Alimohammadisagvand, Behrang; Alam, Sadaf; Ali, Mubbashir; Degefa, Merkebu; Jokisalo, Juha; Sirén, Kai

Influence of energy demand response actions on thermal comfort and energy cost in electrically heated residential house

Influence of energy demand response actions on thermal comfort and energy cost in electrically-heated residential houses

Behrang Alimohammadisagvand[a*], Sadaf Alam[a], Mubbashir Ali[b], Merkebu Degefa[b],

Juha Jokisalo[a], Kai Sirén[a]

[a] HVAC Technology, Department of Energy Technology, School of Engineering, Aalto

University, P.O. Box 14400, FI-00076 Aalto, Finland

[b] Department of Electrical Engineering, School of Engineering, Aalto University, Finland

[*] Corresponding author: B. Alimohammadisagvand, Tel +358 45 801 2666, e-mail address:

behrang.alimohammadi@aalto.fi

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Abstract

   This study has two aims to investigate the energy demand response actions on thermal comfort and energy cost in detached residential houses in a cold climate. The first one is to find out the acceptable range of indoor air and operative temperatures complying with the recommended thermal comfort categories in accordance with the EN 15251 standard. The second one is to minimize the energy cost of electric heating system by means of the demand response (DR) control strategy, without sacrificing thermal comfort of the occupants. This research was carried out with the validated dynamic building simulation tool IDA ICE. Three different control strategies were studied: A) a strategy based on real-time hourly electricity price, B) new DR control strategy based on previous hourly electricity prices and C) new predictive DR control strategy based on future hourly electricity prices. The results show that the lowest acceptable indoor air and operative temperatures can be reduced to 19.4°C and 19.6°C, respectively. The maximum annual saving in total energy cost is about 10% by using the control algorithm C.

Key Words: Demand response actions; Thermal comfort; PMV index; Electric space heating; Control algorithm.

Introduction

The building sector contributes up to 30% of global annual greenhouse gas emissions, primarily through the use of fossil fuels during their operational phase, and consumes up to 40% of all energy used[1]. The level of greenhouse gas emissions from buildings is correlated with the level of demand, supply and source of energy. Hence, due to scarcity of natural resources and continuous increment in the electricity consumption worldwide, it is very important as well as demanding to develop energy-saving strategies. The buildings in the European Union (EU) account for 40% of the total energy consumption, mainly in space heating and hot water[2]. Overall, residential and tertiary sectors in the EU account for 50% of the electricity consumption[2]: 22% of that consumption is for electric heating, 9% for hot water heating and 1% for air conditioning[3]. In Finland, due to its cold climate, the heating in residential buildings accounts for 22% of the total primary energy consumption[4]. In 2012, detached houses comprised 89% of the Finnish residential buildings[5] and 31% of their heating energy is obtained from electricity[4].

Better demand side management and optimal control of Heating, Ventilation and Air Conditioning (HVAC) systems can reduce electricity demand and shift peak loads during shortage times. International Energy Agency (IEA)[6] states that control strategies such as pricing regulation, technical standards of demand response and environmental impacts by

retailers or consumer form the main approach to relieve the global energy crisis. Callaway et al. showed[7] that smart grid investments can demonstrate the potential for buildings to become grid-interactive resources while being just as controllable as or even more controllable than electricity generators. The smart grid concept proposes an electricity network that integrates generation and consumption with real-time two-way communications[8]. The US Federal Energy Regulation Communication (FERC) formulated the basic definition of Demand Response (DR). DR changes the electricity consumption patterns of end consumers to reduce instantaneous demand in times of high electricity prices[9]. DR relates to any program which communicates with the end-customer about prices changes in the market and their own energy use and encourages them to reduce or shift their energy consumption demand. DR actions also include load shifting and dynamic pricing control[10,11].

Annala et al.[12] reviewed previous studies about acceptability of different kinds of DR for Finnish residential buildings and assessed the consumer's awareness of the principle and benefits of DR programs by two separate questionnaire studies. They suggested that price and security of supply are major motives to change consumption behaviour than environmental issues and that the savings expected to trigger any action may be relatively high. Surles et al.[13] focused on utilizing a control analytic tool for evaluating the effectiveness of different demand response actions to shift and reduce energy consumption during peak

pricing periods and lower the total energy cost for residential homes and utilities. Residential DR is used and developed, in interesting ways, to improve systems' energy efficiency[14-15]. Also, the same authors present a scheme for optimal performance of major household loads under smart grid context to get the benefits of the availability of variable tariffs and renewables. Ali et al.[16] optimized the DR control of partial storage electric space heating by using a linear programming approach to minimize the total energy cost of consumers. Thermal comfort was also taken into account by using assumed variation band of indoor temperature ($\pm 2.0°C$). They concluded that combining the heat storage tank and thermal inertia of the house is able to offer much flexibility in DR control. Ali et al.[17] developed the research to find out the effect of storage tank's degree on the flexibility of electric storage space heating load control and to analyze the impact of storage tank losses and demand uncertainty on the DR control optimality. In[18], there is a description of micro grid management where the electricity supplied from the grid is integrated with the use of own renewable generation, more efficient resources, and demand resources connected to the micro-grid by means of an energy management and control system. Reductions of CO_2 emission have been assessed for periods when renewable generation resources and demand management are cheaper than the electricity provided by the grid. Avci et al.[19] proposed a practical cost- and energy-efficient model for a predictive HVAC load control strategy for

buildings with dynamic real-time electricity pricing. The temperature range of thermal comfort is determined by the user to keep the thermal comfort level at a reasonable range. They found significant reductions in total delivered energy and cost saving. Klein et al.[20] presented and implemented a multi-agent comfort and energy system to model alternative management for three different controller strategies and occupants. They model their case test by considering actual thermal zones, temperatures, occupant preferences, and occupant schedules. They found differences between their model and the traditional Predicted Mean Vote (PMV) thermal comfort evaluation for indoor comfort conditions and energy consumption which need more robust comfort standard. They finally achieved a 12% reduction in energy consumption and 5% improvement in occupant comfort in comparison with the baseline control strategy. Liu et al.[21] developed the multi-objective generic algorithm for model predictive control (MPC) to determine the optimal set point of heating and ventilation control system while improving indoor air quality. They found that the performance of the MPC controller with the optimized set points is able to reduce energy consumption by 5.2% in comparison to proportional-integral (PI) controller. Previous research has concentrated on residential DRs to address their actions in the residential sector while preserving indoor thermal comfort by means of temperature[22,23]. Molderink et al.[23] presented a three-step control methodology on domestic energy streams by reshaping house

energy profiles. They stated that objective like peak saving can be achieved without harming the comfort of residents since the indoor temperature deviation from indoor temperature set point is ±0.5°C.

Hoon Joon et al.[24] proposed a controller strategy to save total delivered energy and cost while maintaining reasonable thermal comfort for two house models in Austin, Texas, USA. The control strategy changes indoor temperature set point since the retail price is higher than the preset price of the customers; also, they used the range of indoor air temperature (22.0-25.0°C) for thermal comfort based on ASHRAE standard 55[25]. They stated that energy cost can be saved up to 10.8% by using this control strategy. Arteconi et al.[26] analyzed the influence of demand side management control strategies on the performance of thermally activated building systems (TABS) for a commercial building. They analyzed three different demand side management (DSM) mechanisms to estimate its potential for load shifting requested by the electricity grid while maintaining thermal comfort by assuming specific indoor temperature range (19.0-26.0°C). They concluded high potential of TABS within the DSM framework.

According to the literature review, the indoor air temperature has been used until now as the main indicator for thermal comfort in DR studies. However, thermal comfort includes several other aspects like activity, clothing, humidity, air speed, surface temperatures and

temperature drift. In this study, all these factors are accounted for, which is one of the novel features of this study. Further, two new control algorithms are used in the implementation of DR.

The lower and higher limits of PMV values are used to determine the acceptable minimum and maximum indoor air and operative temperatures. These temperatures are then determined, in accordance with the EN 15251 standard[27], for the electric radiator heating system and electric floor heating system by on-off and P-controller types. Then, changing set point temperatures (air and operative temperatures) will be assessed by three different control strategies: A) a strategy based on real-time hourly electricity price, B) a strategy based on previous hourly electricity price and C) a strategy based on future hourly electricity price. The control strategies monitor and control space heating and reduce the peak load while maintaining thermal comfort of the occupants at acceptable levels.

Building description

The studied building type is a Finnish two-storey detached house (see Figure 1) simulated with three different levels of thermal insulation and thermal mass.

Figure 1. Two-storey building (180 m^2) with area of each zone and window.
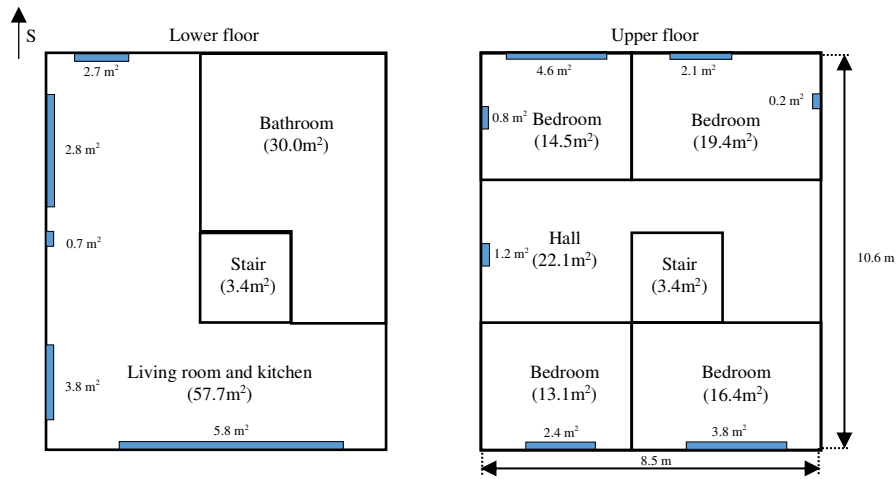
The floor area of the building is 180 m^2, and it has 6 rooms and kitchen with the room height of 2.6 m. Nine different versions of the detached house were simulated, the versions being determined on the basis of differences in construction practice and building regulations during different decades.

Building types and properties

Three different types of buildings (1960, 2010 and Passive) with three different types of structures (Light Weight (LW), Medium Weight (MW) and Massive) were simulated and analyzed. The building of "1960" is an old building built in 1960, and the buildings of "2010" and "Passive" are new buildings. The building envelope specifications are presented in the

Table 1. The Light Weight structures are wood frame constructions. The structures of the Medium Weight buildings are similar to the Light Weight cases except there is a concrete base floor. All the walls of the Massive buildings are lightweight concrete blocks but the roof and floor are concrete.

Table 1. Building envelope specifications.

