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Active demand response with electric heating systems: Impact of market penetration

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HIGHLIGHTS

- Impact of ADR market penetration is analysed.
- ADR by means of electric heating systems coupled with TES is considered.
- Different demand side technologies configurations are analysed.
- Economic benefits for customers and overall system are assessed.
- An integrated modelling approach for ADR is applied.

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ABSTRACT

Active demand response (ADR) is a powerful instrument among electric demand side management strategies to influence the customers' load shape. Assessing the real potential of ADR programmes in improving the performance of the electric power system is a complex task, due to the strict interaction between supply and demand for electricity, which requires integrated modelling tools. In this paper an analysis is performed aimed at evaluating the benefits of ADR programmes in terms of electricity consumption and operational costs, both from the final user's and the overall system's perspective. The demand side technologies considered are electric heating systems (i.e. heat pumps and electric resistance heaters) coupled with thermal energy storage (i.e. the thermal mass of the building envelope and the domestic hot water tank). In particular, the effect of the penetration rate of ADR programmes among consumers with electric heating systems is studied. Results clearly show that increasing the number of participating consumers increases the flexibility of the system and, therefore, reduces the overall operational costs. On the other hand, the benefit per individual participant decreases in the presence of more ADR-adherent consumers since a reduced effort from each consumer is needed. Total cost saving ranges at most between about 400 € and 200 € per participant per year for a 5% and 100% ADR penetration rate respectively.

1. Introduction

Among the different electric demand side management strategies, active demand response (ADR) is defined as 'changes in electric usage implemented directly or indirectly by end use customers/prosumers from their current/normal consumption/injection patterns in response to certain signals' [1]. These signals could be incentive based programmes (direct load control, curtailable load, demand bidding) and/or price based programmes (real time pricing, time of use pricing, peak pricing), each with its own opportunities and drawbacks [2]. ADR can contribute to a more cost efficient operation of the electric power system as it may provide the needed flexibility to cope with the intermittent character of renewable energy sources (RES) such as wind turbines and PV

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Nomenclature

A, B	state space matrix
ACH	air changes per hour
$ACHP$	air coupled heat pump
ADR	active demand response
C_{fi}	internal floor capacitance
C_f	external floor capacitance
C_i	indoor air capacitance
C_w	external wall capacitance
$CCGT$	combined cycle gas turbine
COP	coefficient of performance
cur_j	curtailment at time step j
d_j^{fix}	fixed electricity demand (excluding electric heating) at time step j
$d_j^{H,fix}$	electric heating system fixed demand at time step j
$d_j^{H,var}$	electric heating system variable demand at time step j
DHW	domestic hot water
DRR	demand recovery ratio
DSM	demand side management
$g_{i,j}^{PP}$	power generation from traditional power plant i at time step j
g_j^{RES}	RES power generation at time step j
hor	optimisation horizon
i	index of power plant
j	time step (hourly)
$MILP$	mixed integer linear programming
MO	merit order
nb	number of buildings
$OCGT$	open cycle gas turbine
p^{ADR}	ADR participation rate
P_j^{AUX}	auxiliary heater power at time step j
P_j^{HP}	heat pump power at time step j
PV	photovoltaic
q_j^{DHW}	DHW demand at time step j
q_j^I	internal heat gains at time step j
q_j^S	solar heat gains at time step j
R_c	relative operational costs
R_{fi}	internal floor resistance
R_f	external floor resistance
R_{tank}	DHW tank resistance
R_{wi}	internal wall resistance
R_w	external wall resistance
RES	renewable energy source
SH	space heating
T_j^{max}	maximum temperature comfort bound at time step j
T_j^{min}	minimum temperature comfort bound at time step j
$T_{DHW,max}$	maximum DHW tank temperature
$T_{e,j}$	ambient temperature at time step j
T_{fi}	internal floor temperature
T_f	external floor temperature
$T_{g,j}$	ground temperature at time step j
T_i	indoor air temperature
T_j	vector with temperature states at time step j
$T_{set,max}$	maximum building operative temperature
T_{wi}	internal wall temperature
T_w	external wall temperature
TES	thermal energy storage
U	conductivity
$vent$	ventilation thermal resistance

panels. This allows matching the demand with the variable RES based electricity production [3].

Typical residential examples of technologies usable for ADR purposes are thermostatically controlled loads (such as boilers, heat pumps, refrigerators and air conditioners), plug-in electric vehicles and deferrable loads, e.g. laundry machines and dish washers [4]. One possibly promising group of demand side technologies is electricity based heating systems. These systems could allow modifying their electric load pattern without affecting the quality of the final thermal energy service delivered, thanks to the inherent thermal inertia of the system (both in the building envelope [5] or in additional thermal energy storage (TES) tanks [6]). Small scale electric heating systems can be installed in large numbers in the built environment and control access to these loads could be very inexpensive with the advent of communication platforms; so they are good candidates for ADR [4,7].

However, many challenges remain to be overcome before a large scale roll-out of ADR programmes will emerge. One of these challenges is related to the technical obstacles preventing price signals from being properly transferred to the customers [8], while others are related to the quantification of the benefits for consumers and producers under ADR programmes [9]. In order to quantify the effects of introducing such programmes, the assessment of the interaction between the supply and demand side is of paramount importance, because the electricity prices may change with the demand for electric power and vice versa. When an ADR programme is introduced, customers can react to a price signal and modify their demand. At the same time, this may ask for an adjustment of dispatch of the electricity generation system, possibly changing the market clearing price at the wholesale level. Ideally, the instantaneous cost of electricity generation should make up a significant part of the price signal perceived by ADR adherent consumers. Thus, neglecting the feedback from the demand side to the supply side could introduce major errors in the evaluation. In light of this challenge, the importance of using integrated models for the supply demand system representation is illustrated by Patteeuw et al. [10], especially when storage type customers are involved.

Several studies describe models for ADR in buildings in which the focus is mainly on either the electricity generation or alternatively on electricity demand (for an overview see [10]). However, some studies deal with the analysis of electric heating system management (mainly heat pumps) for ADR purposes by means of an integrated modelling approach. Williams et al. [11], for instance, show that using the thermal mass of the building in conjunction with simple heat pump control strategies can effectively accommodate wind energy fluctuations. Wang et al. [12] present an optimal demand response control of highly distributed electric loads aimed at maintaining voltage stability. Hedegaard et al. [7] assess the potential for wind power integration and fuel consumption reduction using individual heat pumps.

This paper also considers an integrated electricity supply and demand system and, as demand side technology, looks into electric heating systems. This consists of heat pumps and auxiliary electric resistance heaters coupled with thermal energy storage in the building, both in the building envelope and the domestic hot water tank. The purpose of this work is to evaluate, in particular, the effect of different penetration rates of ADR programmes among customers in order to point out positive and negative aspects of a variable introduction of such programmes. The main effort is