THE POTENTIAL OF PREDICTIVE CONTROL IN MINIMIZING THE ELECTRICITY COST IN A HEAT-PUMP HEATED RESIDENTIAL HOUSE

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ABSTRACT

This study aims to investigate the energy demand response (DR) actions on energy consumption and cost for a thermal energy storage system with a ground source heat pump in a detached residential house in a cold climate. This aim was applied for two building structures, including light weight passive and massive passive structures. This study introduces a control algorithm based on checking current hourly electricity price (HEP) and trend of future HEPs. This research was carried out with the validated dynamic building simulation tool IDA Indoor Climate and Energy. The results show that the control algorithm reduces annual delivered energy for heating system and energy cost about 12% and 11%, respectively. The results also illustrate that the performance of the control algorithm is independent of the building structure.

INTRODUCTION

Buildings consume over 40% of the overall energy consumed in the world [1]. Thus, a significant amount of research in the recent years has been carried out on performance of building energy systems. Demand response (DR) actions on buildings have been widely accepted as the effective methods to improve energy efficiency of buildings and minimize energy consumption and cost [2].

DR provides an opportunity for consumers to play a significant role in the operation of the electric grid by reducing or shifting their electricity usage during peak periods by responding to time-based rates or other forms of financial incentives. Meanwhile, one important feature of DR is to maintain indoor thermal comfort conditions. Yang et al. [3] reviewed different parameters of thermal comfort and energy conservation in buildings regarding to social-economic, cultural studies and climate change. Predicted mean vote index (PMV) was considered to maintain thermal comfort of occupants in [4] and [5].

Bianchini et al. [6] defined a control algorithm based on price-volume signals and maximum amount of energy to be consumed during certain hours of the day. They found that both energy consumption and cost can be decreased, and this approach can be applied for different building types and group of buildings. Electricity cost reduction by load shifting in low-energy buildings with heat pumps was analyzed by Patteeuw et al. [7]. Hedegaard et al. [8] presented a model based on low electricity prices for heating system consisted of heat pump and storage tank. They also found benefits in flexible operation of heat pumps. Alimohammadisagvand et al. [9] studied the minimum life cycle (LCC) cost of thermal energy storage over the period of 20 years by observing different temperature set points (55-95°C) and sizes (0.3-1.5m^3) of a hot water storage tank with three different developed DR-control algorithms. According to LCC and delivered energy for heating system (heat loss of storage tank was considered in the bathroom), they found that the minimum energy cost occurs with predictive control algorithm, 0.3m^3 storage tank size and 60°C as the maximum temperature set point of storage tank.

According to the literature review, the different temperature levels of space heating and storage tank using DR-control algorithm has not been greatly studied. This paper introduces a new DR-control algorithm to minimize delivered energy (DE) for heating system and energy cost by adjusting different set point temperatures for space heating (minimum, normal and maximum one) and for storage tank (normal and maximum one) while maintaining thermal comfort of the occupants at acceptable levels.

BUILDING DESCRIPTION

Studied building

The building type is a Finnish two-story detached house (shown in Figure 1) studied in [5].

The floor area of the building is 180m^2, and it has six rooms and a kitchen, with the room height of 2.6m. The building type studied is called passive and has two different types of structures: light weight and massive [5]. 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, 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 [10]. Table 1 shows the level of