Thermal insulation level	Elements of construction	Material composition (thickness of the layer) - external structures from inside to outside
Light weight (typical 1960)	External wall	gypsum (13 mm), wooden frame (150 mm) + mineral wool (50 mm), wind shield board (9 mm)
	Internal wall	gypsum (13 mm), wooden frame (40 mm), gypsum (13 mm)
	Roof	gypsum (13 mm), wooden frame (150 mm) + mineral wool (80 mm), water proof sheet (10 mm)
	Base floor	wood (14 mm), wooden frame (200 mm) + mineral wool (100 mm), wind shield board (9 mm)
	Intermediate floor	wood (15 mm), particle board (22 mm), wooden frame (150 mm), gypsum (13 mm)
Medium weight (standard 2010)	External wall	gypsum (13 mm), wooden frame (250 mm) + mineral wool (250 mm), wind shield board (9 mm)
	Internal wall	gypsum (13 mm), wooden frame (40 mm), gypsum (13 mm)
	Roof	gypsum (13 mm), wooden frame (150 mm) + mineral wool (150 mm), mineral wool (260 mm), water proof sheet (10 mm)
	Base floor	wood (14 mm), concrete (80 mm), EPS thermal insulation (430 mm)
	Intermediate floor	wood (15 mm), particle board (22 mm), wooden frame (150 mm), gypsum (13 mm)
Massive passive	External wall	light weight concrete block (130 mm), polyurethane (340 mm), light weight concrete block (90 mm)

Internal wall	light weight concrete block (100 mm)	
Roof	filler (5 mm), concrete (100 mm), mineral wool (490 mm), water proof sheet (10 mm)	
Base floor	wood (14 mm), light weight concrete (15 mm), concrete (100 mm), EPS thermal insulation (480 mm)	
Intermediate floor	wood (15 mm), light weight concrete (15 mm), concrete (100 mm), filler (5 mm)	

The level of thermal insulation of the "1960" house is based on a typical level Finnish detached house built in 1960s in accordance with the Finnish energy certificate[28]. The level of thermal insulation of the "2010" house complies with the minimum requirements of the Finnish building code C3,[29] and the "Passive" house follows the Finnish guidelines for Finnish Passive houses. [30] Air tightness of the "1960" and "2010" houses is based on the default values of the Finnish energy certificate[28] and air tightness of the "Passive" house abides with the guideline of.[30] Table 2 shows the different cases of structures with their U-value, window properties and air tightness.

Table 2. Properties of different structures: thermal insulation, U-values, window properties and air tightness.

Cases	Thermal insulation	U-values (W/m²K)	Window properties	Air tightness

		Ext wall	Roof	Base floor	Doors	Windows	g^1	ST^2	q_{50} (m³/h.m²)
Lightweight									
LW-1960	Typical 1960	0.81	0.47	0.35	2.2	2.8	0.78	0.74	7.3
LW-2010	Standard 2010	0.17	0.09	0.09	1.0	1.0	0.46	0.39	4.9
LW-Pass	Passive	0.08	0.07	0.08	0.5	0.8	0.46	0.39	0.7
Medium weight									
MW-1960	Typical 1960	0.81	0.47	0.35	2.2	2.8	0.78	0.74	7.3
MW-2010	Standard 2010	0.17	0.09	0.09	1.0	1.0	0.46	0.39	4.9
MW-Pass	Passive	0.08	0.07	0.08	0.5	0.8	0.46	0.39	0.7
Massive									
M-1960	Typical 1960	0.81	0.47	0.35	2.2	2.8	0.78	0.74	7.3
M-2010	Standard 2010	0.17	0.09	0.09	1.0	1.0	0.46	0.39	4.9
M-Pass	Passive	0.08	0.07	0.08	0.5	0.8	0.46	0.39	0.7

[1] Total solar heat transmittance (g)

[2] Direct solar transmittance (ST)

Heating and Ventilation system

This research deals with the electric radiator heating system (ERHS) and electric floor heating system (EFHS), focusing on these two heat distribution systems and two typical controllers for electric heating systems (on-off controller[31] and P-controller[32]) as the alternative systems and controller types for buildings. The value of the on-off controller type dead band is assumed to be 1.0°C and the proportional band of the P-controller type is also assumed to be 1.0°C.

In addition, the ventilation system of different building types is studied. The 1960 building type has a mechanical exhaust ventilation system. The ventilation rate of this building type is based on the average ventilation rate of 55 Finnish houses with mechanical exhaust ventilation[33]. For the 1960s cases, the ventilation rate considered is 0.36 Air Change per Hour (ACH). The 2010 and Passive building types have a mechanical supply and exhaust ventilation system with heat recovery. The system of mechanical supply and exhaust ventilation with heat recovery is the most common ventilation system in new Finnish detached houses. Heat recovery with the efficiency of 60% and 80% for 2010 and Passive cases, respectively, has been employed. In the 2010 and passive building types, ACH is 0.5, in accordance with the guideline of the Finnish building code D2 (2012)[34].

Behaviour of the occupants

Activities and clothing have an effect on thermal comfort[35,36]. Thus, the activity levels of 1.0 met (seated and relaxed) and 1.2 met (standing and relaxed) are used in the simulation and clothing insulation levels of 0.96 clo (trousers, long-sleeved shirts plus suit jackets) and 1.14 clo (trousers, long-sleeved shirts plus suit jackets plus vest and T- shirt) are studied[37].

Because the relative humidity of indoor air also affects thermal comfort[38,36], indoor air moisture is considered in the simulation. Thus, typical Finnish level of moisture production was used as initial data for the simulation. This study used the daily moisture production of

2.7 kg/24h per occupant, in accordance with the study by Vinha et al.[39]; therefore, the total moisture production from persons and equipment is 10.8 kg/24h and 5.4148 kg/24h (0.00006267 kg/s), respectively.

Internal heat gains are considered as an important component in heating load production in buildings. They consist of sensible and latent heat gains from occupants, sensible heat gains from lighting, and sensible and latent heat gains from equipment. The heat gains from occupants were considered when studying different activity levels, but the value of internal heat gains from lighting and equipment still needs further study. To implement these values, typical consumption profiles of appliances and lighting of Finnish detached houses are used in this study.

This study utilizes consumption profiles defined by means of the conditional demand analysis (CDA) technique[40] and applied to 1630 Finnish households. The analysis was carried out by using statistical information gathered through questionnaires and by examining one-year hourly-measured electricity consumption of the households. The analysis resulted in different consumption profiles for weekdays and holidays of the four seasons of the year. The hourly consumption profiles for the equipment and lighting used in the simulation are presented in Figure 2 for winter weekdays.

This research assumed that all the electric energy used for inside lighting and part of the electric energy used for equipment end up as an internal heat gain of the building[41,42]. In accordance with a guideline of the Finnish building code[43], a half of the electricity consumption of the equipment that heat water (e.g. dishwasher or washing machine) can be assumed to end up as internal heat gain of the building. Because of this, 86% of the total electricity consumption of the equipment was assumed to end up as an internal heat gain of the studied houses. According to hourly consumption profiles for lighting and equipment, these values for the studied buildings are 8.5 and 22.2 kWh/(m^2.a.)
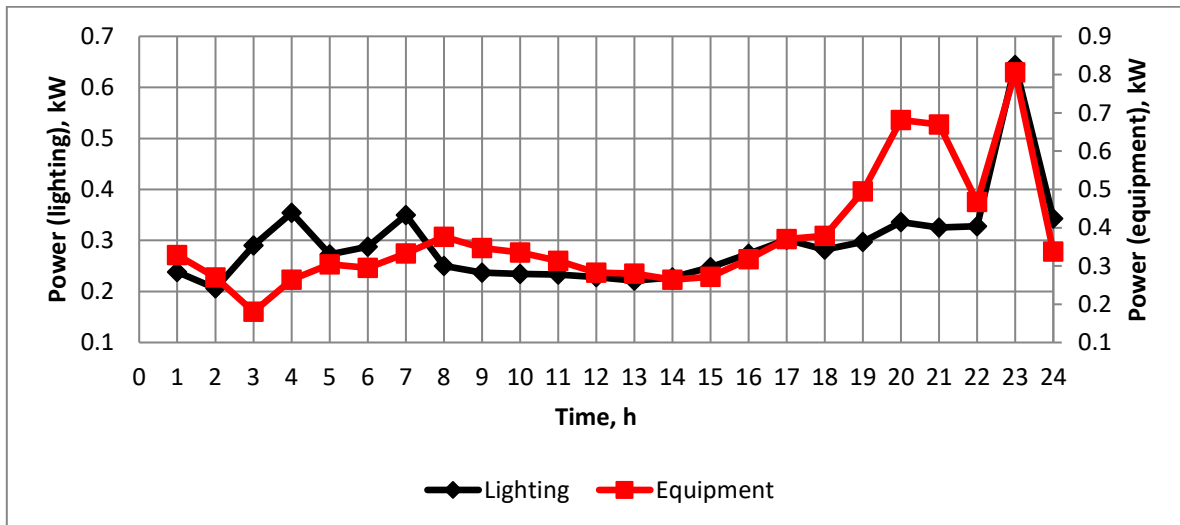

Figure 2. Hourly electric power for lighting and equipment in a typical Finnish household during weekdays of the winter period.

Methodology development

The study structure

Figure 3 shows the study structure consisting of two main parts, including control algorithm and the IDA ICE building simulation software (see Section *"The IDA ICE simulation tool"*). The control algorithm part receives three different inputs from acceptable indoor temperature set points (see Section *"Defining minimum and maximum of indoor temperature set points"*), weather file (see Section *"Weather data"*) and Hourly Electricity Price (HEP). The IDA ICE receives two different inputs from control algorithm and input data. Input data part comprises information about building geometry, envelope, glazing, HVAC systems, lighting, equipment, heating system, etc. Finally, the IDA ICE produces output data (e.g. total delivered energy and cost) by using control algorithm data and input data simultaneously.
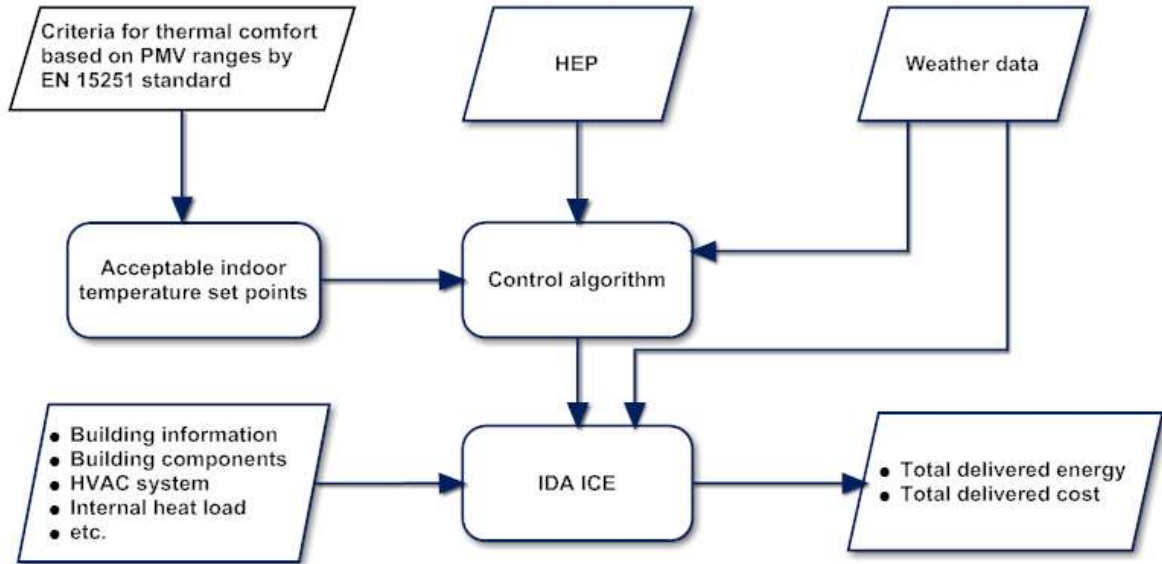
Figure 3. The flow chart of the study.

