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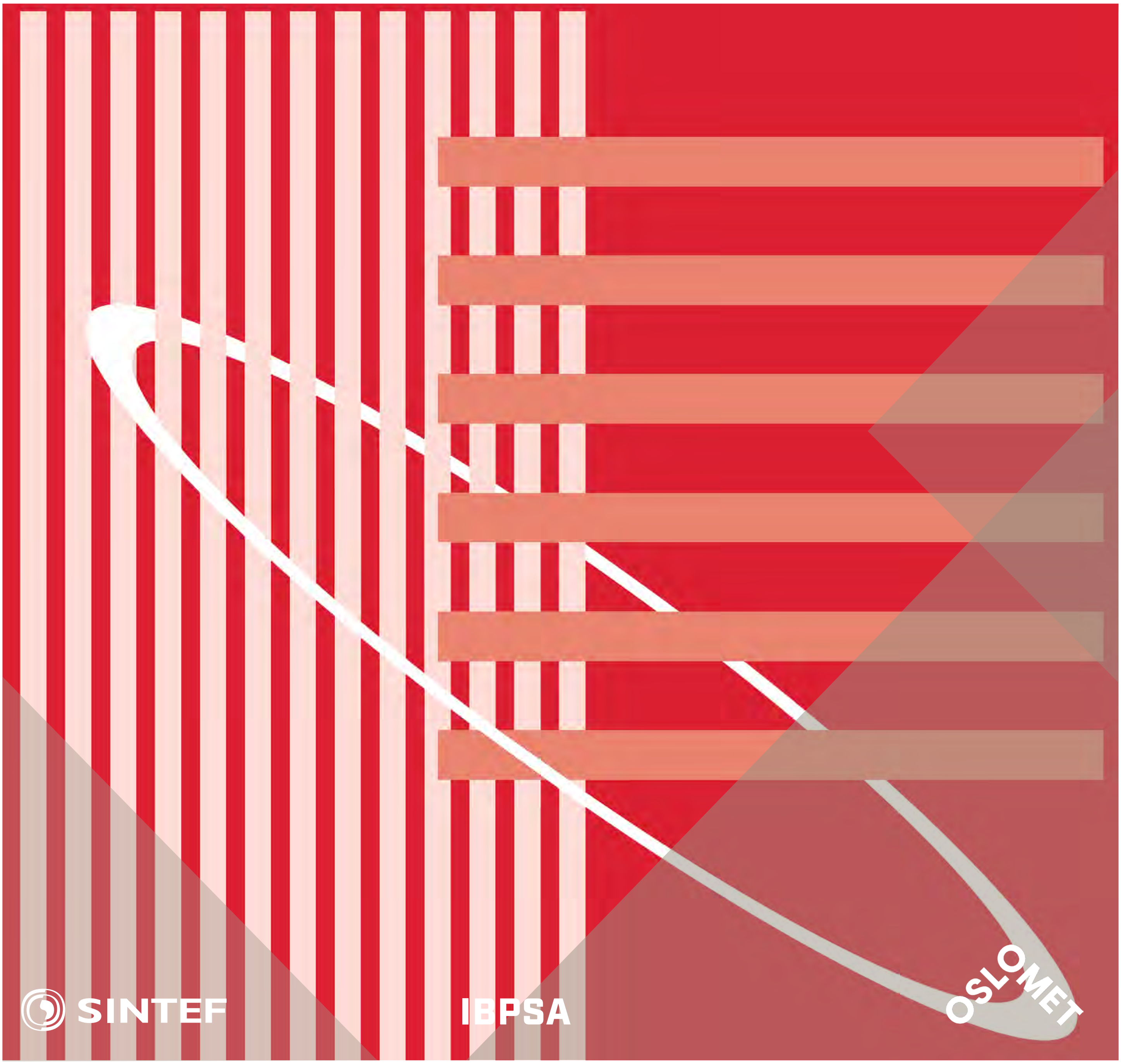

SINTEF Proceedings

Editors:
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SINTEF Academic Press

