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Reduction of heat pump induced peak electricity use and required generation capacity through thermal energy storage and demand response

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HIGHLIGHTS

- A multi-objective MPC strategy for residential heating with heat pumps is presented.
- The simulations employ detailed models for heat pump and thermal energy storage.
- The feedback of individual controllers on the electricity generation is included.
- Results show a significant reduction in required generation capacity is possible.
- Costs carried by the consumer rise when demand response is applied.

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ABSTRACT

Shifting residential space heating from the use of gas boilers towards the use of heat pumps is recognized as a method to reduce green house gas emissions and increase energy efficiency and the share of renewable energy sources. Demand response of these systems could aid in reducing peak loads on the electricity grid. Extra flexibility can be added in the form of a thermal energy storage tank. This paper proposes a multi-objective model predictive control strategy for such a system, which takes into account the users energy cost, the environmental impact of energy use and the impact of expanding the electricity generation capacity. This control strategy is used in a case study inspired by the Belgian electricity generation park with 500,000 heat pumps to investigate the effect of the size of a space heating storage tank on consumer cost, energy use and required electricity generation capacity. Results indicate that the proposed demand response strategy reduces the required peak load capacity substantially with only a small increase in costs for the consumer. When adding a large hot water storage tank, the required additional capacity is nearly eliminated. Independently of the required capacity, the controller shifts energy use from peak to base generating plants. Increasing the storage tank size increases the amount of energy that is shifted. However, when demand response is applied by using a space heating storage tank, the costs for the consumer always increase relative to the case without demand response or storage tank. If demand response is desired by the grid operator, heat pump owners should be encouraged to participate by remunerating them for their additional expenses.

1. Introduction

Global warming caused by the emission of greenhouse gases is expected to have irreversible effects on the environment and human society in the near future unless emissions are decreased [1]. The European Union has set targets for increasing renewable energy use, increasing energy efficiency and reducing greenhouse gas emissions which aid in tackling global warming [2,3].

Electrifying residential heating loads through the use of heat pumps, can contribute to all goals set above. Moreover, this increases the viability of large scale deployment of non-dispatchable renewable energy conversion by increasing the load factor [4–6]. However, the introduction of large numbers of heat pumps in the electricity grid could disrupt the load diversity.

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In an electricity grid, load diversity lowers the required generation capacity [7]. Unfortunately, space heating is a highly simultaneous load as it is predominantly ambient temperature dependent. When heat pumps are deployed for space heating on a large scale, large peak loads are expected in winter times [8]. Demand response (DR) is referred to in the literature as technologies or programs that concentrate on shifting energy use to help balance supply and demand [9]. Several authors have identified DR as a means to reduce peak loads generated by heat pump operation [8,10,11]. At times of abundant electricity generated from renewable sources, heat generated by a heat pump can be stored in the structure of the heated building or in a thermal energy storage tank. During a subsequent period of large electricity demand, the heat production of the heat pump can be decreased while releasing the stored thermal energy. This way the peak loads in the electricity grid are decreased while the thermal comfort of the building inhabitants is maintained provided the system is well-controlled. By using a hot water storage tank as thermal energy buffer, the amount of energy which can be stored is increased, thus increasing system flexibility.