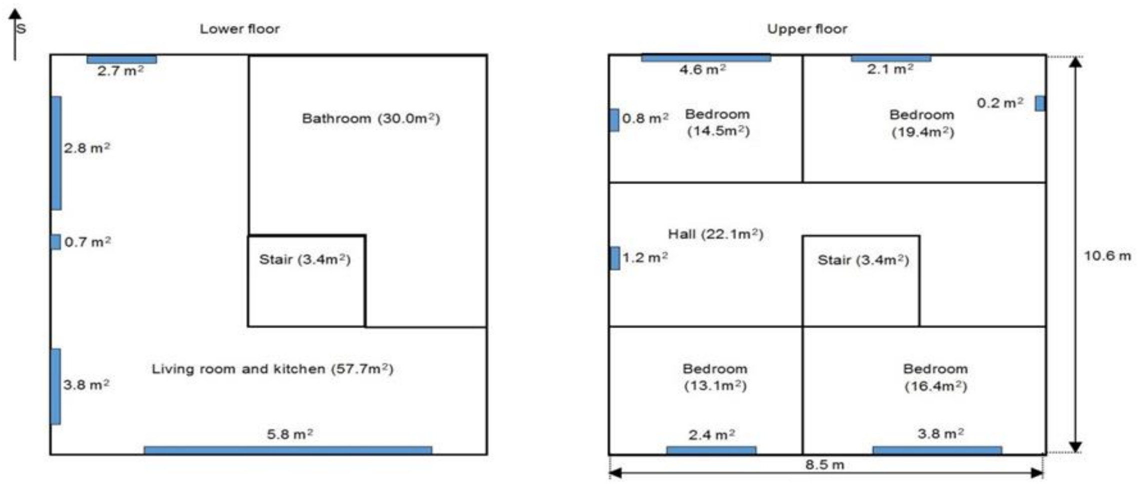

Figure 1. Two-story building (180m^2) with the area of each zone and window.

Table 1. Properties of building envelope, U-values, window properties and air tightness.

Structure	**Thermal insulation**	**U-values (W/(m²,K))**					**Window properties**		**Air tightness**
		External wall	**Roof**	**Base floor**	**Doors**	**Windows**	**g^a**	**ST^b**	**q_{50} (m³/(h,m²))**
Massive/Light Weight	Passive	0.08	0.07	0.08	0.5	0.8	0.5	0.4	0.7

[a] Total solar heat transmittance.
[b] Direct solar transmittance.

the buildings' thermal insulation with their U-value, window properties and air tightness.

Heating system

Ground source heat pump (GSHP) coupled with a thermal storage tank (installed in the bathroom) produces demanded heating energy and they are real commertial products [11] and [12]. The coefficient of performance and heating power of the selected heat pump are, respectively, 4.9 and 8.9kW at the standardized test point (0/35°C) defined in EN 14511-2. Also, the water temperature can be increased up to 65°C using this heat pump.

The studied size of the hot water storage tank is 0.3m^3 defined as the cost-optimal storage tank size [9]. The tank has polyurethane insulation thickness of 70mm. Also, two set point temperatures for storage tank were used, including normal set point temperature (55°C) and maximum one (60°C) defined as the optimal set point temperature in [9] which has minimum energy cost. The heat distribution system of this study is a hydronic floor heating type with the supply and return water temperatures (45/40°C) at the sizing conditions adjusted by a PI-controller.

Ventilation system

Passive building types have a mechanical supply and exhaust ventilation system with heat recovery. This type of ventilation system is the most common ventilation system in new Finnish detached houses. Heat recovery, with the supply air temperature efficiency of 80%, has been applied for these building types. In this kind of building types, air change per hour is 0.5, in accordance with the guideline of the Finnish building code D2 (2012) [13]. The ventilation control system is a constant air volume system and DR is not used to control ventilation air flow rates or reheating the supply air. The air handling unit (AHU) is equipped with an electric reheat coil.

Behavior of the occupants

One important component to heat building is internal heat gains [14], including lighting, equipment, number of occupants, and level of activity and clothing.

Typical consumption profiles of appliances and lighting of Finnish detached houses were used [15] and [16], and their annual electricity consumption are 8.5 and 22.2kWh/(m^2,a) in the studied house [5]. The number of occupants, activities and clothing levels have an effect on thermal comfort [17]. Different activity and clothing levels of four occupants were studied in [5].

