Energy 84 (2015) 161–176

Contents lists available at ScienceDirect

Energy

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

Evaluating synergistic effect of optimally controlling commercial building thermal mass portfolios

Gregory S. Pavlak [a], [*], Gregor P. Henze [a], [1], Vincent J. Cushing [b]

[a] University of Colorado, Boulder, CO, USA
[b] QCoefficient, Inc., Chicago, IL, USA

ARTICLE INFO

Article history:
Received 15 September 2014
Received in revised form
27 January 2015
Accepted 22 February 2015
Available online 20 March 2015

Keywords:
Buildings to grid
Portfolio optimization
Demand response
Frequency regulation
Model predictive control
Smart buildings

ABSTRACT

In order to achieve a sustainable energy future, advanced control paradigms will be critical at both building and grid levels to achieve harmonious integration of energy resources. This research explores the potential for synergistic effects that may exist through communal coordination of commercial building operations. A framework is presented for diurnal planning of multi-building thermal mass and HVAC system operational strategies in consideration of real-time energy prices, peak demand charges, and ancillary service revenues. Optimizing buildings as a portfolio achieved up to seven additional percentage points of cost savings over individually optimized cases, depending on the simulation case study. The magnitude and nature of synergistic effect was ultimately dependent upon the portfolio construction, grid market design, and the conditions faced by buildings when optimized individually. Enhanced energy and cost savings opportunities were observed by taking the novel perspective of optimizing building portfolios in multiple grid markets, motivating the pursuit of future smart grid advancements that take a holistic and communal vantage point.

1. Introduction

Global electricity demand has been projected to increase more than any other final form of energy from 2011 to 2035. The expected growth rates range from 1.7% to 2.5% per year, and are partially attributable to the increasing cooling needs of buildings [1]. To create a more sustainable energy future a transition to greater renewable electricity generation is necessary. This transition, however, does not come without challenges. Numerous electric systems have been developed primarily with predictable generation sources in mind. Coal, gas, and nuclear generating plants produce fairly consistent output for known quantities of input fuel, which allows reliable scheduling of such supply resources to accommodate changing and uncertain consumer demand. Predictable generation sources can be controlled and dispatched to maintain power system balance, ensuring a reliable supply of electricity. In the U.S., the majority of prime hydroelectric resources are currently being utilized and considering present technologies and economics, near future advances towards renewables are likely to be dominated by wind and solar resources. However, unlike traditional resources, the output of wind and solar generation is inherently variable making scheduling and dispatch of such supply sources seemingly impossible [2]. If not properly integrated, large quantities of variable generation may result in power quality issues, power flow imbalances, and grid stability issues [3].

One evident solution to accommodate the variable nature of wind and solar resources is to provide storage capacity. Grid storage technologies such as pumped-hydro, compressed air, and grid-scale batteries allow variable generation to be captured when a resource is available and dispatched as demand necessitates. Additionally, a National Renewable Energy Laboratory report studying the integration of wind and solar resources in the western U.S. determined that pursuing demand response and load participation programs would be critical in achieving higher penetrations of variable resources [4]. Buildings contain significant thermal mass that can be utilized as a valuable distributed storage asset for a variety of applications. At the building level, thermal mass storage can be purposed to tasks such as peak demand management, demand response, and increasing energy efficiency through optimizing HVAC operations. Multiple building thermal mass resources can also be aggregated and operated in concert to achieve grid-

---

[*] Corresponding author. Tel.: +1 269 266 2148.
E-mail addresses: gregory.pavlak@colorado.edu (G.S. Pavlak), vince.cushing@qcoefficient.com (V.J. Cushing).
[1] Tel.: +1 303 492 1094. gregor.henze@colorado.edu

http://dx.doi.org/10.1016/j.energy.2015.02.073
0360-5442/© 2015 Elsevier Ltd. All rights reserved.

scale objectives such as mitigating transmission congestion and the associated real-time nodal price spikes, shifting demand to increase renewable utilization, and displacing inefficient peaking or marginal generating equipment. Achieving such grid-level benefits may require a higher degree of orchestration and a shift in perspective from individual to holistic optimality.

To this end, this research presents a framework for diurnal planning of multi-building thermal mass and HVAC system operational strategies in consideration of real-time energy prices, peak demand charges, and ancillary service revenues, in order to explore the synergistic effects that may exist through communal coordination of commercial building operations. In Section 2 additional context is provided through the review of relevant literature. Section 3 describes the development of building energy models and the multi-building optimization framework. Results for two portfolio simulation case studies are presented in Sections 4 and 5, and closing conclusions are provided in Section 6.

