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Multi-market demand response using economic model predictive control of space heating in residential buildings

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ABSTRACT

Several studies have evaluated the potential for residential buildings participating in demand response programs based on the day-ahead electricity market prices. However, little is known about the benefits of residential buildings providing demand response by engaging in trading on the intraday market. This paper presents a simulation-based study of the performance of an economic model predictive control scheme used to enable demand response through parallel utilization of day-ahead market prices and intraday market trading. The performance of the control scheme was evaluated by simulating ten apartments in a residential building located in Denmark through a heating season (four months) using historical market data. The results showed that the addition of intraday trading to the more conventional day-ahead market price-based control problem increased the total cost savings from 2.9% to 5.6% in the existing buildings, and 13%–19% in retrofitted buildings with higher energy-efficiency. In the existing building the proposed control scheme traded on average 12.7 kWh/m^2 on the intraday market throughout the simulation corresponding to 21% of the reference consumption. For a retrofitted building the traded volume was 9.6 kWh/m^2 which corresponds to 52% of the reference consumption. These results suggest that the benefits of considering intraday market trading as a demand response incentive mechanism apply to a wide range of buildings.

1. Introduction

As the penetration of intermittent renewable energy sources (RES) such as wind power increases, so will the uncertainty associated with electricity production prognoses because of the inherent uncertainties of weather forecasts. This uncertainty complicates the task of maintaining an instantaneous balance between electricity supply and demand [1,2]. A commonly suggested way of addressing the issue of grid balancing under more volatile electricity production is the implementation of smart grids [3–6]. A characteristic of smart grids is effective utilization of Demand Response (DR) programs, where consumers are encouraged to adjust their demand to meet supply and thereby increase the overall efficiency of the energy system. Energy use in residential buildings constitutes a significant potential for DR as it accounts for 25% of the total energy consumption in the EU of which 67% is used for space heating in the North and West regions of EU [7]. This flexible consumption can be activated through different types of DR programs.

1.1. Demand response programs

DR programs are often divided into *direct* and *indirect* control programs [4,8,9]. In direct control programs, the consumer entrusts the energy planners and operators (PO) with direct control of their electrical loads; the PO can change consumption pattern directly. In indirect control programs, the consumer has full control of the electrical loads and the PO can only provide incentives for consumers to change their consumption pattern. One incentive from PO to consumers is to provide time-varying energy prices, which motivates consumers to reduce consumption in high price periods, e.g. by shifting consumption to periods with lower prices. This approach is referred to as *indirect price-based* DR programs. Previous studies have demonstrated that residential building owners may benefit from this type of DR programs. Halvgaard et al. [10] operated a residential-scale heat pump using Economic Model Predictive Control (E-MPC) with day-ahead prices and achieved 25–35% cost savings compared to traditional set point control dependent on comfort constraints. Avci et al. [11] used E-MPC to achieve a 13% cost reduction compared to a two-position thermostatic control of a residential heat pump, and Oldewurtel et al. [12] used MPC with a multi-objective cost-function to reduce consumption peaks by up to 39% and costs by 31.2%. Knudsen and Petersen [13] demonstrated that using E-MPC for space heating can enable cost savings, CO_2

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Nomenclature

Abbreviations

DR	Demand response
E-MPC	Economic model predictive control
RES	Renewable energy sources
PO	(Energy) Planners and operators
SSM	Supply-side management
TSO	Transmission system operator
BRP	Balance responsible party
MILP	Mixed integer linear problem
ITH	Intraday trading horizon
ID	Intraday (market)
DA	Day-ahead (market)

Symbols

x	State vector of the resistance-capacitance building model
p_{da}	Vector containing forecasted day-ahead market prices
u^*_{da}	Optimal sequence of control actions with respect to day-ahead prices
p_{id}	Vector containing prices from intraday market trades
u^*_{id}	Optimal sequence of control actions after intraday optimization
J^*	Cost of implementing the entire optimal control strategy

emission reductions, and shift consumption from periods of peak load to low load periods. The large spread in savings found in the above-mentioned studies may be caused by several factors including the magnitude of price fluctuations, how the reference case is defined as well as the inclusion of taxes. For example, Knudsen et al. [14] demonstrated that the economic incentive of performing DR using E-MPC of residential space heating strongly depends on the taxation mechanism of energy: a case study led to end-user energy cost savings between 2% and 9% depending on the taxation. Furthermore, Pedersen et al. [15] demonstrated that the cost savings of indirect price-based DR programs using E-MPC depends on the energy-efficiency of the building envelope and consequently the storage efficiency, which relates the amount of energy lost during the storage process to the amount of energy actually stored.

