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CHARACTERIZATION OF CONNECTED LIGHTING SYSTEM POTENTIAL FOR GRID SERVICES UNDER REAL-TIME PRICING

Peng Wang, Michael R. Brambley, Michael E. Poplawski, Michael Myer,
Jianming Lian, Robert G. Lutes, Sen Huang, and Alex Vlachokostas
Pacific Northwest National Laboratory, Richland, WA
Email: {peng.wang, michael.brambley, michael.poplawski, michael.myer, jianming.lian,
robert.lutes, sen.huang, alex.vlachokostas}@pnnl.gov

ABSTRACT

We describe initial research to evaluate the potential of connected lighting systems (CLS) to provide grid services. We develop a model for CLS, using a set of parameters to represent operation behaviors and constraints: maximum power, minimum power, nominal power, ramp rate, and time delay. Parameter values are generated for representative CLS. Lighting-power demand curves are constructed, indirectly capturing building-occupant preferences for lighting as functions of electricity price. The CLS model and the demand curves are incorporated into a transactive control platform to simulate CLS providing grid services. Previous research has shown transactive control (TC) to be a powerful tool to enable end uses to provide grid services through a hybrid economic-control approach. Initial quantitative results are provided for CLS in a medium commercial office building to show the amount of demand reduction and the associated energy savings.

INTRODUCTION

Recent advances in, and increasing penetration of, renewable energy technologies pose new challenges to modern electricity grids. Renewable electricity generation, in contrast to traditional generation (e.g., fossil-fuel power stations), is intermittent, volatile, and unpredictable, and at large market penetrations can degrade the performance of electricity grids. To answer the new challenges of properly harnessing renewable energy and maintaining efficiency, security, reliability, and resilience of modern electricity grids, grid services will increasingly play essential roles. Grid services are traditionally provided by the supply side; e.g., fossil-fuel and hydroelectric generators. But providing services using only conventional generation leads to investment in generators that remain idle for long time periods, providing electricity to the grid only when their service is required. Furthermore, use of fossil-fuel-fired generation leads to increased emissions and corresponding environmental concerns. On the other hand, pilot deployments and research on using the demand side (e.g., commercial buildings) to provide grid services are showing promising results (Alstone et al. 2018). The residential and commercial sectors accounted for about 39% of total U.S. energy consumption and more than 70% of total U.S. electricity use in 2018 (EIA 2019b).

Control of building demands may postpone the construction of new energy-generation assets and reduce capacity reserve. Moreover, compared to traditional generation, buildings equipped with modern communications, monitoring, control, and computation technologies can adjust their power usage at a lower cost. They can also respond fast to grid requests or measurements of grid signals. Thus, buildings have advantages over supply-side techniques for providing grid services.

Lighting in the residential and commercial sectors consumes about 232 billion kWh of electricity annually (EIA 2019a). Lighting, if properly controlled, may be able to contribute several types of grid services. Gerke et al. (2018) forecast costs and energy-related benefits of demand response from lighting in California. Sanders et al. (2018) present a framework for achieving lighting demand response at scale, using a benefits-value-intensity model and a sample logic model. Moreover, connected lighting systems (CLS), which are solid-state lighting systems equipped with advanced sensors, controllers, and communications, could potentially respond rapidly to electric-grid service requests by adjusting their power draw more quickly than some other building electricity end uses. CLS are capable of both rapidly reducing and increasing their electricity demand, and CLS power draws can be quickly (i.e., with low latency) modulated by varying light output, spectrum, and distribution, thereby providing grid services at time frames of hours (e.g., for energy services) to seconds or less (e.g., for frequency regulation). Thus, CLS could provide a broad range of grid services.

The availability of these CLS is expected to grow rapidly over the next five to 10 years, from their 2016 share of less than 0.5% share of the installed base (Penning et al. 2017) to a forecasted (DOE Goals Scenario) 52% of all installed luminaires in the commercial sector by 2025 (Penning et al. 2016). The lighting industry is currently focused on developing CLS that deliver value to their owners, operators, and occupants but not necessarily to the electric grid, in large part because vendors and their customers do not understand the value of such grid services or do not believe that lighting systems are well suited for providing grid services.