Indoor thermal comfort according to related standard

Thermal comfort describes a person's psychological state of mind which expresses satisfaction with the thermal environment and is assessed by subjective evaluation[44]. Thermal comfort has great influence on the productivity and satisfaction of occupants in buildings[45]. This study uses the Fanger approach to predict the thermal comfort of the occupants in the buildings[44].

To conduct this research, two reference standards including the EN 15251[27] and ASHRAE standard 55[25] were considered. EN 15251, the European standard, specifies the indoor environmental parameters which have an impact on energy performance of the buildings.

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Through energy simulation, a study and analysis have been carried out to satisfy the thermal conditions for different categories defined in that standard[27].

Table 3 and Table 4 show the four categories, describing the level of expectations for the occupants, and the comfort conditions for those categories of buildings respectively defined in this standard.

Table 3. Description of the applicability of thermal comfort categories of the EN 15251[27].

Category	Explanation
I	High level of expectation and is recommended for spaces occupied by very sensitive and fragile persons with special requirements like handicapped, sick, very young children and elderly persons
II	Normal level of expectation and should be used for new buildings and renovations
III	An acceptable, moderate level of expectation and may be used for existing buildings
IV	Values outside the criteria for the above categories. This category should only be accepted for a limited part of the year

Moreover, the categories in Table 3 and Table 4 are defined by means of PPD and PMV values, and the lower limits of PMV values were used to determine the minimum acceptable indoor air and operative temperatures during the heating season. The maximum PMV values were used to define the maximum acceptable indoor air and operative temperature during the heating season, even though the maximum PMV values have originally been defined for the cooling season.

Table 4. Thermal comfort categories for design of mechanically heated and cooled buildings[27].

| Category | Thermal state of the body as a whole | |
	PPD %	PMV
I	<6	-0.2 < PMV <+0.2
II	<10	-0.5 < PMV < +0.5
III	<15	-0.7 < PMV < +0.7
IV	>15	PMV < - 0.7 or +0.7 < PMV

The EN 15251 standard[27] defines several methods for residential and non-residential buildings to evaluate the fulfilment of comfort indoor conditions. This study uses the percentage falling outside the limits of the acceptable range method. The method allows a slight time deviation from the acceptable range. A 5% deviation [27] is used in this study for temperatures above the criteria, for: 24 minutes (during a weekday), 2 hours (during a week), 9 hours (during a month) and 108 hours (during a year). The ASHRAE standard 55[25] defines the maximum operative temperature change allowed. The monotonic and non-cyclic changes in operative temperature are known as temperature drifts and ramps. Drifts and ramps refer to passive temperature changes of the enclosed space and to actively controlled temperature changes, respectively. Table 5 specifies the maximum allowed variation in operative temperature during a period of time. According to the ASHRAE standard 55[25], for any time period, the variation of operative temperature cannot exceed the limits defined in Table 5. But, if the variations are created as a result of control or adjustments by the occupant, higher variations may be acceptable.

Table 5. Maximum allowed variation in operative temperature[25].

Limits on temperature drifts and ramps					
Time period (h)	0.25	0.5	1	2	4
Maximum operative temperature change allowed (°C)	1.1	1.7	2.2	2.8	3.3

Defining minimum and maximum of indoor temperature set points

In order to determine the acceptable range of indoor air and operative temperatures, the correlation between PVM values and indoor temperatures was studied. The coldest period (8th of January-4th of March) was simulated to determine the critical values of PMVs (minimum and maximum) and indoor temperatures. PMVs and indoor temperature obtained were drawn to find the linear trendline of PMV as a function of indoor temperature. The defined linear trendlines were used to determine the acceptable range of indoor temperatures by inserting the minimum and maximum PMV values of the thermal comfort categories into the equation of linear trendlines. This strategy was simulated to find out the acceptable range of indoor temperatures for different building types with different heat distribution systems and different activity levels, clothing levels and air velocities. Figure 4 shows an example of minimum and maximum lines of indoor air temperatures (T_{air}) for the Light Weight 1960 (LW-1960) building type with electric radiator heating system and P-controller type.
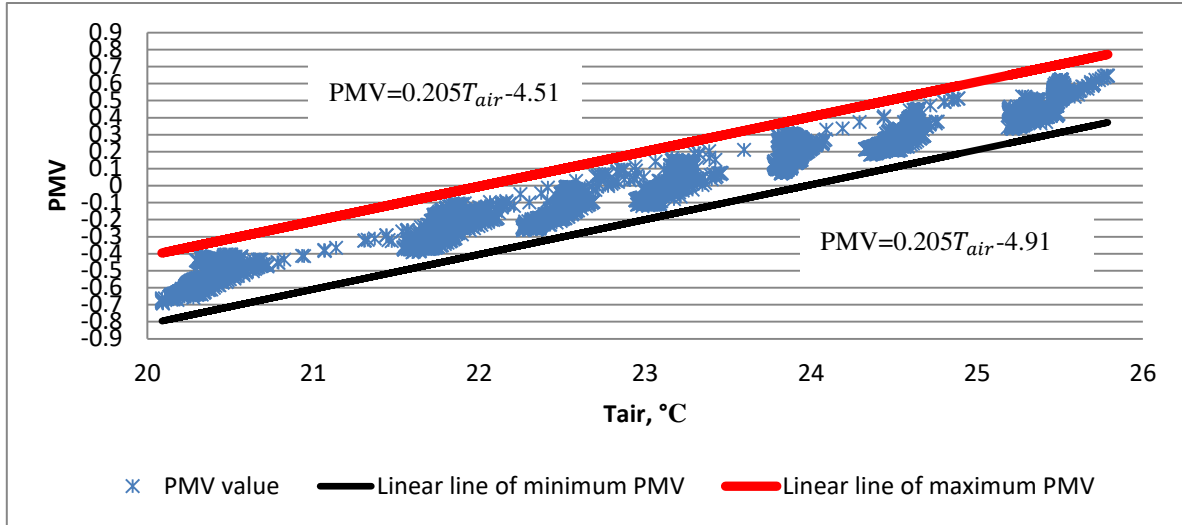
Figure 4. Defining minimum and maximum linear lines of indoor temperature set point in different categories.

The IDA ICE simulation tool

The simulation part of this research was implemented by IDA Indoor Climate and Energy (IDA ICE)[46]. The IDA ICE 4.5 building simulation software is a detailed and dynamic multi-zone simulation application with variable time step for the study of indoor climate and energy. The IDA ICE was validated against the EN 15265-2007 standard[47] and the maximum inaccuracy levels for heating and cooling demand were 8% and 11%. The IDA ICE has been validated in several studies[48,49,50,51] which show good justification to use the IDA ICE in this study. For example, Travesi et al.[52] conducted an empirical validation study of models of the IDA ICE relating to thermal behaviour of buildings and HVAC equipment. They found that

agreement between simulated and measured data was good and disagreements were similar to the measurement uncertainty.

The IDA ICE is a befitting tool for simulation of energy consumption, indoor air quality and thermal comfort in buildings. It can be used for a variety of applications, such as integrated airflow network and thermal models, CO_2 and moisture calculation, and vertical temperature gradients.

Weather Data

This research used the Finnish test reference year (TRY2012) as a weather data for dynamic simulations. The data consists of detailed hourly data of temperature, relative humidity, wind velocity, and solar direction and radiation describing the current climatic conditions of Southern Finland. The weather conditions data was accumulated and computed by recording a 30-year period (1980-2009) in Helsinki region[53]. Finnish climate is highly influenced by the country's geographical position between the 60th and 70th northern parallels in the Eurasian continent's coastal zone, which shows characteristics of both a maritime and a continental climate, depending on the direction of weather front. The annual average temperature for Helsinki-Vantaa region is +5.4°C, bringing the region under climatic zone 1[54]. The average number of degree days at indoor temperature of 17.0°C is 3952 Kd.

Simulated demand response control strategies

In the DR mechanism studied, the customers are motivated to respond to the HEP[55] by changing the indoor temperature set point of space heating to decrease the total energy cost while maintaining the thermal comfort of the occupants at the acceptable level. The DR control algorithm for controlling the electric space heating has different levels of complexity and requisites. Using electricity price as an incentive, the three proposed control algorithms unleash the flexibility of DR. These control algorithms are the extension of the conventional on-off control which use the real time HEP, the previous HEPs or the future HEPs. To investigate the effect of each control algorithm on total delivered energy and energy cost of studied detached houses, these control algorithms are applied with IDA ICE 4.5.

Control algorithm A

This is the simplest algorithm which controls indoor temperature set point (T_{set}) according to HEP. To change the set point, if the HEP is less than limiting price (LP), the normal indoor temperature set point is used; otherwise, it will be the minimum set point in the acceptable temperature range. The pseudo code (1) for the control mechanism is as given in Eq (1):

$$If\ HEP < LP\ then\ T_{set} = T_{set,normal} \tag{1}$$

$$else\ T_{set} = T_{set,min}$$

$$End.$$

The performance of this algorithm is simulated by using the following values of the parameters; $T_{set,normal}$ is the normal set point temperature used for detached houses, in accordance with the Finnish building code (21.0°C)[34,54], $T_{set,min}$ is the minimum indoor temperature set point defined in this study (see Section *"Acceptable indoor temperature set points"*) and the assumed value of the LP is 50€/MWh. The assumed LP is significantly lower than the maximum HEP (300.1€/MWh) and higher than the average HEP (36.7€/MWh) of the studied year 2012 to show the potential of controlling indoor temperature set point in accordance with the assumed LP.

Control algorithm B

The main idea of this new control algorithm is to manage the indoor temperature set point according to previous HEPs. This is done by comparing the median of previous hourly electricity prices (MHEP) and current HEP. The number of previous hours can be selected, and the optimal number of previous hours is analyzed in this study. At every hour when the new price of the Nordpool[57] trading system is announced, the DR control modifies the indoor temperature set point according to HEP, which can be either increased, kept constant or decreased. The control algorithm has two parts: the first part compares MHEP and HEP, and the second part concentrates on the indoor temperature and outdoor temperature trend. The pseudo code (2) for the control mechanism is as given in Eq (2):

$$If \ HEP \geq MHEP, \quad then \quad T_{set} = T_{set,min} \tag{2}$$

$$elseif \quad \begin{cases} HEP < MHEP \\ and \\ T_{max} < T_{set,max} \\ and \\ T_{out}^{ave,24} < T_{out}^{lim} \end{cases} \quad then \quad T_{set} = T_{set,max}$$

$$else \ T_{set} = T_{set,normal}$$

$End.$

where T_{max} is the maximum hourly indoor temperature of the building, $T_{set,max}$ is the maximum acceptable indoor temperature, $T_{out}^{ave,24}$ is the average outdoor temperature of previous 24 hours and T_{out}^{lim} is the limiting outdoor temperature considered as the maximum outdoor temperature when the indoor temperature set point can be increased.