2. Background

Optimal control of building thermal mass has been the subject of much research over the past two decades. Braun showed optimal thermal mass control had the potential for significant savings by applying dynamic optimization to computer simulations [5]. Rabl and Norford investigated night pre-conditioning to reduce peak demand [6]. Morris et al. used simulations to develop minimum energy cost and minimum demand precooling strategies, achieving 10% energy and 38% demand savings when implemented in a test facility [7]. Keeney and Braun similarly developed a precooling strategy for a 1.4 million square foot office building, and showed that peak load was successfully limited to 75% when an appropriate precooling strategy was deployed [8]. Henze et al. described a methodology for including demand charges in the optimization through the addition of a penalty function that deters exceeding a TDL (target demand limit) [9]. Ma et al. developed optimal thermal mass strategies under time-of-use energy pricing [10], and Greensfelder et al. applied real-time energy pricing [11]. Strategies for short-term demand curtailment that utilized building thermal inertia were presented by Olivieri et al. [12].

In general, past work in optimal building control has typically viewed buildings as independent entities consuming grid resources to meet the needs of their respective tenants. Optimal strategies were developed considering a single building's ability to shift load, resulting in savings evaluations performed at the facility level. This operation, while optimal in the individual sense, neglects the fact that buildings are all connected to the same electric grid. The aggregation of individual optimal solutions may in fact be suboptimal when considering the characteristics and operations of other buildings and viewing the problem from a communal perspective.

The potential benefits of a multi-building outlook were explored by ASHRAE RP-1146, which sought to 1) identify situations where managing total multi-building electric demand through load aggregation was attractive, and 2) investigate control strategies that would further reduce energy costs at the aggregate level. Load aggregation may seek to benefit from the fact that the coincident peak load is not necessarily the sum of individual load peaks (i.e. demand diversity). One aspect of this work included a simulation study of an office, retail, and hotel building to illustrate load aggregation benefits as well as explore the combined effects of load aggregation with curtailment measures. Load curtailment included simultaneous lighting power, equipment power, and ventilation rate reductions as well as temperature setpoint increases. Simulation results showed that: 1) approximately 8% of demand cost savings could be achieved through load aggregation, 2) 6% demand cost savings were possible when aggregating loads with curtailment measures already in place, and 3) 36% demand cost savings could be achieved through the combined addition of curtailment measures and load aggregation [13].

Several multi-building load control and optimization examples were also investigated by Xing [14]. In one study, increases in afternoon zone setpoints were explored to minimize peak demand or utility cost. In a second study, the start time of night cooling was examined along with four discharge strategies (i.e. constant 24°, constant 25° from 8 AM–11 AM, slow linear increase, and fast linear increase.) Smart enumeration and genetic algorithm optimization techniques were applied to explore combinations of predefined control strategies.

In addition to bulk load shifting and shaping, recent work has also suggested that the flexibility available in commercial building electric demand can be used to provide electric grid balancing and ancillary services. Kiliccote et al. have successfully bid commercial building demand response into a day-ahead non-spinning reserve market [15]. Simulation test beds have been used to evaluate the modulation of commercial HVAC equipment to provide grid frequency regulation [16–18]. Maasoumy et al. developed a model-predictive controller to direct building frequency regulation as a supplement to traditional AGC (Automatic Generation Control), resulting in improved electric system performance [19]. Lin et al. present experimental results from providing frequency regulation through fan speed modulation [20]. An intelligent demand response management program to coordinate electric vehicle charge scheduling, variable speed HVAC components, and load curtailment measures to maintain a contracted demand limit was introduced by Sivaneasan et al. [21]. Chen et al. implement model-predictive control to coordinate residential appliance scheduling under real-time retail pricing considering building thermal storage [22]. Transactive control and coordination, where participants and devices bid for energy demands in a market-like control network, has been described by Subbarao et al. for coordinating a large number of distributed smart grid assets, including demand-side resources [23]. Additionally, a double-auction market as also been demonstrated for coordinating price-responsive electric loads in an existing utility grid to improve system operations [24].

In general, the surveyed literature depicts buildings as becoming more active and responsive grid participants through the development of enabling technologies and intelligent control paradigms. The literature also highlights the challenge of integrating and orchestrating an increasing number of intelligent systems and subsystems, to achieve higher levels of system-wide efficiency.

Buildings are diverse in physical design and operation and it seems a high-level of coordination may be necessary to achieve the maximum overall benefit by unlocking opportunities to cooperate on achieving joint objectives. More than simply providing a demand response mechanism, it is suggested in this research that model predictive control of building portfolios provides a framework for optimally managing multi-building load resources such that greater benefits can be provided to building owners and the electric grid than when optimizing buildings independently. By giving the optimizer the knowledge of all unique building characteristics available within a portfolio of buildings, various features may be exploited to orchestrate an optimal combined operation of all portfolio members. Fundamental to the idea of this research is the belief that diversity among building characteristics and operations creates opportunities for synergy. Building system interactions are complex and often difficult to comprehend for a single building, which makes it difficult to know how and when synergistic effects may arise among building portfolios. Therefore, further research was needed to investigate the opportunity for synergistic effect among building portfolios and motivate future pursuits of cooperative load control.