Encouraged by the characteristics of CLS and the limited studies on CLS for grid services, we present in this paper an initial evaluation of the potential of CLS for demand reduction and the associated energy savings in response to a real-time (5-minute) electric rate. We describe a CLS model that quantitatively captures the maximum capability of CLS to provide grid services given constraints associated with ensuring occupant satisfaction with the lighting service, namely the maximum reduction in lighting level and the maximum rate of change in lighting level. We apply the CLS model to evaluating the potential of CLS in a medium office building to provide demand reduction and to quantify the associated energy savings with CLS via simulation. In addition to evaluating the maximum potential grid service from the CLS, we also apply a transactive control (TC) method to quantify the amount of potential grid service that can be obtained given a specific price trajectory and demand curve. With TC, CLS adjust their power set point between their nominal power and their minimum power, based on the price. A higher price leads to a lower CLS power set point, and vice versa.

The rest of the paper is organized as follows: CLS are briefly introduced in the section CONNECTED LIGHTING SYSTEMS, and the CLS model for grid services is described in detail in the section CLS MODEL FOR GRID SERVICES. TC, the market-based control method used in the simulation, is briefly described in the section TRANSACTIVE CONTROL. In the section SIMULATION, the lighting model parameters that constrain the amount by which lighting can be modulated are described, as are the CLS demand curves and the simulation platform. The results are presented in the RESULTS AND DISCUSSION section, and we summarize the completed work in the CONCLUSIONS section.

CONNECTED LIGHTING SYSTEMS

CLS, sometimes also referred to as networked lighting control systems or Internet-of-Things lighting systems, are essentially lighting systems that have been enhanced to provide functionality beyond lighting service. This functionality is primarily derived by integrating intelligence, sensors, and modern network communication interfaces into distributed lighting devices (e.g., luminaires, lamps). Data produced by sensors are shared with other lighting devices, as well as with non-lighting systems, to enable valuable data-driven applications. Examples of frequently cited CLS use cases include the monitoring of device electrical characteristics (e.g., operating voltage and current, hours of use) to identify and classify faults, and the use of occupancy data to set back temperature set points for specific HVAC zones or to optimize space utilization.

CLS MODEL FOR GRID SERVICES

In this section, a model for characterizing CLS is described. The model consists of parameters, each constraining the operation of CLS. The model is used to quantify the potential of CLS for participation in grid services. Parameters in the model (see Table 1) relate to two major questions for grid services: What kind of grid services can be provided, and how much of each grid service can be provided by CLS.

Table 1 CLS model showing possible control actions and model parameters

Possible control actions	Turn lights off
	Turn lights on
	Dim lights
	Brighten lights
Model parameters	Time delay
	Maximum power
	Minimum power
	Nominal power
	Maximum ramp rate

The time delay refers to the time interval between when a control action for grid service is requested (i.e., sent) and when the CLS begin to respond. Different CLS have different time delays, which range from 0.2 s to 20 s. It can be inferred that CLS may not be able to supply grid services that require changes in state at time intervals shorter than their time delays, while they may be able to provide services that depend on state changes that occur less frequently than the inverse of their time delay.

Two parameters, maximum power and minimum power, represent the upper and lower power limits of CLS, with the difference between them corresponding to the maximum available change in power that can be used to provide grid services. The maximum power refers to the most power that CLS can physically use, which is their rated power. The minimum power is the least power that CLS can use and still satisfy occupant needs and desires for lighting – which depends on a variety of factors, such as occupant activity, task performance, and real or perceived security. We set values for minimum power based on recommendations found in lighting standards and guidelines. The minimum can be compared to the nominal lighting power that is ordinarily recommended for the building type, based on the activities taking place. The nominal power represents the CLS power usage when no grid service is provided and corresponds to the routine CLS power-demand pattern.

The maximum ramp rate ensures occupant comfort with lighting by limiting the rate of change in illuminance in the lit space to values that are barely perceptible or entirely imperceptible by occupants. If CLS are dimmed or brightened too quickly, occupants may notice the lighting change, leading to complaints about the lighting system. From a dynamic point of view, the maximum ramp rate limits the range of power change during every time step. Thus, the maximum ramp rate provides an additional constraint on the types and amount of grid services that CLS can provide.

