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Optimal electricity rate structures for peak demand reduction using economic model predictive control

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ABSTRACT

Economic model predictive control (EMPC) has recently gained popularity for managing energy consumption in buildings that are exposed to non-constant electricity prices, such as time-of-use prices or real-time prices. These electricity prices are employed directly in the objective function of the EMPC problem. This paper considers how electricity prices can be designed in order to achieve a specific objective, which in this case is minimizing peak electricity demand. A primal-dual formulation of the EMPC problem is presented that is used to determine optimal prices that minimize peak demand. The method is demonstrated on a simulated community of 900 residential homes to create a pricing structure that minimizes the peak demand of the community of homes. The pricing structure shows that homes should be given a 1-h peak demand duration, and that the peak prices given to the homes should be spread unevenly across 6 h of the afternoon.

1. Introduction

Economic model predictive control (EMPC) has found considerable popularity in managing building energy systems. This has in large part occurred as electricity rate structures have moved away from constant electricity prices to variable electricity prices, so the ability of including these variable rates in an objective function is valuable. Buildings inherently contain thermal mass which can be used to store thermal energy, and because a significant component of a building's electricity consumption is related to the heating, ventilation, and air conditioning (HVAC) system, the building's thermal mass can be used as thermal energy storage to shift loads in time. This thermal energy storage allows the building to consume electricity for the electricity-heavy HVAC system during times when electricity prices are lower, and draw from the thermal storage when prices are higher. However, managing this kind of thermal storage system requires advanced control, and model predictive control has been found to be a useful tool for managing such a system [1]. By using model predictive control, the variable electricity prices can be placed directly into the objective function [2,3], and the building's energy system can be modeled using dynamic models. Thus, the EMPC manages the HVAC system, thermal mass, and occupant comfort requirements in a way that minimizes the electricity costs of the system, especially when electricity prices change throughout the day. Other energy systems such electric vehicle charging networks [4], chilling networks [5], and IGCC power plants [6] have also found success using EMPC in the face of variable electricity prices, but this paper will focus on EMPC for residential building HVAC systems.

There are most commonly two general types of variable electricity rate structures: time-of-use (TOU) electricity prices and real-time or spot electricity prices, though variations of each of these rate structures exist. Time-of-use rate structures are known in advance and typically have several levels of electricity prices based on the time of day, day of the week, and season of the year. For example, the TOU rate for residential homes in Austin, Texas, USA, is shown in Fig. 1. Real-time electricity rates are typically set through market mechanisms, where bids for buying and selling electricity are used to set the electricity price. These prices are generally not known in advance and can potentially vary quite dramatically. Fig. 2 shows the real-time market prices for August 21, 2011, in the Austin Load Zone of the Electricity Reliability Council of Texas (ERCOT) grid. This day had a particularly high demand, which is why there were higher-than-normal price spikes during the afternoon.

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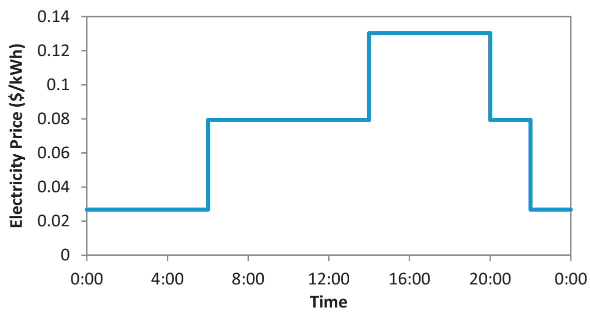

Fig. 1. Time-of-use prices in Austin, TX, for a weekday in the summer [7]. The highest prices ("on-peak" prices) occur from 14:00 to 20:00.

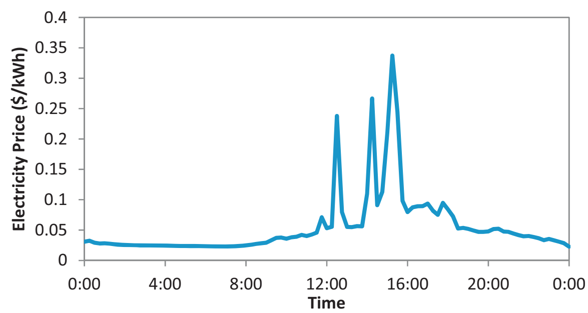

Fig. 2. Real-time settlement point prices for the Austin Load Zone in the ERCOT market on August 21, 2011. These prices are set every 15 min by a bidding process. Electricity demand was especially high this day, which is one of the reasons for the higher-than-normal price spikes during the middle of the day.