One important parameter to estimate the building energy usage, and to be used for system design and

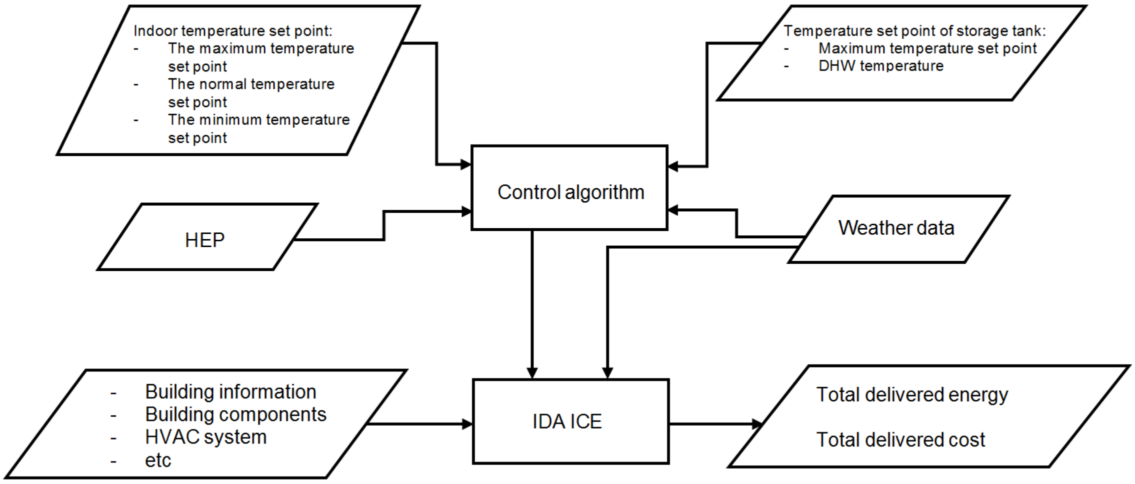

Figure 2. The computational arrangement of the investigation.

Table 2. Minimum, normal and maximum air temperature set point with PI-controller type for LW-Pass and M-Pass building types.

Building	**Indoor temperature set point (°C)**		
LW-Pass/M-Pass	Minimum	Normal	Maximum
	19.5	21	24.9

decision making is domestic hot water consumption. In this study, domestic hot water (DHW) consumption profile was defined based on monthly [18] and daily profiles defined in EN 15316:2007 [19].

METHODOLOGY

Structure of the simulation study

Figure 2 shows the study structure consisted of two main parts, including control algorithm and the IDA ICE building simulation tool.

The control algorithm part receives inputs from hourly electricity price (HEP), the weather data, the acceptable indoor temperature set points, and the temperature set point of the hot water storage tank. The IDA ICE receives inputs from the control algorithm, the weather data and the detailed building information. Finally, the IDA ICE produces output data such as total DE and energy cost by using control algorithm data and input data simultanously. This study used HEP announced 24h ahead by Nord Pool [20].

Acceptable indoor temperature set points

This study used the accaptable range of indoor air temperature set points, shown in Table 2, determined in [5] by the Fanger approach to predict the thermal comfort of occupants in buildings.

This range was determined regarding to the EN 15251 standard according to the lower and higher PMV values during the heating season for different activity levels, clothing levels and indoor air velocities [21]. In this study, the acceptable indoor temperature set points are based on the number of occupants, activity level, clothing level and indoor air velocity, which are, respectively, 4, 1.2met, 0.96clo and 0.1m/s.

IDA ICE simulation tool

IDA Indoor Climate and Energy (IDA ICE) tool was used for simulation part of this study [22]. The IDA ICE 4.6 building simulation tool is a detailed dynamic multi-zone simulation application with variable time step.

Weather data

The Finnish test reference year (TRY2012) was used as a weather data for dynamic simulation. The data on weather conditions were accumulated and computed by recording a 30-year period (1980–2009) at the weather station of the Finnish Meteorological Institute at the Helsinki-Vantaa airport [23].

Storage tank model

The water storage tank was modeled in IDA ICE to be coupled with GSHP. The mixing factor, as the effective parameter of the storage tank in IDA ICE, defines heat exchange between layers to determine the level of mixing process. Thus, the mixing factor defined in [9] was used in this study.

DEMAND RESPONSE CONTROL ALGORITHM

The DR mechanism motivates the end users to adjust different temperature set points for space heating, while maintaining the thermal comfort of the occupants at the acceptable level, and/or maintaining different temperature set points for thermal storage tank by following the HEP.