TRANSACTIVE CONTROL

TC is an innovative approach that integrates economic theory and control technologies to facilitate the active participation of price-responsive assets in power grid systems. TC was first implemented and demonstrated in the Washington Olympic Peninsula a decade ago (Hammerstrom et al. 2008), showing its benefit. With TC, electricity price is used as an input signal to instigate changes in control of the power demand of building assets. The price, in turn, is determined through coordination and negotiation among price-responsive suppliers and consumers. Li et al. (2016) give more details on transactive control.

TC can account for the preferences and needs of building occupants, and therefore will likely be found more appealing in a greater number of buildings than control methods that don't explicitly account for occupant preferences. It uses prices as incentives to motivate building owners and/or managers to adjust the electricity demand of building systems (e.g., lighting) based on the net value of participation to the building. As a result, TC may not be able to achieve the theoretical maximum building demand response, but ultimately it may attract many more buildings to participate in providing demand-response-based grid services, thereby providing the grid with a greater total service resource. In the simulations presented in this paper, the consumer is the CLS in one building, and the supplier is a utility. The consumer does not have enough market power by itself to influence the price from the utility, and in aggregate CLS will only have market power when the utility program becomes sufficiently large. So, the utility has a flat supply curve – i.e., the electricity price from the utility is fixed, regardless of the power used by the CLS – and the transactive control becomes a price-responsive control. At the beginning of each market period, the utility announces its price. The CLS, upon receiving the utility price, adjusts its power set point by finding the power corresponding to the utility price on its demand curve.

SIMULATION

Using simulation, we evaluate the potential of CLS for providing a basic grid service, real-time demand reduction, and the associated energy savings. We provide an example comparison between the maximum potential service of CLS and the amount of service obtained under TC.

DOE Prototype Building Models

Lighting in a medium office building, one of 16 publicly available prototype building models developed by the U.S. Department of Energy (DOE) (Deru et al. 2011; U.S. DOE 2018), was simulated in the work reported in this paper. DOE developed these models to represent new and existing commercial buildings in the U.S. commercial sector. Together, these prototypes represent 75% of the U.S. average new-construction volume between 2003 and 2018 and are widely used in building-energy research and development. Other recent research in grid-integrated efficient buildings (GEB) has made use of the prototype commercial building models. A recent Rocky Mountain Institute analysis of the GEB value potential of the U.S. General Service Administration buildings portfolio used the large office building prototype model (Jungclaus, et al. 2019). The medium (53,600 ft^2) office building model was used in other GEB analyses (ASHRAE 2019).

Lighting Demand Profile

Within the DOE building prototype models, each building is subdivided primarily into thermal blocks. Within the thermal blocks, the spaces are further subdivided into smaller spaces. Standard 90.1-2019 (ASHRAE 2019) values for lighting power density (LPD) were used to determine the maximum potential demand of each space in the medium office building. The maximum demand is calculated as

$$\sum_{spaces} fraction\ of\ total\ building\ area \times total\ building\ area \times LPD\ of\ the\ space \tag{1}$$

A determination was made that spaces would default to being grid-services eligible, except for spaces where safety issues associated with lower lighting levels might be a concern (e.g., stairways and electrical/mechanical rooms), spaces with very low occupancy (e.g., storage rooms), and other spaces with special considerations (e.g., guest rooms and hospital operating rooms). Finally, an assignment is made as to whether the space

Table 2 Medium office building space types and for each the portion of total building area represented by the space type, the lighting power density (LPD) to comply with ASHRAE Standard 90.1-2019, eligibility for U.S. Department of Energy Grid Enabled Buildings (GEB) space, and identification as daylit perimeter or core building space

