Energy and Buildings 152 (2017) 216–226

Contents lists available at ScienceDirect

Energy and Buildings

journal homepage: www.elsevier.com/locate/enbuild

Explaining inefficiencies in commercial buildings providing power system ancillary services[☆]

Yashen Lin[a], Johanna L. Mathieu[b,*], Jeremiah X. Johnson[c], Ian A. Hiskens[b], Scott Backhaus[d]

[a] University of Michigan, Department of Electrical Engineering & Computer Science and School of Natural Resources & Environment, United States
[b] University of Michigan, Department of Electrical Engineering & Computer Science, United States
[c] University of Michigan, School of Natural Resources & Environment, United States
[d] Los Alamos National Laboratory, Center for Nonlinear Studies, United States

ARTICLE INFO

Article history:
Received 29 December 2016
Received in revised form 14 May 2017
Accepted 14 July 2017
Available online 17 July 2017

Keywords:
Ancillary services
Commercial buildings
Energy efficiency
HVAC

ABSTRACT

Ancillary services are required to balance supply and demand in electric power systems. Demand response may provide attractive options for these services, through means such as varying the power consumption of commercial building HVAC systems. However, experimental results from a 30,000 m^2 office building suggest that when a building provides ancillary services it consumes more energy than when it is operated normally. This translates to additional costs and environmental impacts.

This paper investigates potential causes for building inefficiency associated with ancillary services provision. We develop a physics-based simulation model that captures heat exchange processes and fan and air duct dynamics. During an ancillary service event, we vary the fan power consumption, and then compute the difference between the baseline and actual energy consumption to determine the efficiency of the actions. We explore the impact of building parameters, control design, and baseline model accuracy on the efficiency.

In simulation, we find that shorter duration power changes and less aggressive controllers result in less change in energy consumption. We also find that baseline error has outsized effects on the efficiency calculations. These results offer new understanding of the mechanisms underlying inefficiency and point to opportunities to reduce associated costs and environmental burdens.

1. Introduction

In an electric power system, electricity supply and demand must be balanced to maintain the system frequency at its nominal value (e.g., 60 Hz). With more variable renewable energy sources, such as wind and solar power, integrated into the system, this task becomes harder as they introduce more supply-side variability and uncertainty. Thus, more ancillary services are needed to correct the supply-demand mismatch in real time [2,3]. Ancillary services are defined by the Federal Energy Regulatory Commission (FERC) as "those services necessary to support the transmission of electric power from seller to purchaser given the obligations of control areas and transmitting utilities within those control areas to maintain reliable operations of the interconnected transmission system" [4]. Ancillary services include balancing services such as frequency regulation and load following.

Traditionally, balancing services have been provided by conventional generators, such as natural gas power plants, which hold some capacity in reserve so that they can ramp up or down according to the power grid's needs. Recently, researchers have explored the potential of using the demand-side to provide balancing [5]. Similar to conventional generators, aggregations of electric loads can increase and decrease their consumption to help balance the power system. A few examples of loads that can provide balancing include residential loads [6], electric vehicles [7], pool pumps [8], and commercial buildings. Commercial buildings consume about

---

[☆] A preliminary version of this work was presented at the ACEEE Summer Study on Energy Efficiency in Buildings [1]. This work was funded by the University of Michigan Energy Institute, the University of Michigan MCubed Program, and National Science Foundation Grant CBET-1510788. The work at LANL was funded by the Microgrid Program in the Office of Electricity in the U.S. Department of Energy and was carried out under the auspices of the National Nuclear Security Administration of the U.S. Department of Energy at Los Alamos National Laboratory under Contract No. DE-AC52-06NA25396.

[*] Corresponding author at: University of Michigan, United States.

E-mail addresses: yashen.lin@nrel.gov (Y. Lin), jlmath@umich.edu (J.L. Mathieu), jxjohns@umich.edu (J.X. Johnson), hiskens@umich.edu (I.A. Hiskens), backhaus@lanl.gov (S. Backhaus).

http://dx.doi.org/10.1016/j.enbuild.2017.07.042
0378-7788/

40% of the electricity in the United States, and half of it is by heating, ventilation, and air conditioning (HVAC) systems [9]. Also, the large thermal inertia of commercial buildings makes it possible to provide balancing without significantly affecting the indoor climate [10–15].

In simulations and demonstrations, it has been shown that commercial building HVAC systems are capable of providing satisfactory ancillary services [10–15]; however, the impacts of providing such services on the energy consumption of the building are not well understood. In an experimental study [16] with a 30,000 m^2 office building in New Mexico, the building fan power was made to track a square wave power reference signal designed to be energy neutral with respect to the building's baseline energy consumption. It was observed that the building consumed more energy than under normal operation. Modeling the building as an energy storage unit, the round-trip efficiency of the fan and chiller was found to be only 42% on average. This additional energy translates to additional costs and environmental impacts.

