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Comparison of load shifting incentives for low-energy buildings with heat pumps to attain grid flexibility benefits

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HIGHLIGHTS

- Assessment of load shifting with heat pumps by integrated model.
- Individual buildings perform model predictive control.
- Comparison price and load control incentives for decentralized control.
- Need for integrated modeling for setting up incentives.
- Poor performance of price profiles for large number of participating buildings.

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ABSTRACT

This paper aims at assessing the value of load shifting and demand side flexibility for improving electric grid system operations. In particular, this study investigates to what extent residential heat pumps participating in load shifting can contribute to reducing operational costs and CO_2 emissions associated with electric power generation and how home owners with heat pump systems can be best motivated to achieve these flexibility benefits. Residential heat pumps, when intelligently orchestrated in their operation, can lower operational costs and CO_2 emissions by performing load shifting in order to reduce curtailment of electricity from renewable energy sources and improve the efficiency of dispatchable power plants. In order to study the interaction, both the electricity generation system and residences with heat pumps are modeled. In a first step, an integrated modeling approach is presented which represents the idealized case where the electrical grid operation in terms of unit commitment and dispatch is concurrently optimized with that of a large number of residential heat pumps located in homes designed to low-energy design standards. While this joint optimization approach does not lend itself for real-time implementation, it serves as an upper bound for the achievable operational cost savings. The main focus of this paper is to assess to what extent load shifting incentives are able to achieve the aforementioned savings potential. Two types of incentives are studied: direct load control and dynamic time-of-use pricing. Since both the electricity generation supply system and the residential building stock with heat pumps had been modeled for the joint optimization, the performance of both load shifting incentives can be compared by separately assessing the supply and demand side. Superior performance is noted for the direct-load control scenario, achieving 60–90% of the cost savings attained in the jointly optimized best-case scenario. In dynamic time-of-use pricing, poor performance in terms of reduced cost and emissions is noted when the heat pumps response is not taken into account. When the heat pumps response is taken into account, dynamic time-of-use pricing performs better. However, both dynamic time-of-use pricing schemes show inferior performance at high levels of residential heat pump penetration.

1. Introduction

Demand response is a form of demand-side management for altering consumers' electrical demand profiles by means of incentives such as dynamic electricity prices [1]. According to Strbac [2],

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Nomenclature

$\mathbf{A}$	state space model matrix
$\mathbf{B}$	state space model matrix
$co_2t_{i,j}$	CO_2 emission cost
cur_j	curtailment of RES
d_j^{HP}	heat pump electricity demand
d_j^{IM}	centrally-suggested demand profile
d_j^{trad}	traditional electricity demand
$fc_{i,j}$	fuel cost
$g_{i,j}^{PP}$	power plant electricity generation
g_j^{RES}	RES electricity generation
nb	number of buildings
$p_{s,j}^{AUX}$	electricity demand auxiliary
$p_{s,j}^{HP}$	electricity demand heat pump
$price_j^G$	price profile from generation model
$price_j^I$	price profile from integrated model
$q_{s,j}^{DHW}$	domestic hot water demand
q_j^S	solar heat gains
$q_{s,j}^S$	internal heat gains
$rc_{i,j}$	ramping cost
$sc_{i,j}$	start-up cost
t_j^e	ambient air temperature
t_j^g	ground temperature
$t_{s,j}^{max}$	maximum comfort temperature
$t_{s,j}^{min}$	minimum comfort temperature
$t_{s,j}$	temperature vector
w	weighting factor load shaping
$z_{i,j}$	power plant commitment status
HP	heat pump
PP	power plant
RES	renewable energy sources