Space Type	Portion of Building	Standard 90.1-2019LPD	GEB Eligible	Daylight or Core
Office open plan	42.4%	0.61	Yes	Daylight
Office enclosed	18.7%	0.74	Yes	Daylight
Corridor/transition	9.1%	0.41	Yes	Daylight
Conference meeting	5.2%	0.95	Yes	Daylight
Storage small	5.2%	0.51	No	Core
Storage large	1.9%	0.37	No	Core
Stairway	3.7%	0.48	No	Core
Lobby	3.7%	10.9	Yes	Daylight
Restrooms	3.6%	0.61	Yes	Core
Electrical /mechanical	3.0%	0.43	No	Core
Lounge /recreation	1.8%	0.56	Yes	Daylight
Dining area	0.9%	0.41	Yes	Daylight
Classroom /lecture	0.6%	0.71	Yes	Daylight
Food preparation	0.4%	1.09	Yes	Core

has access to daylight or is located within the core of the building. Table 2 provides a list of the spaces in the medium office building prototype, the portion of the building that each space type represents, and whether each space is eligible for grid service and has access to daylight.

As stated earlier in this section, the maximum lighting demand of the building is determined as in (1). However, this is the total demand allowed to be installed by Standard 90.1 (ASHRAE 2019). The DOE prototype building models also include lighting schedules for weekdays, weekends, and holidays. The schedule is expressed as a fraction of the maximum lighting demand by hour (e.g., 0.30 at 8:00 am,). The lighting model applies the DOE prototype lighting schedule by hour to the maximum demand to generate a nominal demand over the course of a day for the building type. A variety of lighting standards and guidelines were considered for establishing the maximum lighting reduction below nominal (i.e., the minimum lighting power). A 30% reduction – which is based on lighting research that has long suggested that 30% is the threshold for detection – was chosen for use in this work. An example lighting demand profile on a weekday in a medium office building is presented in Figure 1, where the maximum, nominal, and minimum demand profiles are shown.

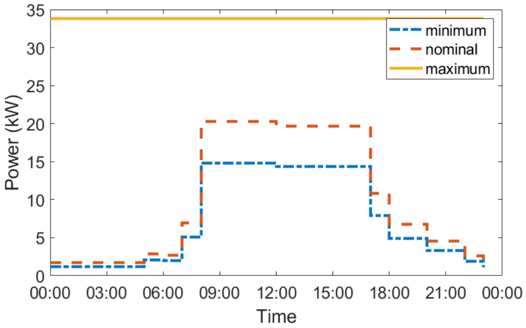

Figure 1 The minimum, nominal, and maximum CLS power profiles for weekdays

CLS Demand Curves

Demand curves that describe the relationship between lighting-power demand and electricity price, each at a specific time of day, were developed for use in the simulation of TC. For the stepped CLS power profiles in Figure 1, there is a unique demand curve for each fixed power level and the time period for which it applies, thus multiple demand curves. The demand curves were developed under the assumption that the building management always wants to reduce the CLS power below the nominal CLS power, and the slopes of the demand curves quantitatively describe the building management's willingness to change the lighting power demand in response to changes in electricity price. When

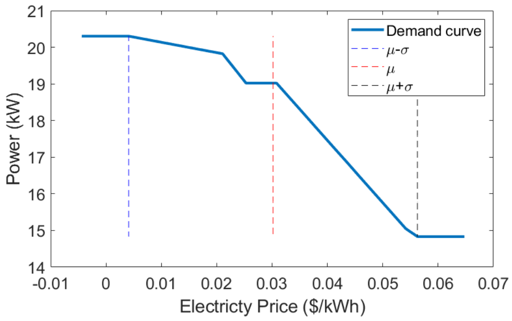

Figure 2 Demand curve from 8 a.m. to 12 p.m., 01/30/2019, for a 30% maximum decrease from the nominal CLS power

the price is lower than the difference between the mean (μ) and the standard deviation (σ) of the 5-minute price-time series for the last year, the CLS demands the nominal power. When the price is higher than $\mu + \sigma$, the CLS maintains the power at the minimum power (which corresponds to the maximum reduction in CLS power**).** An example lighting-demand curve corresponding to a specific time period is shown in Figure 2. When the electricity price decreases below μ, the curve shows that the lighting power demand could increase by as much as 1.3 kW (6.8%). While such an increase is not likely with today's rates being predominantly flat, utilities and other grid entities may offer real-time pricing programs to commercial customers in the future, as the need for grid services from nonconventional generation resources potentially increases. If electricity price increases above μ, the demand curve shows that lighting power use decreases. A higher price provides an incentive for decreasing power demand, enabling grid entities to use price as an incentive for commercial customers to decrease demand when the grid requires the associated service to maintain system operation in normal ranges. This lighting system would incrementally decrease its power demand as the price rises and would increase its demand as the price falls. When the price is too high (e.g., larger than $0.06 /kWh) or very low (e.g., close to $0.00/kWh or even a negative value), the CLS would not respond to any price change, because further increases in the amount of lighting have no value for uses in the building spaces, as indicated by the flat demand curve for prices below $\mu - \sigma$; further decreases in lighting would be unacceptable for prices above $\mu + \sigma$, because the risk of reduced task performance is too great with less lighting.