In contrast, in an experimental study with a 120 m^2 test facility at Lawrence Berkeley National Laboratory, Berkeley, CA [17,18], it was observed that when the fans conditioning a thermally isolated 60 m^2 test cell were made to track a frequency regulation signal (specifically, a PJM Interconnection RegD signal [19]) the energy consumption was *slightly lower* than that of a 60 m^2 control test cell. In addition to being much smaller than the New Mexico building, the test facility has both a chilled water tank and a hot water tank, and uses a single chiller for both test cells. The water tanks provide thermal inertia, likely improving the round-trip efficiency. Note that [17,18] consider two types of efficiency loss – reserve availability efficiency loss (i.e., additional energy use from operating the building at a suboptimal operating point in order to be able to provide reserves) and reserve utilization efficiency loss [20]. The latter corresponds to the efficiency considered in this paper.

It may still be a net cost and/or environmental "win" to use commercial buildings to provide ancillary services to power systems even if their energy use increases, for example, if it enables higher renewable energy penetrations. Similar scenarios with energy storage devices have been studied by many researchers; see, for example, [21,22]. It has been demonstrated that even with round trip losses, energy storage devices can be beneficial for the system. However, to determine if this is the case for commercial buildings, we need to know (i) if the findings in [16] and/or [17,18] are generalizable and (ii) what are typical efficiencies. Additionally, we would like to know (iii) what is causing the inefficiency observed in [16] and (iv) if there are ways to improve the efficiency.

In this paper, we consider item (iii), specifically we investigate the causes of inefficiencies associated with using commercial building HVAC systems to provide balancing. This is challenging due to the complex building dynamics, which motivated us to investigate if there is inefficiency in a more ideal setting and what are the fundamental drivers that cause the inefficiency. We develop a model for a commercial building and its HVAC system, and undertake simulations to study the impacts of providing ancillary services on building energy consumption. Our goal is not to accurately model the New Mexico building, but rather to understand the fundamental drivers for the observed inefficiency. Therefore, we develop a simple first principles physics model rather than using building simulation software like EnergyPlus [23]. We model the heat exchange processes between the rooms and the ambient environment, in addition to the fan, air duct, and cooling coil dynamics, and assume a nonlinear mapping between room thermostat set point deviations and the resulting changes in the fan power. We investigate the impact of the following factors on the efficiency: magnitude of the power change, duration of the power change, order of the power change (increase/decrease vs. decrease/increase), controller objective (power vs. temperature), aggressiveness of controller, shape of the power reference signal, building thermal capacitance, and outdoor air ratio. We find that multiple factors contribute to the change in building energy consumption including nonlinearities, heat exchange with the outside, control actions, and baseline estimation error. Building parameters, such as thermal capacitance, also impact the efficiency.

The remainder of this paper is organized as follows. Section 2 describes the experimental results of Beil et al. [16], lists our modeling assumptions, presents the mathematical formulation of our model, defines our efficiency-related metrics, and describes our simulation study. Section 3 presents the simulation results and Section 4 presents a discussion of the results. Section 5 concludes and describes directions for future work.

2. Methods

In this section, we describe results from the previous experiments, our modeling assumptions, the building/HVAC model, and the simulation setup.

2.1. Summary of previous experiments

In the experiments reported in [16], the room temperature set points were actuated so that the supply air fan power deviation from the baseline approximately tracks a square wave power reference signal, using the temperature set point/power mapping developed in [24]. All experiments were conducted in the summer, when the building HVAC was in cooling mode. Fig. 1 shows a conceptual example of the experiment. At the beginning of an ancillary service event, the temperature set points are changed to increase/decrease the power, after 15 min the temperature set points are changed again to decrease/increase the power, and after 15 additional minutes the temperature set points are returned to normal. Estimated baselines were computed by linearly interpolating "short windows of data" directly before the event and two hours after the start of the event [16]. We refer to events that first increase and then decrease power as "up-down" events (as in Fig. 1), and we refer to events that first decrease and then increase the power as "down-up" events. Both types of events were tested in [16].

In [16] it was observed that after an ancillary service event ends, the fan power does not return to the baseline power immediately. Instead, there is an overshoot (as shown in Fig. 1), which leads to additional fan and chiller energy consumption. It was also observed that the sequence of the power change (up-down vs. down-up) affects the results. Let E_{in} be the energy consumption above the baseline and E_{out} be the energy not consumed below the baseline during the interval corresponding to the baseline estimate (i.e., two hours from the start of the event), as depicted in Fig. 1. In [16] the round-trip efficiency is defined as:

$$\eta_{RT} = \frac{E_{out}}{E_{in}}. \tag{1}$$

The average round-trip efficiency over all experiments was found to be 0.46 for the fan alone and 0.42 for the fan and chiller. For up-down events the average efficiency was 0.61 and for down-up events the efficiency was 0.34. Efficiencies computed for individual events exhibit a large variation, from 0.10 to 1.80 (see Fig. 5 in [16] for the empirical probability density function of efficiencies).

There could be multiple causes of the inefficiency observed in [16], including nonlinearities, heat exchange with the outside, controller design, and baseline estimation errors. In this study, we undertake simulations that have a similar form as the experiments of [16] in an effort to understand the underlying drivers of the inefficiency.