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Cost-optimal thermal energy storage system for a residential building with heat pump heating and demand response control

Behrang Alimohammadisagvand [a,*], Juha Jokisalo [a], Simo Kilpeläinen [a], Mubbashir Ali [b], Kai Sirén [a]

[a] HVAC Technology, Department of Energy Efficiency and Systems, School of Mechanical Engineering, Aalto University, P.O. Box 14400, FI-00076 Aalto, Finland
[b] Department of Electrical Engineering and Automation, School of Electrical Engineering, Aalto University, Finland

HIGHLIGHTS

- The cost-optimal solution is obtained based on DR for thermal storage with a GSHP.
- The three DR control algorithms are developed for space heating and storage tank.
- The storage tank of the IDA ICE simulation tool is regulated by measured data.
- The maximum savings of annual delivered energy and cost are 12% and 10%.

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ABSTRACT

This study aims to define a cost-optimal solution based on demand response (DR) actions for a thermal energy storage system with a ground source heat pump in detached residential houses in a cold climate. This study finds out the minimum life cycle cost (LCC) of thermal energy storage over the period of 20 years by observing different temperature set points (55–95 °C) and sizes (0.3–1.5 m^3) of a hot water storage tank with developed DR control algorithms. Three different control algorithms were studied: (A) a momentary DR control algorithm based on real-time hourly electricity price (HEP), (B) a backwards-looking DR control algorithm based on previous HEPs and (C) a predictive DR control algorithm based on future HEPs. This research was carried out with the validated dynamic building simulation tool IDA Indoor Climate and Energy. The results show that by using the predictive DR control algorithm the maximum annual savings in total delivered energy and cost are about 12% and 10%, respectively. The minimum LCC can be achieved by the smallest studied storage tank size of 0.3 m^3 with 60 °C as the temperature set point, but the effect of storage tank size on LCC is relatively small.

1. Introduction

Buildings consume over 40% of the overall energy consumed in the world and play a major role in sustaining electric grid power balance [1,2]. Demand response (DR) control algorithms on buildings have been widely accepted as effective methods to improve energy efficiency of buildings and to minimize energy consumption and cost [3,4]. DR control is an approach to match generated electricity and demand by controlling heating, ventilation and air conditioning (HVAC) systems and by reducing electricity demand when so required.

Yang et al. [5] reviewed and discussed thermal comfort of the occupants and the implications for building energy efficiency. They identified a better understanding of thermal comfort and energy conservation in buildings based on social-economic, cultural studies and consideration of future climate scenarios. Sehar et al. [6] used the predicted mean vote index to maintain thermal comfort of the occupants. One important feature of DR in relation to buildings is the ability to maintain thermal comfort conditions by adjusting the various indoor temperature set points considered [7–9].

Demand for heating energy is decreased with increasing thermal mass, due to the beneficial effects of fabric energy storage [10]. For example, Kensby et al. [11] concluded that the heavy buildings can tolerate relatively large variations in heat deliveries while still maintaining a good indoor climate. Also, thermal energy storage has been shown to be advantageous in increasing energy efficiency of buildings and in reducing their energy cost [12–14]. Arteconi et al. [15] found that combination of the DR and storage tank can have the potential market. It can be noted that since the thermal energy storage is combined with different types of heat

* Corresponding author.
E-mail address: Behrang.alimohammadi@aalto.fi (B. Alimohammadisagvand).