The nominal power and minimum power of CLS vary with time of day, as shown in Figure 1. To make full use of the lighting profile and TC to achieve demand reduction and the associated energy savings, the price-responsive part of the demand curve, which represents the prices for which power demand varies (e.g., the sloped parts of Figure 2), is scaled to fit the nominal and minimum powers in the lighting profiles. This is a reasonable assumption, because the occupancy of the medium office building varies with time. The total building lighting power increases from the unoccupied level overnight as occupants enter the building in the morning and decreases in the late afternoon through the evening as occupants leave work, until it again reaches the unoccupied level. Therefore, the changes in CLS power over the day (in the absence of electricity price changes) are presumed to be attributable to lights turned on and off rather than to dimming and brightening of lighting.

Simulation Platform

The simulations are carried out on the VOLTTRON platform, an open-source, distributed sensing and controls platform for buildings and the power grid. VOLTTRON enables the integration of buildings with the grid to support the deployment of energy efficiency and grid distribution reliability and resilience services (Katipamula, Haack, et al. 2016; Katipamula, Lutes, et al. 2016; Katipamula, Gowri, and Hernandez 2017). To run the TC for the CLS on VOLTTRON, four agents are constructed: the CLS agent, the control agent, the price publisher, and the database. An Information Exchange Bus (IEB) allows all agents to publish and subscribe to data points. The CLS model agent represents the characteristics of CLS, including the maximum power, nominal power, minimum power, and time delay. The control agent is used to determine the value of the CLS power set point from the electricity price and the demand curve. The control agent responds to varying electricity prices with a knowledge of the CLS power profile, the CLS ramp rate, and the CLS demand curve, which are obtained from external inputs. The database stores all the input and output data for postprocessing.

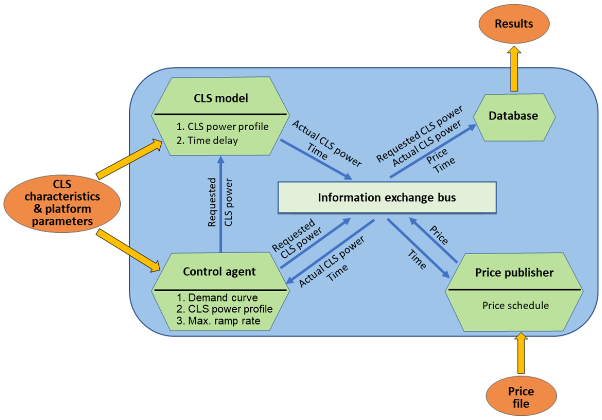

Figure 3 Structure of the simulation platform for TC of CLS, including external inputs and data flows

The price publisher publishes the electricity price on the IEB every time a new price is available (every five minutes for real-time electric rates, which defines a transactive market period). The structure of the software platform is illustrated in Figure 3.

At the beginning of each market period, the price publisher first reads the electricity price from a price file and publishes it to the IEB. Because the control agent subscribes to the electricity price, it automatically receives the new price upon its publication on the IEB. Using the new price and the demand curve, the control agent updates the power set point implementing constraints associated with the maximum ramp rate and the upper and lower bounds on the lighting power at the present time. The control agent then publishes the new CLS power set point on the IEB. The CLS model, which subscribes to the power set point, then begins to change its power to the requested set point after the time delay has passed.