All of the mentioned studies use forecasts of energy prices and weather with durations upwards of days to prepare the building for DR by utilizing the inherent thermal inertia of the building as an energy storage. However, previous studies have demonstrated that buildings can also help solve grid balancing issues that arise on a shorter time scale. Oldewurtel et al. [16] used MPC with critical peak pricing to quantify the flexible consumption immediately available in buildings that have not been prepared to deliver flexibility, by introducing two performance metrics: Power Shifting Potential and Power Shifting Efficiency. De Coninck et al. [17] used MPC to derive cost curves describing the costs associated with deviation from optimal control strategies to activate flexibility. Both studies conclude that the availability and associated cost of flexibility in building space heating depend on several dynamic factors such as the current thermal state of the building and weather conditions, but they do not attempt to investigate whether the cost of the flexibility is aligned and compatible with the current electricity markets or incentive mechanisms. The following section describes the structure of wholesale electricity markets and clarifies why these may be suitable for activating the DR potential in residential space heating.

1.2. Electricity markets as DR platforms

This study evaluates an indirect price-based DR program utilizing two European-based wholesale electricity markets: the day-ahead market Elspot and the intraday market Elbas. Both markets are a part of the cross-border electricity market Nord Pool. Each participating country is divided into individual bidding areas that reflect geographical and grid characteristics. For example, Denmark consists of two bidding areas of which the Western Denmark region (DK1) is characterized by a high penetration of wind power production [18]. In 2015 the accumulated annual wind power production constituted approximately 55% of the total annual consumption of the DK1 region [19].

In DK1, the majority of electricity is traded on the day-ahead market Elspot, where electricity trades confirmed upon market closure is to be delivered the following day. The market closes each day at 12:00 CET and shortly thereafter the hourly day-ahead prices (p_{da}) for the following day are available to the public. The hourly price is settled through the pay-as-clear principle in which, for each hour, the price that balances supply and demand applies to all electricity traded across different market regions. However, in periods where transmission lines between bidding areas are congested (bottlenecks), a market split occurs resulting in different prices on each side of the congestion. The physical limitations of transmission lines thus lead to increased price fluctuations in regions with high shares of intermittent RES such as DK1. Fig. 1 shows how high wind power production within the region has a tendency to reduce the DK1 day-ahead clearing prices in 2015. Furthermore, the production from wind exceeded the regional consumption in 1442 h while negative prices were observed in 65 h. It is these day-ahead prices that have served as the sole price signal in many E-MPC or rule-based studies on DR for space heating in buildings [10,12,13,20–23].

The significance of wind power production in the region for the day-ahead market principle means that the trades depend strongly on the accuracy of production (and consumption) prognoses. The market therefore needs a way of correcting the already traded quantities on the day-ahead market to be consistent with updated production prognoses. Such corrections can be made through trading on the intraday electricity market (Elbas) which remains open from the day-ahead market closure up until one hour before the electricity is to be delivered. Despite the fact that trades can be made up to 33 h before delivery, over 50% of all intraday trades are made within the last three hours before intraday market closure as the accuracy of prognoses increase [18]. The total volumes traded on the Elbas market are currently small, constituting only approximately 3% of the annually sold and bought electricity on Elspot in 2015 [19]. However, Scharff et al. [18] identified high shares of intermittent production from RES to be a contributing factor towards increased intraday trading.

In conventional power systems grid balancing is achieved through supply-side management (SSM), where the transmission system operator (TSO) hires power plants that are able to adjust their power output to address any imbalanced operation from market actors. In all trades on the day-ahead electricity market, one of the actors involved with the trade assumes the role of the Balance Responsible Party (BRP). The BRP is committed to cover any expenses of the TSO to counteract any imbalance associated with the trade. The balancing power price is thus directly linked to the expenses associated with balancing carried out by the TSO. As the share of fluctuating renewable production increases, the task of balancing the grid becomes increasingly complicated which, consequently, increases the expenses resulting from imbalanced operation. As the balancing expenses increase, BRPs are expected to be more involved in intraday trading to ensure a balanced operation.