Several studies investigate the potential of residential DR with heat pumps. Kreuder and Spataru [12] used a simplified model of heat pump space heating for residential buildings to investigate the effect of demand response on the peak load at household level and electricity generation level. They assumed a DR algorithm which alters the heat pump load to have a constant daily demand profile in each household. Without demand response, the heat pumps cause an increase in peak load of about 2500 W at household level. By introducing a DR method, this peak load is decreased by about 700 W per household. In the model, they calculated the heating loads and heat pump efficiency based on the daily average temperature. Furthermore, effects of part load on heat pump efficiency were neglected. These model simplifications could have a large effect on the results as daily temperature variations significantly affect the heat pump load. Vanhoudt et al. [8] experimentally investigated the effect of an actively controlled heat pump on the buildings energy demand profile. They found that their multi-agent market-based control algorithm decreases the peak load but does not decrease the consumption of fossil-based electricity. The combination of heat pumps and a hot water storage tank for space heating was investigated by Arteconi et al. [13]. They show that even without a storage tank, when sufficient thermal mass is present in the emission system, the heat pump can be turned off during a 3 h peak period without affecting thermal comfort. Arteconi et al. [11] also investigated the effect of the number of DR participants on the total operational costs of electricity generation. In that study, DR is supplied by space heating and DHW production using a domestic hot water tank, no space heating storage tank is considered. In several scenarios of the future Belgian electricity grid they show that with more DR penetration the operational costs decrease but the savings per customer also decrease. As the DR penetration increases the peak residual demand also decreases. However, it remains well above the fixed peak residual demand. The peak demand decrease is driven by the higher energy costs assigned to high demand by a merit order model. Patteeuw et al. [14] computed the cost of a reduction in CO_2 emissions through DR and the use of heat pumps in residential buildings on a large scale. They found that DR reduces the cost although there is a large spread in costs depending on the building insulation level and the heating system. Hedegaard et al. [15] discuss the investment in storage tanks used for space heating with heat pumps in a DR context and compare it with using the building thermal mass to offer flexibility to the electricity generation park. Using simplified models for building and storage tank, they conclude the fuel savings cost is higher for the cases with storage tank than with passive thermal energy storage. However, in the case of passive thermal energy storage the building temperature is allowed to fluctuate in a temperature band around the reference temperature. This implies that there are times the temperature is below the reference temperature meaning the thermal comfort of the building inhabitants is decreased. This difference in thermal comfort results in an unfair comparison between cases.

The afore mentioned studies employ optimal control problems (OCP) with either perfectly stratified or perfectly mixed models to represent the dynamics of hot water storage tanks. However, when using a hot water storage tank for space heating in a demand response context, the effective storage capacity is highly dependent on the degree of stratification inside the tank [16]. The use of simplified models to represent the storage tank behavior thus may over- or underestimate the energy retrievable from the storage tank and the power at which it can be retrieved. On the other hand, the solution of an optimization problem with an accurately modeled hot water storage tank is too time consuming when results on a yearly time scale are required. To resolve this problem a moving horizon optimal control or model predictive control (MPC) simulation can be used. In an MPC simulation a simplified OCP is used to generate control signals for a simulation with a detailed model, known as the system emulator.

In the literature, several authors use MPC or other advanced control strategies to investigate the operation of thermal energy storage in an energy system [17–23]. Bianchini et al. [17] present an MPC algorithm for a large multi-zone building heated by a heat pump. They considered a scenario where an aggregator proposes DR requests, in the form of a price-volume signal, to the building management system. The building owner is rewarded if the requests are fulfilled. Results indicate good thermal comfort while addressing the DR request. However, the effects on the electricity generation were not investigated. Another MPC algorithm which minimizes the cooling costs of a large building based on the day-ahead electricity price is proposed by Zhao et al. [18]. They conclude that using combined cooling and power generation can reduce the buildings primary energy use and CO_2 emissions. Adding a 125 m^3 chilled water energy storage further enables savings in the building energy cost. However, these results are only valid when the penetration of such buildings in the electricity market is low, as no feedback effects are taken into account. Dahl Knudsen and Petersen [19] present an MPC controller which minimizes electricity costs or CO_2 emissions for electric space heating. Depending on the controller settings lower emissions or lower costs compared to a PID control can be obtained. However, the presented control strategies neglect the feedback effects of the demand side changes on the electricity generation side which can be significant [24].

Schibuola et al. [20] investigated several price signal based control strategies for maximizing self consumption in an apartment building. Here, a decrease of imported and exported energy of up to 11% and 21% respectively is seen. Dar et al. [21] found that with different rule based control strategies, self consumption or the energy bill of a net-zero energy building can respectively increase by 40% and decrease by 19%. However, both values are obtained with mutually exclusive control strategies and effects on the electricity generation side are not taken into account.

Furthermore, often price signals are used to represent the electricity generation side. When DR is widespread, the feedback of the individual controllers on the electricity generation must be taken into account [24].

When DR is applied on a large scale, individual controllers impact loading and even commitment of electricity generation units, hereby altering the generation mix. Existing studies on building-level MPC with DR objectives do not take these effects into account. Often price signals are used to represent the