In this control algorithm, if HEP is higher than or equal to MHEP, the indoor temperature set point is decreased, otherwise the indoor temperature set point is either increased or the normal one is used, depending on the indoor temperature and outdoor temperature trend. The indoor temperature is compared with constant parameter $T_{set,max}$ to avoid overheating. Then, to find out whether the outdoor temperature is getting colder or warmer, the average outdoor temperature of the previous 24 hours is compared by the limiting outdoor temperature. If the maximum indoor temperature of the building is less than the maximum indoor temperature set points, acceptable or lower one (see Section *"Acceptable indoor temperature set points"*),

and the outdoor temperature is lower than the limiting outdoor temperature, the indoor temperature can be increased. Otherwise, the normal indoor temperature set point is used.

In order to improve the performance of the algorithm, the optimal number of previous hours was examined. These numbers of previous hours, ranging from 2 to 24 hours, were then used by the algorithm to simulate the annual energy cost of space heating (ECSH) of the building. Figure 5 shows the effect of previous hours on the ECSH for Massive Passive (M-Pass) building type simulated with HEP of three years (2010–2013). Because the HEP of 2011 is quite similar to the HEP of 2012, it was not studied; and the HEP of 2010 and 2012 or 2013 are quite different, Figure 5 shows results in two price scales. For minimizing the ECSH for the studied building types, the optimum number of previous hours among the studied time periods is 14. Moreover, it was found that the level of thermal insulation and thermal mass of the building does not affect the resultant optimum number of hours. Also, the optimum number of previous hours is independent of the studied time period and building types. Furthermore, the optimal number of previous hours does not depend on the heat distribution systems and temperature controller types studied.
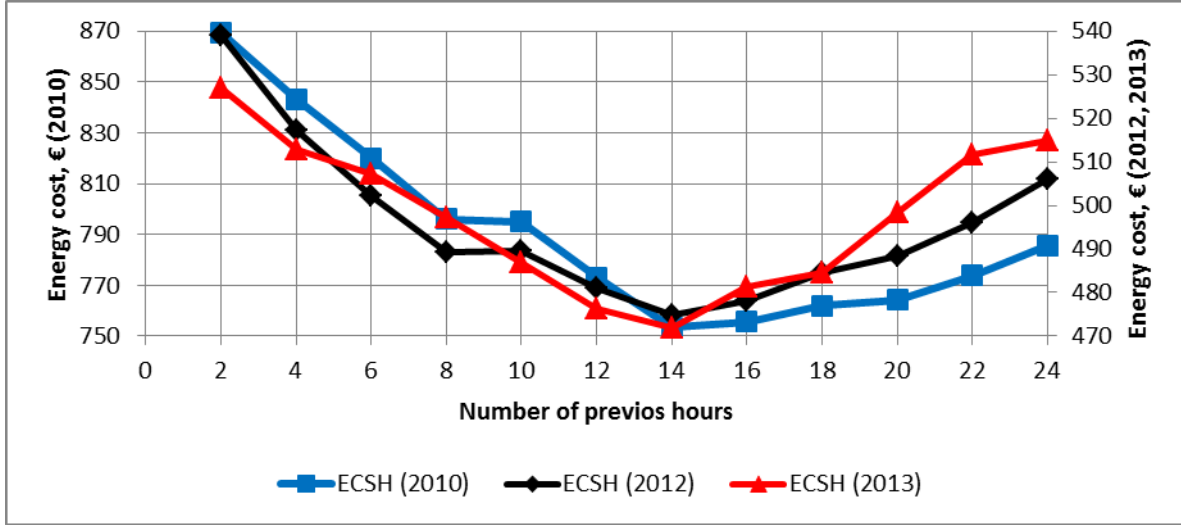
Figure 5. Total energy cost of space heating in M-Pass building (see Table 2) with different number of previous hours, which have been used in the algorithm B.

These results were simulated for LW-1960 and M-Pass building types with electric radiator heating system and P-controller type. The normal indoor temperature set point was 21.0°C[49,52], the limiting outdoor temperature (T_{out}^{lim}) was 0.0°C and the acceptable range of indoor temperature set point according to the thermal comfort category III was used.

Control algorithm C

The principle of this new predictive control algorithm is to control the indoor temperature set point by adjusting it in accordance with future hourly prices. This algorithm generates a control signal by utilizing maximum subarray problem. 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[56]. By means of this

concept, the HEPs can be accordingly sorted to realize their rising or falling trend; hence, corresponding control signals can be assigned to the limited future prices.

This control algorithm has two parts: first, the control algorithm calculates the control signal (CS); second, the indoor temperature set point of building is controlled according to the CS, the indoor temperature and outdoor temperature trend (the indoor temperature and outdoor temperature trend rules are similar to the rules used with control algorithm B).

The principle of such control algorithm is; the algorithm generates CS = +1 to increase the indoor air temperature set point to the maximum one before the HEP increases. As soon as the HEP starts to increase, the algorithm generates CS = -1 to decrease the indoor air temperature set point to the minimum one. In other conditions, the algorithm generates CS = 0 and the indoor air temperature set point is the normal set point temperature. The pseudo code (3) of the control mechanism is as given in Eq (3):

$$If\ CS = -1 \qquad then \quad T_{set} = T_{set,min} \tag{3}$$

$$elseif \quad \begin{Bmatrix} CS = +1 \\ and \\ T_{max} < T_{set,max} \\ and \\ T_{out}^{ave,24h} < T_{out}^{lim} \end{Bmatrix} \quad then \quad T_{set} = T_{set,max}$$

$$else \ CS = 0, \qquad then \quad T_{set} = T_{set,normal}$$

$$End.$$

The optimal number of limited future hours was studied by simulating the annual ECSH of the building with different number of future hours ranging from 2 to 24 hours. The latter number of hours was used as a maximum period because HEPs are published 24 hours ahead[57]. Figure 6 shows the effect of different future hours to the ECSH of the M-Pass building type simulated with HEP over three different years. The optimum number of hours among the studied time periods is 12 and it is independent of thermal insulation, thermal mass, studied time period, building type, heat distribution systems and temperature controller types studied.
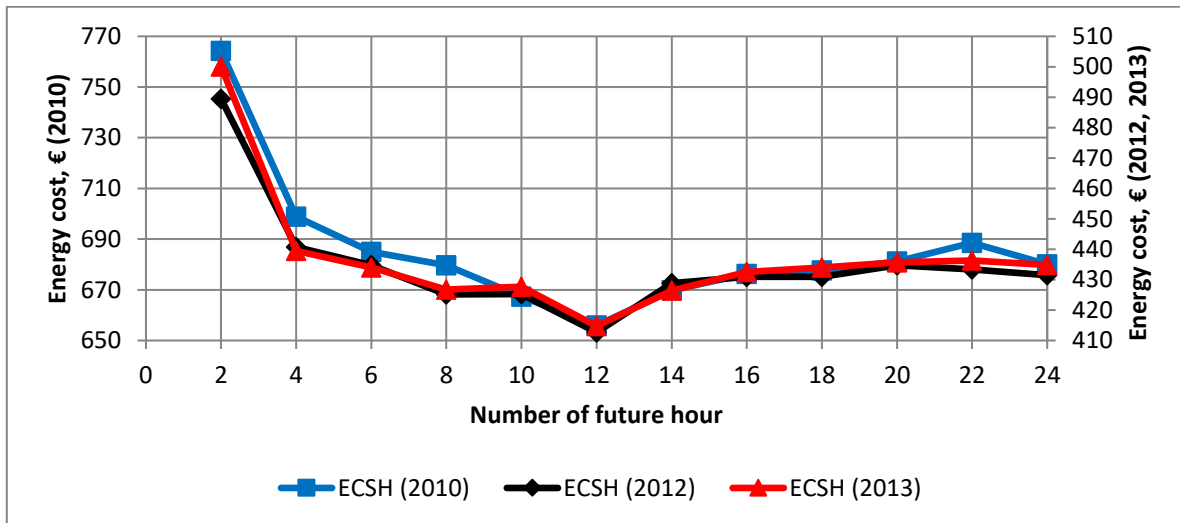

Figure 6. Total energy cost of space heating in M-Pass building (see Table 2) with different number of future hours which have been used in the algorithm C.

Results and discussion

The results present an assessment of the indoor operative temperature changes to find out the level of fulfilment of the ASHRAE standard 55[25]. Then, the acceptable indoor air and operative temperatures are presented in accordance with the EN 15251 standard[27] for the LW-1960 and M-Pass building types as the extreme ones. Finally, the control algorithms are applied in the on-off and P-controller types for ERHS and EFHS.

Fulfilment of the ASHRAE standard 55

To assess the speed of the indoor operative temperature drift in the nine studied buildings, Figure 7 shows the indoor operative temperature during four hours of January (as typical winter temperatures in Finland) since the heating system is switched off. It shows that LW-1960 and Medium Weight 1960 (MW-1960) buildings do not fulfil the ASHRAE standard 55[25], the variation of the indoor operative temperature exceeding the allowed variation. The ASHRAE standard 55[25] states that higher variations may be acceptable because the studied temperature variations are created by the control system. The LW-1960 building was selected for the energy and cost simulations because it represents the extreme building type due to the very low thermal mass and poor level of thermal insulation.
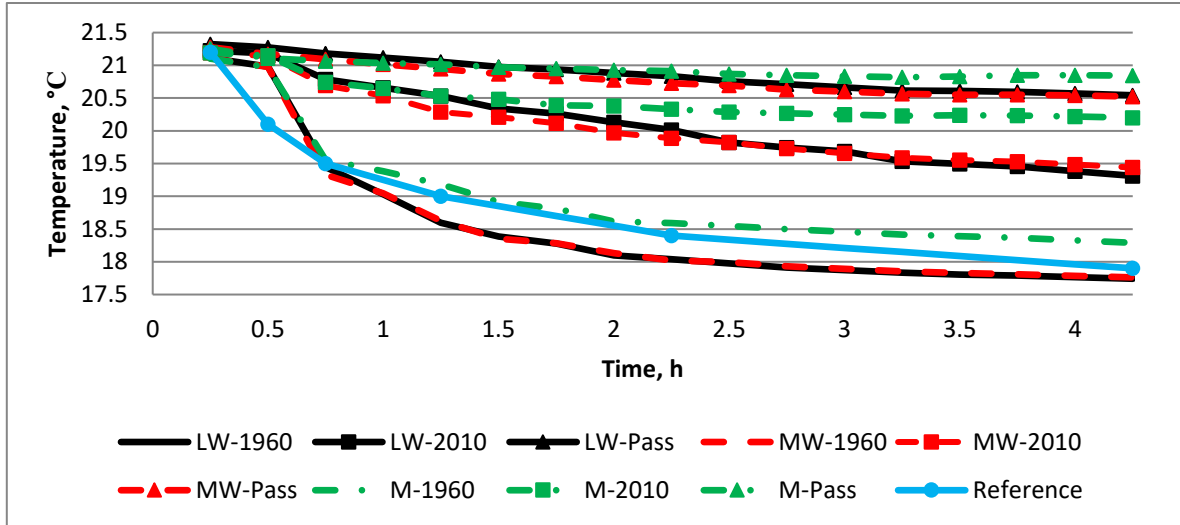
Figure 7. Fulfilment of ASHRAE standard 55 rule for operative temperature change for the nine studied buildings.

