented by the load management system embedded in the ABB Emax2 circuit breaker, described in detail in [12] and [13]

The changes in loads reach a saturation point at $75/MWh, since most variations in price fall below this range. There are occasional times when the price rises beyond this point, such as between 2:00 and 5:00 p.m. on August 7th. In these cases the consumption will saturate the controls, reaching the minimum setpoints dictated by the limits for safety and productivity.

Fig. 5 illustrates the consumption of the Smart Building using the baseline and price responsive control systems. Generally speaking the price is low in the morning and rises to a peak over the course of the late morning and early afternoon. The price increases more sharply starting around 2:00 p.m., reaching a peak around 4:00 p.m. and falling back to normal values around 6:00 p.m. It returns to the low price level overnight. This is reflected in the price responsive behaviour on August 3rd, with a higher consumption during the morning while prices are cheap and a sharp decrease in consumption during the peak price period around 4:00 p.m.

The building zone temperature can be used as an indicator of how the control impacts the comfort and productivity of the building. Fig. 6 illustrates outdoor and zone temperatures for baseline control while Fig. 7 illustrates those temperatures for price-responsive control. The temperatures are lower in the morning while the building takes advantage of low prices, then there is a small rise in temperatures in all zones from 4:00 to 5:00 p.m. during peak pricing. Similar impacts on productivity and comfort can be expected in the other electrical loads in the building.

By comparison, August 7th experiences much larger reductions in loads along with larger disruptions to productivity and comfort. Power consumption is slightly curtailed even in the mid-morning and early afternoon, with a small rise in temperatures as seen in Fig. 7. The large spike in prices from 2:00 p.m. to 6:00 p.m. result in drastic reductions in power consumption, with the controller being pushed to the limits of comfort, safety, and productivity. The temperatures rise as high as can be safely maintained, with similar significant disruptions to other electrical loads. However, the load is reduced to one-third of its value under baseline control. This represents significant reductions in congestion and reduces the need to bring new, more expensive generation online.

5. Conclusion

This paper has presented a review of how the technologies that enable Smart Grid and Smart Buildings can be harnessed using energy market principles to lower congestion and reduce the need for peak generation. It was seen that the communication networks of Smart Grids, particularly OpenADR, enable the utility to communicate price information to retail consumers. This price information automatically reflects congestion, maintenance outages, unplanned outages, and periods of high demand. The automation technology of Smart Buildings enables the retail level loads to respond to these signals by reducing their power consumption. In the example shown in this paper, the Smart Building was able to reduce loads by over 60% while staying within the constraints of safety, comfort, and productivity. This action saves the building owners money during periods of peak demand while also helping the utility manage its resources. In this way the market aligns the interests of the individual with the broader community, improving outcomes for all participants.

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