RESULTS AND DISCUSSION

CLS in a medium office building are simulated using a minimum power that is 30% below nominal. The maximum, nominal, and minimum powers are obtained from the lighting profiles (see Figure 1). The time delay and the maximum ramp rate are set to be two seconds and 0.5% of the maximum CLS power per second, respectively. The maximum potential of CLS for demand reduction is first determined from the CLS model. The maximum demand reduction is the difference between the nominal power and the minimum power at any time, and the maximum cumulative energy saving is the integral of the maximum demand reduction over time. Constraints imposed by the time delay and maximum ramp rate in the CLS model prevent the CLS from instantly reaching their power set points (for non-zero delays and lighting-power rates of change that exceed the ramp rate). Thus, the maximum achievable demand reduction may be less than the ideal maximum demand reduction. However, in this simulation, as the time delay and the ramping process take a very short time (from sub-seconds to seconds) compared to the period of the service request – e.g., five minutes for real-time (as the grid industry refers to this) demand-response-based services – their impacts are negligible. Therefore, in this paper, the maximum demand-reduction potentials of the CLS equal the difference between the nominal power and the minimum power as provided in the lighting profiles, examples of which are shown in Figure 1.

To achieve the maximum potential, the grid service requester (e.g., the local utility) needs to notify the building in some way that a service based on demand response is needed. A common approach to this in utility programs today is direct load control, which the building signs up to participate in. When service is needed, the requester takes control of the applicable building system and changes its state (e.g., by forcing air-conditioning systems to suspend cooling for a fixed time period). Such commands, which do not directly consider the needs of the building occupants at the time that action is taken, impact the quality of service (e.g., comfortable temperatures) to the building occupants.

To explore the potential for capturing the maximum reduction in CLS power in practice, we apply transactive control to the CLS and determine, for an example electricity price-time series that is updated every five minutes, how much service can be obtained. With TC, the market is cleared every five minutes. At the beginning of each five-minute market period, the utility submits its supply curve, which is flat in this simulation under the assumption that there is an insufficient number of program participants to affect the electricity prices (although over time this could change). The electricity price comes from historical commercial customer real-time (5-minute) price-time series for the Commonwealth Edison commercial real-time rate (ComEd 2020), which the simulation uses as the price schedule input file. The price-responsive part of the demand curve lies between the $\mu - \sigma$ and $\mu + \sigma$ prices. The lighting power of the CLS demand curve ranges between points on the nominal CLS power profile and the minimum CLS power profile at the present time (see Figure 1). An example CLS demand curve is shown in Figure 2. This demand curve is overall down-sloped, with lighting-power demand decreasing in the range from $\mu - \sigma$ to $\mu + \sigma$. For prices below $\mu - \sigma$, the demand does not increase, because additional light is of no value to occupants; for prices above $\mu + \sigma$, demand does not increase, because lower lighting would not support task performance.

The results of a simulation of TC between January 28, 2019 and February 1, 2019 (the workweek in 2019 with the greatest variability in the ComEd real-time electric rate) are presented in Figure 4.

The maximum potential of CLS for demand reduction, the demand reduction with TC, and the associated energy savings in a medium office building are presented for the same time period in Figure 5, where the upper subplot shows the power-demand reductions corresponding to the power profiles shown in Figure 4, and the lower subplot shows the cumulative energy savings compared to the nominal lighting profile. In each of the five weekdays, the maximum potential demand reduction is greater in the occupied business hours than in the off-business hours. The cumulative maximum potential and TC energy savings shown in the lower plot of Figure 5 are the integrals of the respective demand-reduction curves over time. The demand-reduction curve shown

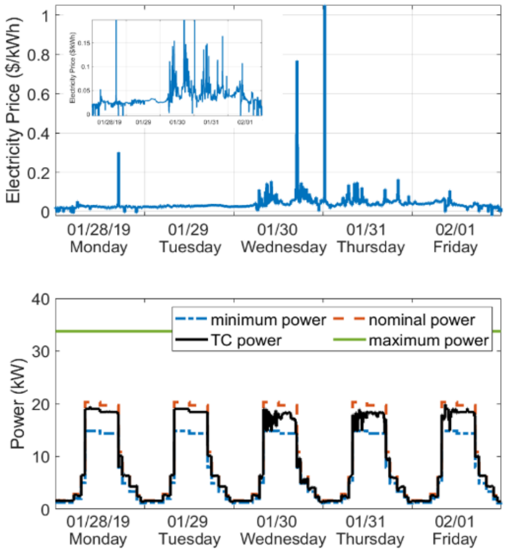

Figure 4 Real-time price data (top) and CLS profile and TC controlled CLS power (bottom)