One variation of TOU prices that is important to the results in this paper is critical peak pricing (CPP). Critical peak pricing is typically a higher-priced, shorter duration TOU rate structure that is only implemented on a few days during a season. Customers are generally notified a day in advance of a critical peak day, and then the high prices are realized. An example CPP rate structure is shown in Fig. 3. A review of time-varying pricing trials by Newsham and Bowker [8] suggests that CPP is the most effective pricing strategy for peak reduction, yielding peak reductions of 30% when enabling technology is available. They also suggest that a simple TOU rate will result in a 5% peak reduction.

Commercial building energy systems have received more attention in the literature for EMPC than residential buildings, primarily due to the larger scale of commercial buildings. Ma et al. [10] developed a simulation environment for EMPC of a commercial building using TOU electricity prices. They were able to implement the strategy for an actual office building [11], demonstrating its ability to reduce peak energy consumption.

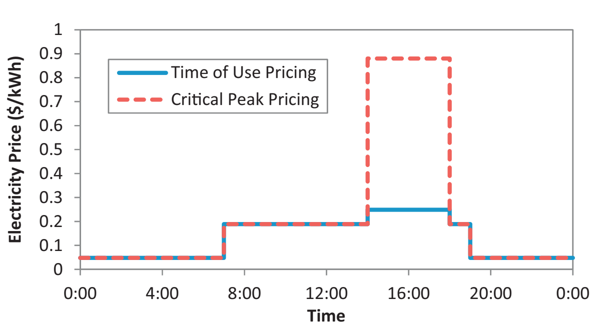

Fig. 3. Critical peak pricing (CPP) rate structure from a utility in Milwaukee, Wisconsin [9]. The CPP pricing event can be called by the utility up to 25 times per year. Customers are notified by 19:00 on the evening before a CPP event occurs.

Henze et al. [12,13] evaluated EMPC for active and passive thermal storage systems. Passive thermal storage systems take advantage of the thermal mass in the building, while active thermal storage systems also have a chilled water or ice tank to store additional thermal energy. They found EMPC to be an effective means for managing both passive and active systems. Similar investigations of EMPC for commercial buildings have been performed by a variety of other researchers [14–18].

Oldewurtel et al. [19] used an EMPC formulation in conjunction with forecasts for electricity spot prices to lower peak demand. They concluded that the electricity prices must be properly tuned in order to optimally decrease peak demand, but did not investigate methods to do so.

Economic MPC for residential buildings has been performed, but in fewer instances. Touretzky and Baldea [20] compared EMPC to set point tracking MPC using nonlinear reduced-order models for residential homes, finding that EMPC can maintain the required thermal comfort while simultaneously reducing costs. Halvgaard et al. [21] used EMPC to manage a ground source based heat pump for providing heating to a residential home. They found that in the face of variable electricity prices, the EMPC system can reduce electricity costs by 25–35%.

Electricity use in the residential sector is especially important in regions with high penetration of air conditioning. For example, in the ERCOT grid residential homes accounted for over 50% of the summer peak demand during 2011 [22]. Increasing peak demand creates challenges for utilities because peaking plants are generally unattractive due to the fact that they may operate for only tens or hundreds of hours per year. This underutilization often results in peaking plants that are the least capital intensive, and therefore often the most inefficient. The residential sector creates a ripe area for shaping demand to lower its peak, rather than increasing supply in order to meet that peak.

In this paper, a method is presented that uses a primal-dual formulation to determine the optimal pricing structure for reducing the peak demand in a simulated community of homes. Coupling the primal and dual formulations of the system makes it possible for the prices to become decision variables for achieving the desired peak reduction results. The next section, Section 2, gives an overview of the community of homes that comprises the dynamic system considered here. The following section, Section 3, presents the methodology for using the dual formulation to obtain the optimal prices. The results and some discussion are presented in Section 4, and the paper is concluded in Section 5.

The use of a dual formulation to find optimal prices for an electricity system is not new. Bohn et al. [23] used the dual variables of a minimum cost optimization problem to find optimal electricity prices 30 years ago. The difference in this work is that the minimum peak problem is not an economic formulation, so the dual variables do not represent electricity prices. Rather in this case, the minimum peak problem is solved, and its solution is used in conjunction with the dual formulation of the minimum cost problem in order to determine optimal prices. While we only consider a peak demand reduction case in this paper, the methodology presented can readily be applied to a wide variety of situations, including emissions reduction, renewable energy generation capacity, standby capacity, etc.

2. System description

The system considered in this paper is a simulated community of 900 homes. These homes are based on energy audits, electricity meter measurements, homeowner surveys, and images of 60 physical homes in Austin, Texas, USA. The average year of construction for the 60 homes is 1965 with a standard deviation (σ) of 18 years.