This study developed a control algorithm based on real-time HEP and trend of future HEPs to control the temperature set point of space heating and storage tank. The previous versions of this control algorithm were able to control the temperature set point of space heating [5], and space heating and storage tank [9] based either on real-time HEP or trend of future HEPs. The developed control algorithm has two main parts, including checking the real-time HEP and trend of future HEPs.

To find out the influence of the real-time HEP, the selected value of HEP named limiting price (LP) is defined. The LP is selected between 20 and 65€/MWh which indicate the common range of the HEPs. The first step of the control algorithm is to check the real-time HEP. If HEP is higher than the LP, the heating system is turned off if the indoor and storage tank temperatures are at the acceptable level, otherwise it is turned on. Also, the temperature set point of space heating and storage tank are minimum and normal values.

Secondly, if the real-time HEP is lower or equal than LP, the trend of future HEPs is checked. In this condition, the control algorithm has two portions: primary, the control algorithm calculates the control signal (CS); next, the heating system is controlled

and the set point temperatures of the space heating and the storage tank are defined.

This control algorithm generates CS based on the maximum subarray problem [24] in accordance with the optimum future HEPs (12) [5]. The maximum subarray problem calculates a contiguous subarray which has the largest sum within a one-dimensional array of numbers containing at least one positive number [24]. By means of this concept, HEPs can be accordingly sorted to realize their rising, levelling out or falling trend; hence, corresponding CSs can be assigned to the limited future prices. If HEP has falling trend (CS=+1), the heating system is turned on, set point of space heating is controlled depending on the maximum indoor temperature and average outdoor temperature of previous 24 hours, and the maximum temperature set point is used for storage tank. If HEP has rising trend (CS=-1), the heating system is turned off if the indoor and storage tank temperatures are at the acceptable level. Otherwise the heating system is turned on and the minimum temperature and the normal temperature set points are used for space heating and storage tank, respectively. In other conditions, the heating system is turned on and the normal temperature set points are used for space heating and storage tank. The flowchart for the control mechanism is as given in Figure 3:

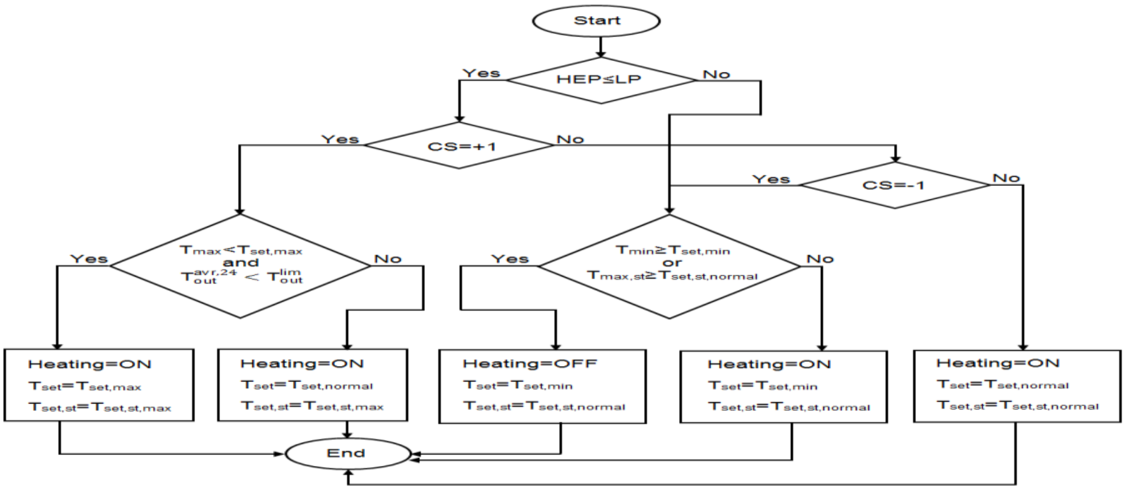

Figure 3. The flowchart of control algorithm.

Table 3. Breakdown of delivered energy in the reference cases.