Acceptable indoor temperature set points

The acceptable indoor temperature set point depends on various conditions such as different occupants' behaviour (e.g. different met levels and different clothing levels), heat distribution systems and the controller types installed in different buildings. To find out about the influence of these conditions on acceptable indoor temperatures, this research studied different activity levels, clothing levels and air velocities.

Table 6 presents the acceptable indoor temperatures for the ERHS and EFHS with the on-off and the P-controller types. The minimum and maximum indoor temperature set points are shown for three different thermal comfort categories defined in the EN 15251 standard.

The lowest minimum indoor air temperature set points for category I, II and III are 21.8°C, 20.4°C and 19.4°C, respectively, and the minimums of indoor operative temperature set points for categories I, II and III are 22.1°C, 20.6°C and 19.6°C, respectively. In all the studied cases in category III, the minimum indoor air and operative temperature set points are lower than the normal set point temperature used in detached houses in accordance with the Finnish building code (21.0°C); but in some of the studied cases from category II are lower than the normal set point temperature. Thus, the results indicate that the thermal comfort category III of the EN 15251 standard[27] can be used for control algorithms. The decrease in the range of indoor temperature set points of thermal comfort from category III to category I indicates smaller fluctuation from indoor temperature set points. The decreasing fluctuation of indoor temperature set point verifies the increasing expectation levels of occupants.

The calculated minimum operative temperature set points imply that these values are higher than the recommended one by the EN 15251 standard[27] (18.0°C) for living spaces of residential buildings in category III. Also, the maximum operative temperatures are either lower or higher than the recommended maximum indoor temperature set point defined by the EN 15251 standard[27] (25.0°C). Therefore, the recommended minimum operative

temperature set point of the EN 15251 standard cannot be used for such acceptable minimum

temperature set points in the studied cases.

Table 6. Minimum and maximum of air and operative temperatures in ERHS and EFHS with on-off controller and P-controller types for LW-1960 and M-Pass building types (the activity and clothing levels are 1.2 met and 0.96 clo, and air velocity is 0.1 m/s).

Category	LW-1960		M-Pass	
	Min-Max of T_{air} (°C)	Min-Max of T_{op} (°C)	Min-Max of T_{air} (°C)	Min-Max of T_{op} (°C)
ERHS , on-off control				
I	22.4-22.5	22.6-22.7	22.6-22.8	22.7-22.9
II	21.0-22.9	21.2-24.0	21.2-23.6	21.3-24.1
III	20.0-24.0	20.2-24.4	20.2-24.4	20.3-24.6
ERHS , P-control				
I	22.8-22.9	22.3-22.8	22.3-22.7	22.2-22.7
II	21.4-24.3	20.8-24.3	20.8-24.1	20.7-24.1
III	20.4-25.3	19.8-25.3	19.8-25.1	19.7-25.1
EFHS , on-off control				
I	22.5-22.6	22.7-22.8	22.6-22.8	22.6-22.8
II	21.0-23.0	21.3-23.5	21.2-23.5	21.2-24.0
III	20.0-24.1	20.3-24.4	20.2-24.5	20.2-24.7
EFHS , P-control				
I	21.8-22.2	22.1-22.4	22.0-22.3	22.1-22.5
II	20.4-23.6	20.7-23.7	20.5-23.9	20.6-24.1
III	19.4-24.6	19.7-24.7	19.5-24.9	19.6-25.1

The maximum and minimum temperature decreases from the normal set point are 1.6°C

and 0.6°C calculated for the LW-1960 building type by using EFHS and ERHS with the P-

controller type. Such decreases prove the potential of changing indoor temperature set point

to achieve lower total delivered energy and energy cost in comparison with using a normal

set point temperature for the whole year. Also, the highest temperature increase, 4.3°C, from the normal set point occurred in the LW-1960 building type using ERHS with the P-controller type; however, the lowest one is 3.0°C and calculated in LW-1960 where both ERHS and EFHS with the on-off controller type were used. The difference of the minimum indoor air temperatures between LW-1960 and M-Pass building types are insignificant. But, in most of the studied cases, the maximum indoor air temperature for M-Pass building is a bit (0.1°C-0.7°C) higher than the LW-1960 building types. Thus, the range of acceptable indoor air temperatures for the M-Pass is wider than LW-1960 building type, which meaning thermal mass and insulation are slightly effective on this range. The results of most of the studied cases show that increasing thermal insulation slightly increases the acceptable indoor temperature ranges. Also, in the same controller system, the different heat distributions are insignificant in the acceptable indoor temperature ranges; however, the range of acceptable indoor temperature set points of the P-controller type is wider than that of the on-off controller type.

In the on-off controller type cases, the differences between indoor air and operative temperatures are insignificant. But, smaller fluctuation of the indoor temperature in P-controller type cases causes more differences between indoor air and operative temperatures.

The results show that the minimum indoor temperature set points in ERHS with the P-controller type are higher than with the on-off controller type, which can be the reason of the fluctuations of the indoor temperature with the on-off controller type. But, the minimum indoor temperature set point in EFHS with the P-controller type is lower than with the on-off controller type.

This research assessed influence of acceptable indoor temperature on different activity levels, clothing levels and air velocities, including the velocities of 0.1 m/s and 0.2 m/s, because they are typical air velocities in detached houses [58,59]. The effect of air velocity depends on the thermal comfort category; it means that by changing the air velocity from 0.1 m/s to 0.2 m/s, the minimum indoor air and operative temperature set point for categories I, II and III, shown in Table 6, increases from 0.6°C to 1.0°C depending on the cases. The effect of activity level also depends on the thermal comfort category: the minimum indoor temperature set point can be increased up to 2.0°C for categories I and up to 2.5°C for category II or III by changing the activity level from 1.2 to 1. Moreover, the effect of a change in clothing level from 1.14 clo (shown in Table 6) to 0.96 clo is to increase the minimum indoor air and operative temperatures between 0.9°C and 1.3°C.

Performance of control algorithms

The control algorithms were implemented in the IDA ICE. The pseudo code for each control algorithm was defined by the logic applications of IDA ICE, then the weather data and HEPs are called as the input values. In order to examine different control algorithms to find out total delivered energy and cost, the performance of each control algorithm is analysed. Figure 8 shows the operation of control algorithm A during the weekdays of the first week of February 2012 (see Section *"Weather data"*). It shows the adjustment of T_{set} according to HEP; if the HEP is less than 50€/MWh, the normal indoor temperature set point is used; otherwise, the minimum indoor temperature set point will be used.
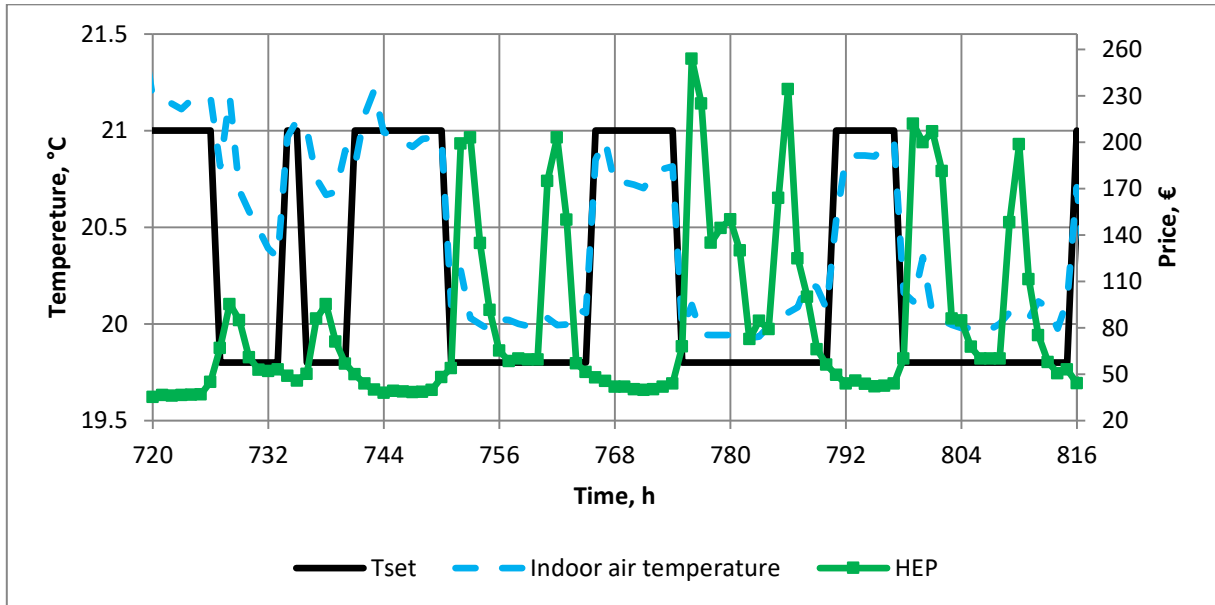
Figure 8. Operation's results of control algorithm A for M-Pass building type.