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Nomenclature

A	cross-section area of storage tank (m^2)
E_{cost}	energy cost of building for present year (€)
e	electricity price escalation (%)
H	height of layer of storage tank (m)
I	investment cost (€)
Q	heat transfer between the layers of storage tank (W)
r	real interest rate (%)
r_e	escalated real interest rate (%)
t	number of year
ΔT	water temperature difference between the layers of storage tank (°C)

Abbreviations

AHU	Air Handling Unit
aux	auxiliary
CS	control signal
DE	delivered energy
DHW	Domestic Hot Water
DCW	Domestic Cold Water
DR	demand response
EC	energy cost
GSHP	ground source heat pump
HEP	hourly electricity price (€/MW h)
HVAC	heating, ventilation and air conditioning
LCC	life cycle cost
LP	limiting price (€/MW h)
LW	light weight passive building type
MF	mixing factor
M	massive passive building type

Subscripts

i	index for the vertical position of a horizontal layer of storage tank
M	measured
max	maximum temperature of building or storage tank
min	minimum temperature of building or storage tank
normal	normal temperature
Out	outdoor temperature
S	simulated
set	set point temperature
st	storage tank

Superscripts

avr,24	average outdoor temperature of previous 24 h
lim	limiting outdoor temperature

pumps, these combinations are potentially more energy efficient, cost efficient and environmentally-friendly [3,16–18].

Siano and Sarno [19] combined Monte Carlo Simulation and real time distribution market to assess the operation and impact of the DR. They defined four different indoor temperature set points according to the price of energy. They showed the proposed method allows saving costs for residential end-users. Bianchini et al. [20] developed a predictive control algorithm based on price–volume signals in order to affect their consumption pattern. These signals are typically sent once or twice a day to specify a price if power consumption, during certain hours of the day, is below or above a specified maximum amount of energy to be consumed during hours. They proposed this approach for different building types and groups. Patteeuw et al. [21] showed that load shifting affects to reduce the electricity cost for low-energy buildings with heat pumps. Hedegaard and Balyk [22] presented a model that facilitates analyses of individual heat pumps and complementation of heat storages in integration with the energy system. By operating for hours with low marginal electricity costs, they found benefits in flexible operation of heat pumps. Arteconi et al. [23] showed that a heat pump with radiators or a floor heating system coupled with a thermal storage tank is a good tool for DR. They achieved a good control of indoor temperature since the heat pump is switched off during peak hours and the electricity cost was reduced by "time of use" tariff.

According to the literature review, the cost-optimal size and the temperature level of a hot water storage tank combined with DR control has not been investigated before. The purpose of this study is to minimize life cycle cost (LCC) of the thermal energy storage system coupled with a ground source heat pump (GSHP) and developed DR control algorithms. Cost-optimal size and temperature set points of thermal energy storage tank were defined. Then, the changing set point temperatures of space heating and storage tank were assessed by three different control algorithms: (A) a control algorithm based on real-time hourly electricity price (HEP) [24], (B) a control algorithm based on previous HEP and (C) a control algorithm based on future HEP. The control algorithms monitor and control space heating and the storage tank and reduce the peak load while maintaining thermal comfort of the occupants at acceptable levels.

2. Building description

2.1. Studied building

The building type is a Finnish two-story detached house (shown in Fig. 1) studied in [7]. The floor area of the building is 180 m^2, and it has six rooms and a kitchen, with the room height of 2.6 m. Two different versions of the detached house were simulated, the versions being determined on the basis of the difference in construction practice.

The building type studied is called passive. It has two different types of structures: light weight (LW) and massive (M) [7]. The building envelope specifications are presented in Table 1.

The light weight structures are wood frame constructions, and the massive structures are light weight concrete or massive concrete structures. All the walls of the massive building are of light weight concrete, but the roof and the intermediate and base floor are of massive concrete.

The level of the thermal insulation of passive houses follows the Finnish guidelines for Finnish passive houses, and air tightness of the passive houses abides with the guideline [25]. Table 2 shows the level of the buildings' thermal insulation with their *U*-value, window properties and air tightness.

2.2. Heating system

The heating energy is produced by GSHP coupled with a thermal storage tank. Heat pump and storage tanks used in this study are real commercial products [26,27]. The storage tank is installed in the bathroom. The coefficient of performance (COP) and heating power of the selected heat pump are, respectively, 4.9 and 8.9 at the standardized test point (0/35 °C) defined in EN 14511-2. This heat pump can increase water temperature up to 65 °C. For higher