Building type	Delivered energy (kWh/(m^2,a))						Energy cost (€/(m^2,a))
	Space heating+DHW	AHU heating	HVAC auxiliary[b]	Lighting	Equipment[a]	Total	
LW-Pass/M-Pass	21.7/21.8	3.0/2.3	5.0/5.1	8.5/8.5	22.2/22.2	60.6/59.9	6.17/6.15

[a] It is assumed 86% of the electricity consumption of equipment ends up as internal heat gain [25].

[b] HVAC auxiliary states energy used by fans and pumps.

RESULTS AND DISCUSION

Reference case

Table 3 shows the breakdown of DE and energy cost of the studied reference case for the massive passive (M-Pass) and light weight passive (LW-Pass) building types without DR-control. These buildings were simulated with the normal temperature set point of space heating (21°C) and storage tank (55°C) with 0.3m^3 size coupled with GSHP and hydronic floor heating system with PI controller.

The results show that the heat demand of the M-Pass building is slightly lower than the LW-Pass building.

Total delivered energy and energy cost

To find out the effect of the building structure on the DR performance, two above mentioned building types were studied. Total DE and energy cost were simulated with the developed control algorithm. The studied cases were compared with the reference one, and the energy cost is calculated by the Finnish HEP of 2012, including energy [20], transfer price and taxes [25].

One important factor in the control algorithm is the LP which affects on the DE for heating and energy cost. The results of the saving of DE for heating system and energy cost by using the DR-control algorithm for different LPs for both building types are presented in Figure 4. It shows that for different LPs, this control algorithm is able to reduce the total DE and energy cost.

Figure 4 illustrates that the DE for heating system decreases with increasing LP. The DE for heating system consists of DE of spaces and DHW and/or the reheat coil of AHU shown in Figure 5.

Lower LPs reduce the DE of spaces and DHW because the minimum set point temperature for space heating and normal set point for storage tank are used more. This also allows indoor temperature to drop more around minimum acceptable set point temperature, thus ventilation supply air temperature is always constant, but the heat demand of the supply air increases if the temperature of the exhaust air is lower. Increasing the LP increases the number of hours to use normal and maximum set point temperatures for space heating and maximum set point temperature for storage tank. Thus, the DE of spaces and DHW, and AHU heating system is increased and decreased, respectively, and the total DE for heating system is decreased. The maximum savings of total DE for heating system are 11.3% in M-Pass building type and 10.9% in LW-Pass building type by using the LP 60€/MWh and 57€/MWh respectively. The heating demand of the M-Pass building is slightly lower than that of the LW-Pass building. These results show that the effect of the control algorithm on the DE does not depend significantly on the thermal mass of the building structure.

In most of the studied cases for both building types, increasing the LP, decreases the energy cost. Because the HEP is variable, the energy cost trend by increasing the LP has some fluctuations. The Figure 4 shows that differences of the energy cost saving between LW-Pass and M-Pass building cases depend on LPs. Thus, the effect of the control algorithm on the energy cost can depend slightly on the thermal mass of the building structure. The maximum energy cost saving occur since LP is 60€/MWh and 57€/MWh for M-Pass and LW-Pass, respectively. Also, these LPs save the energy cost up to 11.5% and 11.1% for M-Pass and LW-Pass, respectively, which these savings are slightly higher compared with the predictive control algorithm without the LP (it is only based on the trend of HEPs) [9].