Figure 9a shows the operation of control algorithm B. It displays the adjustment of T_{set} according to other parameters. It displays the dynamic behaviour of changing indoor air temperature according to T_{set} (acceptable indoor temperature set points are presented in Section *"Defining minimum and maximum of indoor temperature set points"*). Figure 9b illustrates that the comparison of indoor air temperatures for LW-1960 and M-Pass building types with indoor air temperature set point. It shows the dynamic behaviour of the LW-1960 building derived by changing indoor air temperature is faster than that of the M-Pass building. Because of more thermal mass and insulation, the changing indoor air temperature of M-Pass building type is so slowly.
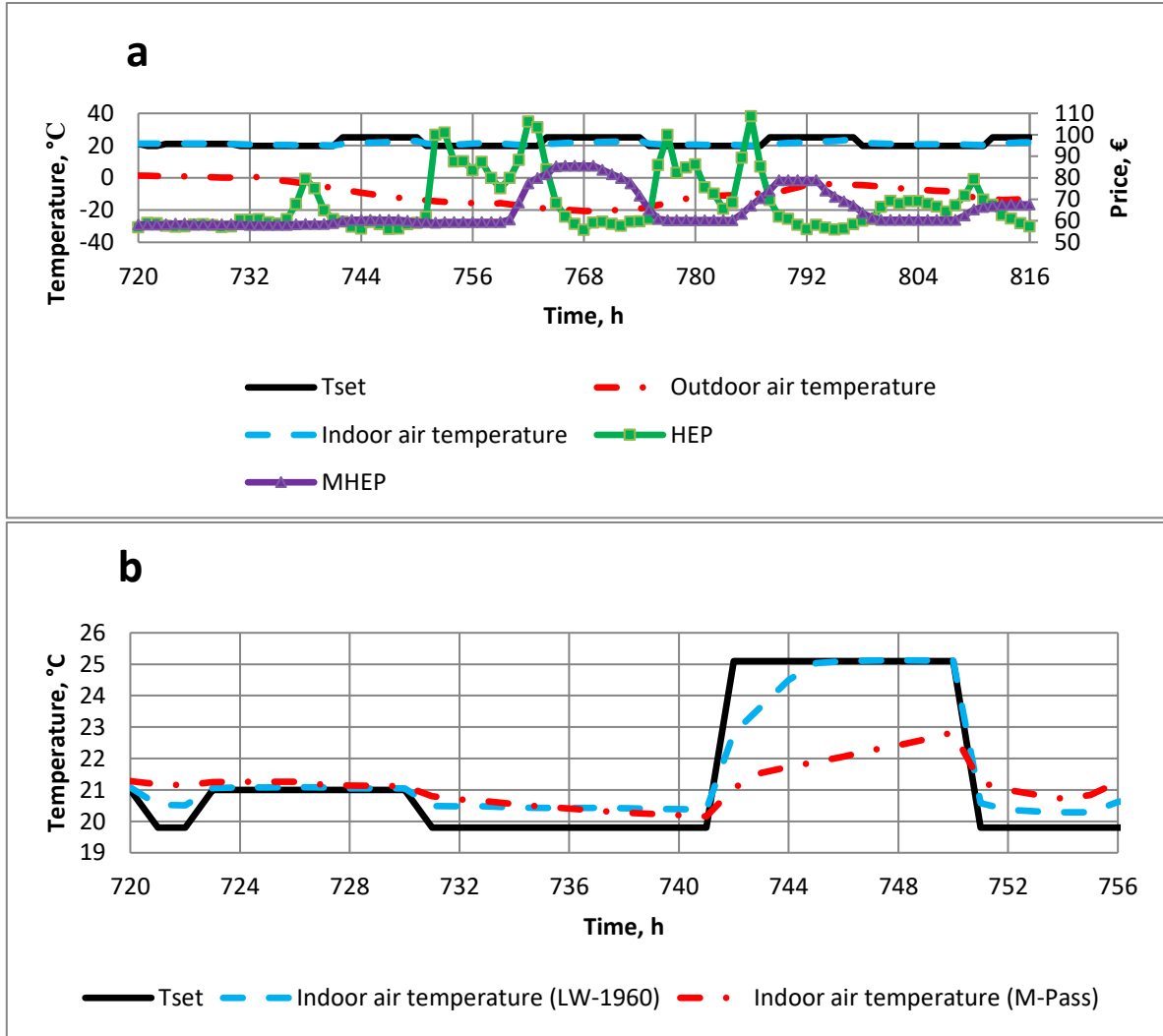
Figure 9. Operation's results of control algorithm B in different variables for M-Pass building type (a) and comparing indoor air temperatures for different building types with indoor air temperature set point (b).

Figure 10a shows the output signal of control algorithm C in accordance with the HEP. The control algorithm controls the set point of space heating by responding to the volatility of future prices. The prices are updated after certain hours. The operation of control algorithm

C is shown in Figure 10b. Also, the comparison between Figure 10b and Figure 9a shows that T_{set} (acceptable indoor temperature set points) is controlled quite differently and increased much less by control algorithm C. These results were simulated for an electric floor heating system with P-controller type and the thermal comfort category III.
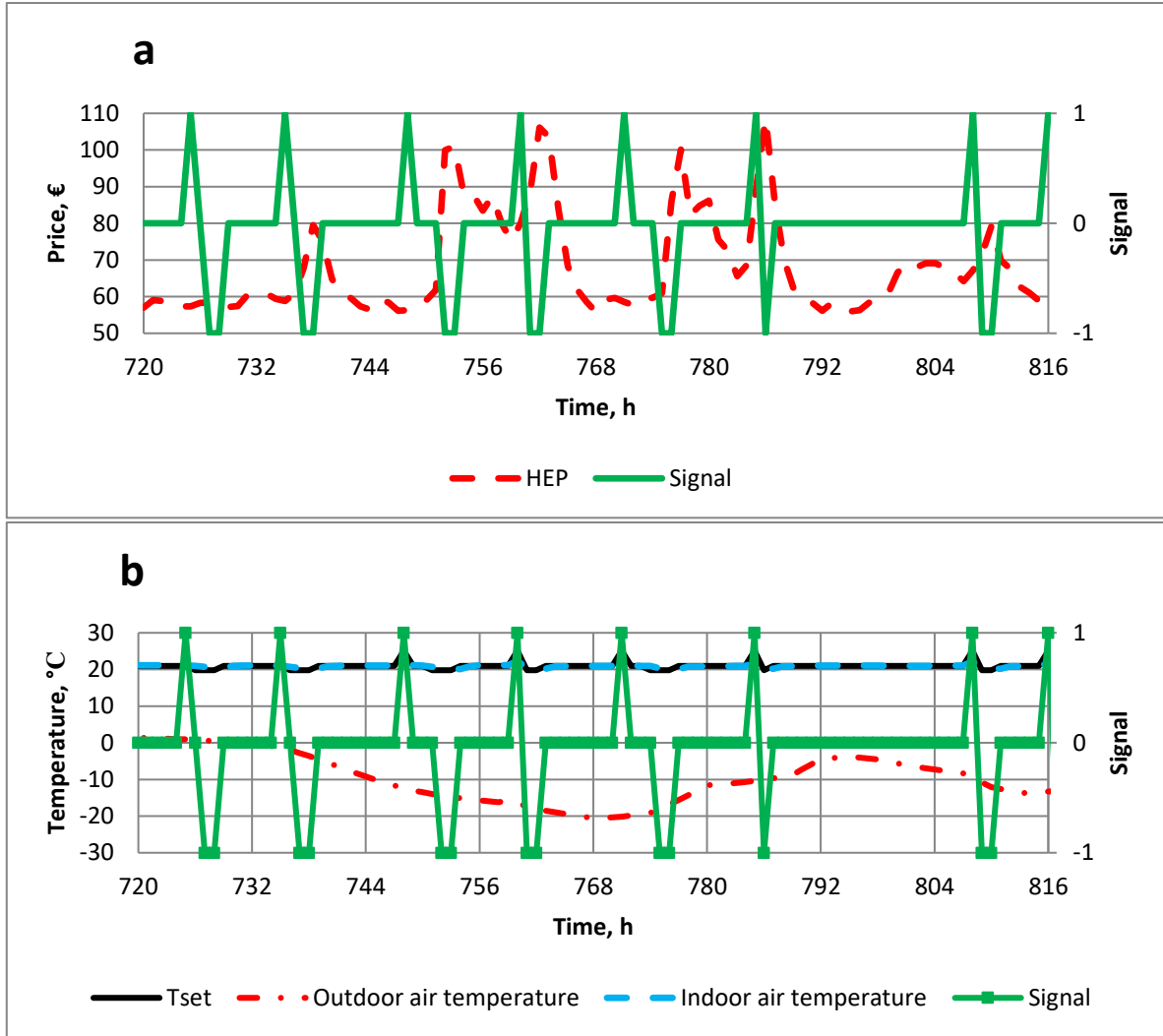
Figure 10. Output signal of control algorithm C with the HEP (a), and operation's results of control algorithm C in different variables for M-Pass building type (b).

Breakdown of delivered energy consumption

Breakdown of delivered energy consumption of the LW-1960 and M-Pass building types with the normal indoor temperature set point (21.0°C), ERHS and P-controller is shown in

Table 7. The main difference between delivered energy items in these building types is between space heating originated from different level of thermal insulation, air tightness and ventilation heat recovery.

Table 7. Breakdown of delivered energy consumption of the LW-1960 and M-Pass building types.

| Building type | Delivered energy, kWh/m^2.a | | | | | | |
	Space Heating	AHU Heating	Domestic Hot Water	HVAC aux.	Lighting	Equipment[a]	Total
LW-1960	232.0	0.0	39.4	1.5	8.5	22.2	303.6
M-pass	25.2	3.0	39.4	5.1	8.5	22.2	103.4

[a] It is assumed 86% of the electricity consumption of equipment ends up as internal heat gain[43].

Total delivered energy and cost

Description of the simulation study

Total delivered energy and energy cost were examined for different control algorithms with the on-off and P-controller types for two above mentioned building types. Because of the higher potential of the thermal comfort category III to achieve lower energy cost, it was selected for this examination. For this end, the related acceptable indoor temperature set points for each studied case were used. Air temperature was used as a control variable, because it is more commonly used as a control variable in detached houses in Finland. The studied cases were compared with the reference one. The indoor temperature set point of heating in the reference case is a constant 21.0°C, which is the normal set point temperature used in detached houses in accordance with the Finnish building code. To realize the lowest

total delivered energy and cost, these were calculated according to the minimum indoor set point temperature for the whole year. This study considered two options for the maximum indoor temperature set point values used in the simulation: the higher one is the maximum acceptable indoor temperature set point according to this study and the lower one (22.0°C) is to determine the effect of small temperature increase. Also two options were considered for limiting outdoor temperature: the first one, 0.0°C, to allow increase in the indoor temperature set points and the second one, -21.0°C, meaning that indoor temperature set points are not increased at all because that is the lowest outdoor temperature of the weather data used. The results of the total delivered energy and the energy cost for ERHS and EFHS are presented in Table 8, which shows different control algorithms for the on-off and P-controller types in connection with the LW-1960 and M-Pass building types. The energy cost is calculated by Finnish HEP of 2012 including energy[57], transfer prices and taxes[60].

Reference cases with the normal indoor temperature set point

The results of the reference cases shown in Table 8 (without using the control algorithms) show that the total delivered energy and the energy cost of the LW-1960 building type are 3.0 and 3.3 times more than those of the M-Pass building types, respectively. Also, the results illustrate that the total delivered energy of the LW-1960 building type in EFHS is up to 7.4% higher than that of ERHS for both the on-off and P-controller types; the total energy cost of

EFHS being 7.2% and 6.5% higher for the on-off and P-controller types, respectively. Also, the comparison results for the M-Pass building type reveal that the difference of the total delivered energy between ERHS and EFHS is small for on-off and P-controller types; but, the total energy cost of EFHS is 4.5% and 1.3% higher than ERHS for the on-off and P-controller types, respectively. In most of the studied cases, the total energy cost in M-Pass building type with the on-off controller type and in LW-1960 building type with the P-controller type are lower.

The minimum indoor temperature set point

In most of the studied cases, the total delivered energy and cost with minimum indoor temperature set point are the lowest ones without the use of control algorithms; but, in few cases (the M-Pass building type with EFHS used the control algorithm B and C in options of T_{out}^{lim}= -21.0°C and 0.0°C, respectively), the total delivered energy and cost are lower.