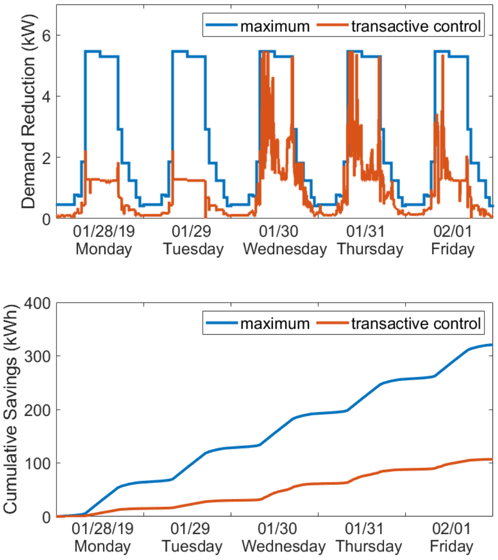

Figure 5 Demand reduction (top) and cumulative energy savings (bottom)

for TC varies day by day and over the hours of each day. These variations in demand reduction are caused by price differences across the five days. When the price is relatively low (e.g., on 01/28 and 01/29), the CLS under TC demand more power (Figure 4) due to the downward slope of the demand curve, and thus have relatively small demand reductions. When the price is considerably higher on the other days, the CLS under TC consume less power, and thereby providing more grid service. The resulting cumulative energy savings for TC for this workweek are only 33% of the maximum savings possible for the CLS analyzed.

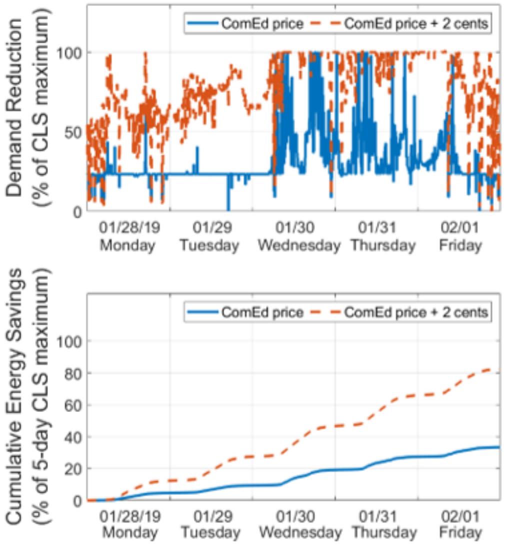

Figure 6 Comparison of demand-reduction percentage (top) and energy-savings percentage (bottom) of CLS at different prices

The demand reductions and energy savings from TC increase substantially at higher electricity prices. To examine the impact of a price increase, TC was simulated for a second real-time price-time series having the same variability as the profile shown in Figure 4, but with the price increased by $0.02/kWh relative to the time series in Figure 4. The demand reductions and energy savings as percentages of the maximums possible for the CLS using the new prices are compared to those for the original ComEd price-time series in Figure 6. The electricity price increase substantially increases demand reductions (top plot) and energy savings (bottom plot), with the cumulative savings increasing from 33% to 80% of the CLS maximum, showing that that selection of the right prices during times when grid service is needed is critical to obtaining the desired contribution from building CLS.

CONCLUSIONS

A model of CLS was constructed to evaluate the potential of CLS to provide grid services. The model consisted of maximum power, nominal power, minimum power, maximum ramp rate, and time delay of the CLS.

The potential of CLS for demand reduction and the associated energy savings were explored with the CLS model for a representative medium office building subject to the ComEd real-time commercial electric rate. TC was applied to the CLS to quantify the fraction of the maximum potential demand reduction that can be captured under this control approach. Two example price profiles were simulated, yielding 33% and 80% of the maximum potential energy savings. Continuing work will extend this investigation to other price profiles, CLS characteristics, building types, kinds of grid services, and coordinated control with other building systems.

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