demand response can reduce the need for investments in electricity generation, transmission, and distribution infrastructure, as well as mitigate negative effects associated with the large-scale introduction of generation from intermittent and variable renewable energy sources (RES). Among the multiple methods to attain demand response, as discussed by Gellings [3], this paper focusses on load shifting. In this paper, load shifting is employed to avoid electricity demand at times when power plants with lower efficiency are running and to increase demand at times when renewable energy sources are curtailed. There are various methods to attain load shifting with minimal to no impact on process quality [4], including the process of providing heating or cooling in a building context. Load shifting of heating and cooling demand can either be performed manually by the building occupants or automatically. As shown by Wang et al. [5] and Dupont [6], automatic control achieves higher participation in demand response than manual control. The smart thermostat, an enabling technology to achieve automatic control for heating and cooling demand [7], has drastically increased its market share in recent years [8]. Apart from improving energy efficiency [9], some of these internet-connected smart thermostats already perform peak shaving while maintaining thermal comfort [10].

In the literature, one can find two approaches to determining the potential benefits of load shifting, either from a grid perspective or a building owner's perspective. In order to evaluate the potential benefits of load shifting from an electric system perspective, authors typically consider direct load control [11–15]. In this way, applying load shifting to residential buildings with heat pumps allows numerous benefits, such as balancing short-term power fluctuations of wind turbines [11], providing reserves [12] or voltage stability [13], reducing wind energy curtailment by up to 20% [14], and reducing CO_2 emissions by up to 9% [15].

On the other hand, studies conducted from a building owner's perspective typically consider a wholesale electricity price profile and assume the actions taken under load shifting do not effect this price profile. For example, Kamgarpour et al. [16] found that for a set of 1000 residential buildings, savings of up to 14% can be attained with respect to a wholesale electricity price profile. Henze et al. [17] attained savings up to 20% by employing the passive energy storage present in an office building with respect to an on-peak and off-peak electricity tariff. Kelly et al. [18] also investigated the use of thermal energy storage to shift electricity demand to off-peak periods, but reported significant increases in energy use. In addition, Kelly et al. observed a loss of load diversity causing a peak demand during off-peak tariff periods (rebound), which is up to 50% higher than normal. This loss of load diversity phenomenon for thermostatically controlled loads is explained well by Lu and Chassin [19]. More advanced and dynamic price profiles have been suggested in different studies, e.g. Oldewurtel et al. [20] suggest a price profile based on the spot price and on the level of the traditional electricity demand. A good overview of different price based incentives for consumers is provided by Dupont et al. [21].

The motivation for the work presented in this paper revolves around the question what value grid flexibility offers. While there appears to be universal agreement that elasticity in electrical demand will be instrumental in dealing with variable and intermittent RES, little is known regarding the quantitative extent of the benefits resulting from load flexibility vis-a-vis conventional supply side options for accommodating the RES variability. This work begins this valuation of grid flexibility by investigating the optimal control of thermostatically controlled loads of electrically driven heat pumps under a set of simplifying assumptions, which are necessary to solve this approximated problem in human time. Future work will consider other flexible loads including, but not limited to, electric vehicle charging, commercial building thermal mass and HVAC systems control, and dispatchable home appliances.

In this research a unique approach is suggested and evaluated: First, both the electricity generation system and the buildings equipped with heat pumps are modeled and optimized *jointly* in order to evaluate the theoretically maximum benefits and impact of load shifting, similar to [22,23]. Modeling both systems also allows studying different load shifting incentives. Both supply and demand systems are assumed to behave rationally and strive to minimize their observed cost. To this aim, all buildings considered feature a model predictive controller (MPC) developing optimal thermostat setpoint strategies. This could be achieved, for example, by a massive deployment of smart thermostats performing MPC. In this context, MPC is a control approach, which optimizes the control of a building's heating and/or cooling system by harnessing a simplified physical model of the building's thermal characteristics and energy systems along with predictions on occupancy and weather conditions. As shown in experiments in tertiary buildings by Širokỳ et al. [24], MPC can reduce energy use up to 28%. Buildings with MPC can easily cope with dynamic price profiles, as shown by Oldewurtel et al. [20].

The aim of this paper is twofold. First, it is of interest how much operational costs and CO_2 emissions of the electric system can be