The variable indoor temperature set point controlled by the algorithms

In most of the studied cases, the total delivered energy and cost are decreased for control algorithm B and C by two alternatives; the first one is to change the maximum indoor air temperature set point to a lower one (22.0°C) and the second one is to decrease the limiting outdoor temperature to the lowest one (-21.0°C). In most of the studied cases, the control

algorithm B is more effective with different heat distribution systems, controller types and options of $T_{set,min}$ and T_{out}^{lim}.

The control algorithm B and C are able to save the total delivered energy and cost in most of the studied cases. But, depending on the values of the parameters and the controller type used with the control algorithms, the control algorithm B increases total delivered energy and cost by 5.4% and 26.1%, respectively; and the control algorithm C increases them by 3.6% and 20.7%, respectively in M-Pass building type with EFHS. This indicates that a performance of the control algorithms B and C is sensitive to the values of the parameters and the controller types.

When compared with the reference case, the maximum energy and cost saved by the use of control algorithm A are 0.8% and 2.1%, respectively. The control algorithm B can save total delivered energy and cost up to 3.1% and 7.7%, respectively. The maximum total delivered energy and cost saved by the use of control algorithms C are 1.3% and 9.6%, respectively.

Table 8. Results for the total delivered energies and energy costs of different set points and control algorithms for ERHS and EFHS with P-controller (P-C) and on-off controller (O-C) types with normal indoor temperature set point (21.0°C).

Control algorithm type	$T_{set,min}$, °C		$T_{set,max}$, °C		$T_{lim,out}$, °C	Total delivered energy				Total energy cost			
	P-C	O-C	P-C	O-C		kWh/m².a		Difference, %		€/a		Difference, %	
LW-1960 with ERHS						P-C	O-C	P-C	O-C	P-C	O-C	P-C	O-C
Normal set point			(Reference case)			303.7	303.9	0.0	0.0	5892.0	6049.8	0.0	0.0
Minimum set point	20.4	20.0	-	-	-	293.0	285.9	-3.5	-5.9	5687.1	5688.0	-3.5	-6.0
Control algorithm A	20.4	20.0	-	-	-	302.3	301.6	-0.5	-0.8	5848.1	6006.1	-0.7	-0.7
Control algorithm B	20.4	20.0	25.3	24.0	0.0	309.6	301.3	1.9	-0.9	6050.2	6060.1	2.7	0.2
	20.4	20.0	25.3	24.0	-21.0	298.5	295.6	-1.7	-2.7	5776.3	5852.3	-2.0	-3.3
	20.4	20.0	22.0	22.0	0.0	300.3	296.5	-1.1	-2.4	5837.1	5822.8	-0.9	-3.8
	20.4	20.0	22.0	22.0	-21.0	298.5	295.6	-1.7	-2.7	5776.3	5824.5	-2.0	-3.7
Control algorithm C	20.4	20.0	25.3	24.0	0.0	302.3	300.7	-0.5	-1.1	5856.7	5977.0	-0.6	-1.2
	20.4	20.0	25.3	24.0	-21.0	301.0	299.8	-0.9	-1.3	5815.4	5855.1	-1.3	-3.2
	20.4	20.0	22.0	22.0	0.0	301.2	300.0	-0.8	-1.3	5822.9	5931.7	-1.2	-2.0
	20.4	20.0	22.0	22.0	-21.0	301.0	299.8	-0.9	-1.3	5815.4	5915.8	-1.3	-2.2
M-Pass with ERHS													
Normal set point			(Reference case)			103.4	102.0	0.0	0.0	1916.1	1891.6	0.0	0.0
Minimum set point	19.8	20.2	-	-	-	99.4	98.7	-3.9	-3.2	1836.8	1823.7	-4.1	-3.6
Control algorithm A	19.8	20.2	-	-	-	103.1	101.7	-0.3	-0.3	1890.5	1863.1	-1.3	-1.5
Control algorithm B	19.8	20.2	25.1	24.4	0.0	106.7	104.8	3.2	2.7	1975.9	1938.1	3.1	2.5
	19.8	20.2	25.1	24.4	-21.0	102.2	101.2	-1.2	-0.8	1868.6	1844.5	-2.5	-2.5
	19.8	20.2	22.0	22.0	0.0	102.8	102.0	-0.6	0.0	1888.9	1875.9	-1.4	-0.8
	19.8	20.2	22.0	22.0	-21.0	102.2	101.2	-1.2	-0.8	1868.6	1840.2	-2.5	-2.7
Control algorithm C	19.8	20.2	25.1	24.4	0.0	103.3	101.9	-0.1	-0.1	1883.4	1853.7	-1.7	-2.0
	19.8	20.2	25.1	24.4	-21.0	103.0	101.7	-0.4	-0.3	1882.0	1857.3	-1.8	-1.8
	19.8	20.2	22.0	22.0	0.0	103.1	101.8	-0.3	-0.2	1887.2	1844.4	-1.5	-2.5
	19.8	20.2	22.0	22.0	-21.0	103.0	101.7	-0.4	-0.3	1882.0	1854.0	-1.8	-2.0
LW-1960 with EFHS													
Normal set point			(Reference case)			324.5	326.6	0.0	0.0	6279.4	6484.3	0.0	0.0
Minimum set point	19.4	20.0	-	-	-	295.7	308.6	-8.9	-5.5	5725.1	5990.2	-8.8	-7.6

Control algorithm A	19.4	20.0	-	-	-	322.0	324.5	-0.8	-0.6	6163.4	6382.1	-1.8	-1.6
Control algorithm B	19.4	20.0	24.6	24.1	0.0	324.7	326.1	0.1	-0.2	6175.0	6525.1	-1.7	0.6
	19.4	20.0	24.6	24.1	-21.0	314.3	319.1	-3.1	-2.3	5795.8	6192.2	-7.7	-4.5
	19.4	20.0	22.0	22.0	0.0	317.0	320.3	-2.3	-1.9	6042.4	6399.0	-3.8	-1.3
	19.4	20.0	22.0	22.0	-21.0	314.3	319.1	-3.1	-2.3	5796.4	6160.8	-7.7	-5.0
Control algorithm C	19.4	20.0	24.6	24.1	0.0	324.3	325.5	-0.1	-0.3	7203.0	6695.4	14.7	3.3
	19.4	20.0	24.6	24.1	-21.0	321.4	323.6	-1	-0.9	6961.7	6663.3	10.9	2.8
	19.4	20.0	22.0	22.0	0.0	322.0	323.9	-0.8	-0.8	7050.9	6473.7	12.3	-0.2
	19.4	20.0	22.0	22.0	-21.0	321.4	322.7	-1.0	-1.2	6961.7	6703.5	10.9	3.4
M-Pass with EFHS													
Normal set point			(Reference case)			104.6	102.8	0.0	0.0	1942.0	1976.8	0.0	0.0
Minimum set point	19.5	20.2	-	-	-	100.0	99.1	-4.4	-3.6	1851.4	1864.5	-4.7	-5.7
Control algorithm A	19.5	20.2	-	-	-	104.8	102.7	0.2	-0.1	1914.9	1934.4	-1.4	-2.1
Control algorithm B	19.5	20.2	24.9	24.5	0.0	109.9	108.3	5.1	5.4	2449.1	2125.7	26.1	7.5
	19.5	20.2	24.9	24.5	-21.0	104.8	102.2	0.2	-0.6	1829.3	1863.2	-5.8	-5.7
	19.5	20.2	22.0	22.0	0.0	105.2	103.4	0.6	0.6	1964.7	1999.3	1.2	1.1
	19.5	20.2	22.0	22.0	-21.0	104.8	102.3	0.2	-0.5	1829.2	1861.6	-5.8	-5.8
Control algorithm C	19.5	20.2	24.9	24.5	0.0	108.4	106.4	3.6	3.5	1910.2	1787.8	-1.6	-9.6
	19.5	20.2	24.9	24.5	-21.0	105.3	102.7	0.7	-0.1	2343.6	2100.0	20.7	6.2
	19.5	20.2	22.0	22.0	0.0	105.8	103.3	1.1	0.5	2113.1	1835.4	8.8	-7.2
	19.5	20.2	22.0	22.0	-21.0	105.3	102.7	0.7	-0.1	2343.6	2099.4	20.7	6.2

Conclusions

This study investigated the acceptable range of indoor air and operative temperatures, complying with the thermal comfort categories recommended by the EN 15251 standard, for a detached house. Nine different houses, including three different insulation levels and three different thermal mass levels were simulated in the cold climate of Finland. The goal was to

minimize the total delivered energy and cost of electrically-heated detached houses by means of three different demand response control algorithms, without sacrificing the occupants' thermal comfort.

According to this study the lowest and highest indoor operative temperature set points are 19.6°C and 25.1°C, respectively. As the thermal comfort based set point for the lower limit of the operative temperature (19.6°C) is higher than the recommended minimum operative temperature by EN 15251 standard (18.0°C), this study suggests different ranges of temperatures than mentioned by EN 15251 standard for the studied detached houses in the Finnish climate. The studied light and medium weight houses with the lowest level of thermal insulation do not strictly fulfil the rule of the ASHRAE standard 55 for the maximum allowed operative temperature change.

All three used control algorithms were able to reduce the energy demand and cost of electricity. However, the control algorithm based on the previous hourly electricity prices is the most effective algorithm in most of the studied cases. When compared with the reference case (the indoor temperature set point of heating is a constant 21.0°C), the maximum total delivered energy and cost saved by the use of control algorithms are 3.1% and 9.6%, respectively. The performance of the control algorithms depends on house type, heat distribution system, controller type and the parameters of the control algorithm. In some of

the studied cases, the control algorithms decrease the total delivered energy and cost even more than using the constant minimum indoor temperature set point for whole heating season. The approach of this study can be applied to places which have cold climates and where dynamic hourly electricity prices are available. The results depend on weather conditions, hourly electricity price, building construction, thermal mass and insulation of building and type of building.

Authors' contribution

Behrang Alimohammadisagvand carried out literature review, model development, assessment of thermal comfort, development of the control algorithms, computer simulations, analyses and conclusions of the study, responding to comments of the editors and reviewers.

Sadaf Alam contributed literature review, modelling of the studied houses and examined fulfilment of the ASHRAE standard 55 for the studied houses.

Mubbashir Ali developed control algorithms.

Merkebu Degefa analyzed the consumption profiles of the Finnish houses.

Juha Jokisalo advised the 1st and 2nd authors.

Kai Sirén supervised the 1st and 2nd authors.

Answer to the editor's comment could be for example:

If it is possible, I would like to ask your permission to keep all the five persons as my co-author. Especially Juha Jokisalo and Kai Sirén have given significant contribution to this study. The following text was added into the manuscript in order to clarify their contributions more detailed:

"Juha Jokisalo contributed to the development of the research idea, selection of the reseach methodology, development of the models and control algorithms, analyses and conclusions of the study.

"Kai Siren contributed to the development of the research idea, selection of the reseach methodology, analyses and conclusions of the study.

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The authors declared no potential conflicts of interest with respect to the research, authorship, and publication of this article.

References

1. Intergovernmental Panel on Climate Change. Climate Change 2007: Synthesis Report, http://www.ipcc.ch/pdf/assessment-report/ar4/syr/ar4_syr.pdf.