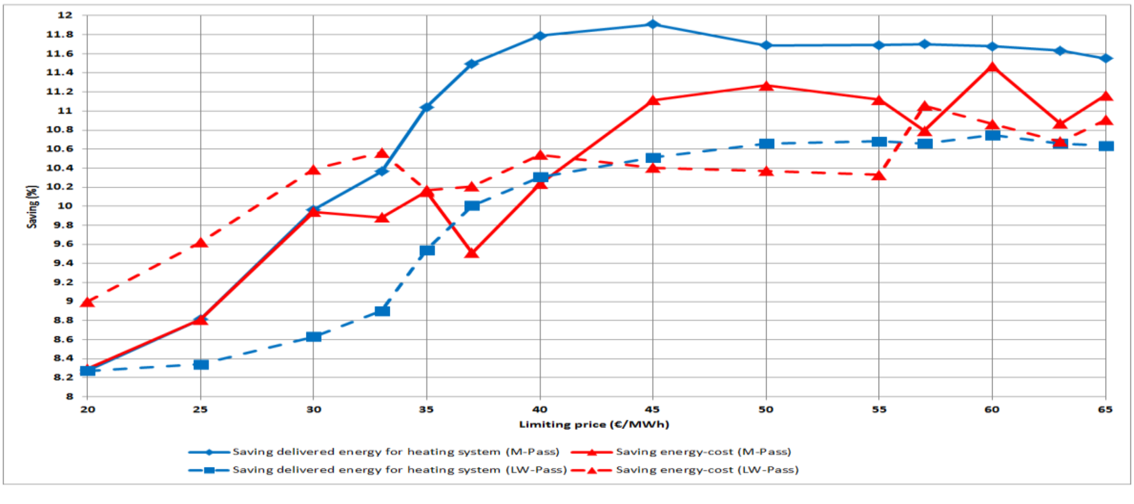

Figure 4. Saving of delivered energy for heating system and energy cost by using the control algorithm for both buildings.

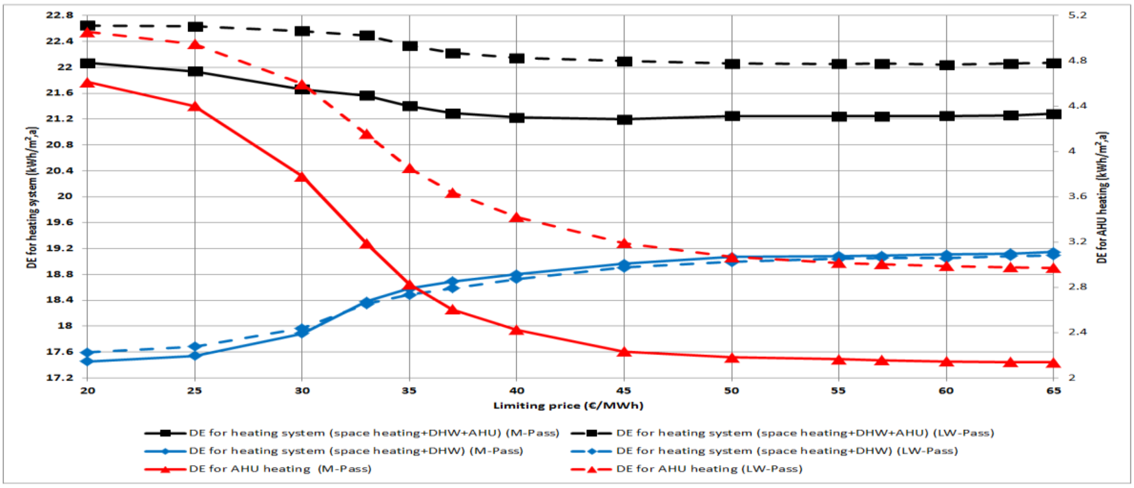

Figure 5. Delivered energy of heating systems with different LPs.

CONCLUSION

This study investigated the performance of the demand response to minimize the delivered energy for heating system and energy cost of a residential building with heat pump and thermal energy storage tank system. Two different houses, including different thermal mass levels were simulated in the cold climate of Finland.

The control algorithm is able to take into consideration both the present value and the trend of the hourly electricity price. The control algorithm uses different set point temperatures for space heating, including minimum, normal and maximum one, complying with the thermal comfort categories recommended by the EN 15251 standard for a detached house. It also uses two set point temperatures for storage tank, including 55°C and 60°C. The optimal value of limiting price was studied with the massive and light weight passive building types. It was found that the maximum energy cost saving takes place with the limiting prices 60€/MWh and 57€/MWh depending on the building type. The proposed demand response control algorithm was able to reduce delivered energy for heating system and energy cost up to 11% and 12% in the studied buildings. The energy cost depends slightly on the thermal mass of the building structure. Also, the effect of the control algorithm does not depend on the thermal mass of the building structure on delivered energy or energy cost point-of-view.

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