2. Official Journal of the European Union. DIRECTIVE 2010/31/EU OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 19 May 2010 on the energy performance of buildings (recast).

3. Bertoldi P, Atanasiu B. Electricity Consumption and Efficiency Trends in the Enlarged European Union. 2007.

4. Statistics Finland. Energy consumption in households [e-publication]. ISSN=2323-329X. Helsinki, Finland, 2012., http://www.stat.fi/index_en.html (accessed 19 May 2014).

5. Statistics Finland, Buildings and free-time residences, ISSN=1798-6796. Helsinki, Finland 2012.

6. INTERNATIONAL ENERGY AGENCY. THE POWER TO CHOOSE; Demand Response in Liberalised Electricity Markets, http://www.schneider-electric.us/documents/solutions1/demand-response-solutions/powertochoose_2003.pdf.

7. Callaway D, Hiskens I. Achieving Controllability of Electric Loads. Publisher?? City?? 2011; 99.

8. The SmartGrids European Technology Platform | SmartGrids, http://www.smartgrids.eu/node/81 (accessed 19 May 2014).

9. Federal Energy Regulatory Commission. Industries-Reports on Demand Response & Advanced Metering, https://www.ferc.gov/industries/electric/indus-act/demand-response/dem-res-adv-metering.asp (accessed 16 May 2014).

10. Albadi MH, El-Saadany EF. A summary of demand response in electricity markets. *Electric Power Systems Research* 2008; 78: 1989–1996.

11. Chu C-M, Jong T-L. A Novel Direct Air-Conditioning Load Control Method, http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=6303359 (accessed 19 May 2014).

12. Annala S, Viljainen S, Tuunanen J, et al. Does Knowledge Contribute to the Acceptance of Demand Response? *JOURNAL OF SUSTAINABLE DEVELOPMENT OF ENERGY, WATER AND ENVIRONMENT SYSTEMS year??*; 2: 51–60.

13. Surles W, Henze GP. Evaluation of automatic priced based thermostat control for peak energy reduction under residential time-of-use utility tariffs. *Energy and Buildings* 2012; 49: 99–108.

14. Abdelkafi A, Krichen L. New strategy of pitch angle control for energy management of a wind farm. *Energy* 2011; 36: 1470–1479.

15. Escrivá-Escrivá G, Segura-Heras I, Alcázar-Ortega M. Application of an energy management and control system to assess the potential of different control strategies in HVAC systems. *Energy and Buildings* 2010; 42: 2258–2267.

16. Ali M, Jokisalo J, Siren K, et al. Combining the Demand Response of direct electric space heating and partial thermal storage using LP optimization. *Electric Power Systems Research* 2014; 106: 160–167.

17. Mubbashir A, Koivisto M, Lehtonen M. Optimizing the DR Control of Electric Storage Space Heating Using LP Approach. *International Review on Modelling and Simulations* 2013; 6.

18. Álvarez-Bel C, Escrivá-Escrivá G. Renewable generation and demand response integration in micro-grids: development of a new energy management and control system. 2013; 6: 695–706.

19. Avci M, Erkoc M, Rahmani A, et al. Model predictive HVAC load control in buildings using real-time electricity pricing. *Energy and Buildings* 2013; 60: 199–209.

20. Klein L, Kwak J, Kavulya G, et al. Coordinating occupant behavior for building energy and comfort management using multi-agent systems. *Automation in Construction* 2012; 22: 525–536.

21. Liu H, Lee S, Kim M, et al. Finding the optimal set points of a thermal and ventilation control system under changing outdoor weather conditions. *Indoor and Built Environment* 2014; 23: 118–132.

22. Du P, Lu N. Appliance Commitment for Household Load Scheduling. IEEE TRANSACTIONS ON SMART GRID, JUNE 2011; VOL. 2, NO. 2,pages???

23. Molderink A, Bakker V, C. Bosman MG, et al. Management and Control of Domestic Smart Grid Technology. IEEE TRANSACTIONS ON SMART GRID. September 2010; VOL. 1, NO. 2, pages?? (accessed 19 May 2014).

24. Yoon JH, Bladick R, Novoselac A. Demand response for residential buildings based on dynamic price of electricity. *Energy and Buildings* 2014; 80: 531–541.

25. ANSI/ASHRAE Standard 55-2010: Thermal Environmental Conditions for Human Occupancy. Atlanta: ASHRAE 2010.

26. Arteconi A, Costola D, Hoes P, et al. Analysis of control strategies for thermally activated building systems under demand side management mechanisms. *Energy and Buildings* 2014; 80: 384–393.

27. SFS-EN 15251: Indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting and acoustics. Finnish Standards Association SFS, Helsinki, 2007..

28. Decree for the energy certificate (176/2013). Ministry of Environment, Helsinki., http://www.finlex.fi/en/ (accessed 9 June 2014).

29. The National Building Code of Finland. C3 Finnish code of building regulations, Thermal Insulation in a building. Helsinki: Ministry of the Environment, 2010.

30. RIL 249 – 2010 Matalaenergiarakentaminen, Asuinrakennukset (Low energy construction, residential buildings). Helsinki, RIL, 2009.

31. Peffer T, Pritoni M, Meier A, et al. How people use thermostats in homes: A review. *Building and Environment* 2011; 46: 2529–2541.

32. Misir D, Malki HA, Guanrong Chen. Design and analysis of a fuzzy proportional-integral-derivative controller. *Fuzzy Sets and Systems* 1996; 79: 297–314.

33. Ruotsalainen R, Ronnberg R, Sateri J, et al. Indoor climate and the performance of ventilation in Finnish residences. Indoor Air 1992; 2(3): 137-145.

34. The National Building Code of Finland. D2 Finnish code of building regulations.Hepac and Energy Management: Indoor Climate and Ventilation of Buildings. Rakennnusten sisäilmasto ja ilmanvaihto. Helsinki, Ministry of the Environment, 2012.

35. Liu J, Yao R, McCloy R. An investigation of thermal comfort adaptation behaviour in office buildings in the UK. *Indoor and Built Environment* 2013; 23: 675–691.

36. Brunsgaard C, Heiselberg P, Knudstrup M-A, et al. Evaluation of the Indoor Environment of Comfort Houses: Qualitative and Quantitative Approaches. *Indoor and Built Environment* 2012; 21: 432–451.

37. Huizenga C, Abbaszadeh S, Zagreus L, et al. Air Quality and Thermal Comfort in Office Buildings: Results of a Large Indoor Environmental Quality Survey.Publisher?? 2006;,Vol?? pp. 393–397.

38. Jing S, Li B, Tan M, et al. Impact of Relative Humidity on Thermal Comfort in a Warm Environment. *Indoor and Built Environment* 2012; 22: 598–607.

39. Vinha J, Korpi M, Kalamees T, et al. *Asuinrakennusten ilmanpitävyys, sisäilmasto ja energiatalous (Air tightness, indoor climate and energy economy). Research report 140. Structural Engineering laboratory , Tampere University of Technology, Tampere, Finland.* 2009.

40. Ampatzi E, Knight I. Modelling the effect of realistic domestic energy demand profiles and internal gains on the predicted performance of solar thermal systems. *Energy and Buildings* 2012; 55: 285–298.

41. Menezes AC, Cripps A, Buswell RA, et al. Estimating the energy consumption and power demand of small power equipment in office buildings. *Energy and Buildings* 2014; 75: 199–209.

42. Ampatzi E, Knight I. Modelling the effect of realistic domestic energy demand profiles and internal gains on the predicted performance of solar thermal systems. *Energy and Buildings* 2012; 55: 285–298.

43. The National Building Code of Finland. D5 Finnish code of building regulations. Hepac and Energy Management: Calculation of power and energy needs for heating of buildings. Rakennuksen energiankulutuksen ja lammitystehontarpeen laskenta (Calculation of energy consumption and heating power of buildings). Helsinki: Ministry of the Environment, 2007.

44. Fanger PO. *Thermal comfort: Analysis and applications in environmental engineering*. Malabar, Fla. : R.E. Krieger Pub. Co., 1982, c1970.

45. Freire RZ, Oliveira GHC, Mendes N. Predictive controllers for thermal comfort optimization and energy savings. *Energy and Buildings* 2008; 40: 1353–1365.

46. Sahlin P. *Modelling and Simulation Methods for Modular Continuous Systems in Buildings*. Royal Institute of TechnologyRoyal Institute of Technology, http://www.equa.se/dncenter/thesis.pdf (1996). Access date??

47. *Equa Simulation A., Validation of IDA Indoor Climate and Energy 4.0 with respect to CEN Standard EN 15265-2007,Publsiher?? City?? May 2010*.

48. Bring A, Sahlin P, Vuolle M. *Models for Building Indoor Climate and Energy Simulations. A report of IEA Task 22* 1999. *(http://www.equa.se/dncenter/T22Brep.pdf)Accessed date??* .

49. Moinard S, Guyon G (eds). Empirical Validation of EDF ETNA and GENEC Test-Cell Models. A Report of Task 22 Building Energy Analysis Tools. Project A.3 Empirical validation, International Energy Agency (IEA), Solar Energy & Cooling Programme, Paris, France, February 2000.

50. Achermann M, Zweifel G. *RADTEST–Radiant heating and cooling test cases. Subtask C. A report of IEA Task 22. Building Energy Analysis Tools.* IEA, Paris, 2003.

51. *Equa Simulation AB. Validation of IDA Indoor Climate and Energy 4.0 build 4 with respect to ANSI/ASHRAE Standard 140-2004.*.Equa Simulation AB, Solna, Sweden, *April 2010.*

52. Travesi J, Maxwell G, Klaassen C, et al. Empirical Validation of Iowa Energy Resource Station Building Energy Analysis Simulation Models. Publisher?? City?? 2001.

53. Kalamees T, Jylhä K, Tietäväinen H, et al. Development of weighting factors for climate variables for selecting the energy reference year according to the EN ISO 15927-4 standard. *Energy and Buildings* 2012; 47: 53–60.

54. The National Building Code of Finland. D3 Finnish code of building regulation. Hepac and Energy Management: Energy management in buildings. Rakennusten energiatehokuus (Energy efficiency of buildings). Helsinki: Ministry of the Environment, 2012.

55. Zhang H, Davigny A, Colas F, et al. Fuzzy logic based energy management strategy for commercial buildings integrating photovoltaic and storage systems. *Energy and Buildings* 2012; 54: 196–206.

56. H.Cormen T, E.Leiserson C, L.Rivest R, et al. *Introduction to Algorithms, third edition*. MIT University, Cambridge, Massachusetts, 2009.

57. Nord Pool Spot, leading power market in Europe, http://www.nordpoolspot.com/ (accessed 20 May 2014).

58. Wang Z, Zhang L, Zhao J, et al. Thermal comfort for naturally ventilated residential buildings in Harbin. *Energy and Buildings* 2010; 42: 2406–2415.

59. Wang Z. A field study of the thermal comfort in residential buildings in Harbin. *Building and Environment* 2006; 41: 1034–1039.

60. Sähkön hintavertailu, Agency of electricity price, Finland (accessed 18 July 2014).