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Keywords:
Building acoustics, Building Information Modelling (BIM), Building physics, CFD and air flow, Commissioning and control, Daylighting and lighting, Developments in simulation, Education in building performance simulation, Energy storage, Heating, Ventilation and Air Conditioning (HVAC), Human behavior in simulation, Indoor Environmental Quality (IEQ), New software developments, Optimization, Simulation at urban scale, Simulation to support regulations, Simulation vs reality, Solar energy systems, Validation, calibration and uncertainty, Weather data & Climate adaptation, Fenestration (windows & shading), Zero Energy Buildings (ZEB), Emissions and Life Cycle Analysis

Cover illustration: IBPSA-logo

ISSN 2387-4295 (online)
ISBN 978-82-536-1679-7 (pdf)

SINTEF Academic Press
Address: Børrestuveien 3
PO Box 124 Blindern
N-0314 OSLO
Tel: +47 40 00 51 00

www.sintef.no/community
www.sintefbok.no

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Influence of space heating distribution systems on the energy flexibility of Norwegian residential buildings

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Abstract

This work evaluates the influence of the heating distribution system on the energy flexibility of highly insulated single-family residential buildings. The behavior of three different systems (air heating, radiator heating, and floor heating) is assessed for schedule-based and price-based rule-based control of the heating system aiming at peak shaving and cost reduction. Dynamic building performance simulations are performed in the software tool IDA ICE.

The investigated controls activate the thermal mass and water storage tanks. When activating only the thermal mass, the energy use during peak hours decreases by nearly 10% in the radiator heating cases, in the air heating cases the effect is less pronounced and shows little to no shifting potential. In the floor heating cases, a slight decrease in energy use is found for the price-based control, whereas a slight increase is observed with a schedule-based control.

In contrast, when domestic hot water and space heating tank set points are adjusted, the energy use during peak hours decreases in all versions. The schedule-based control achieve reductions between 20% to 30% among the different heat emission systems. The price-based control however, is less effective, leading to lower reductions in energy use. The total energy use and operational costs increase in each case, most pronounced with the schedule-based set point variations for the domestic hot water and space heating tank.

It is found that a good demand response measure is not only dependent on a correct selection of the set point at the supervisory control level, but also a good implementation of the local controller that considers the thermal dynamics of the heating system is required.

Introduction

In the current electricity supply structure, power generation follows demand. The ongoing integration of intermittent renewable energy sources into the power grid in Europe is a challenge for grid stability. The control of the demand side to match the instantaneous production may be one key to solve this problem (Lund *et al.*, 2015). This is usually done by shifting loads using storages. For example, the thermal masses of buildings can be considered storages, which enable postponing active cooling and heating without violating thermal comfort (Arteconi *et al.*, 2012). The storage potential is largely depending on the type of construction, the heat distribution system and user specific comfort criteria. In combination with electricity-based heating, buildings can therefore offer different services for the grid by applying demand side management (DSM) and load control strategies (IEA DSM, 2016). In general, DSM describes the change of use in magnitude and/or time. Flexibility can also be obtained by using storage tanks, or in different form, by managing onsite generation and batteries. This work focuses on the influence of the space heating (SH) distribution system on the energy flexibility of residential buildings.

Many studies on energy flexible buildings have been carried out under the framework of IEA Annex 67, which defines "energy flexibility" as "*the ability to manage [a building's] demand and generation according to local climate conditions, user needs, and energy network requirements" (Jensen et al., 2017).*

Even though heating flexibility of buildings plays an important role for district heating, most studies on building energy flexibility focus on all-electric buildings. Naturally, the focus is on power generation from photovoltaic or combined heat and power and the main consumers, which typically are white goods, cooling appliances, air handling units and in case of electrified heating, heat pumps or resistance heaters. Heat pump systems with thermal storages are seen as an attractive heating system in cold climates. Most related studies focus on floor heating as a heat distribution system. However, radiator systems were studied in (Baetens *et al.*, 2010; Le Dréau and Heiselberg, 2016; Reynders *et al.*, 2013; Wolisz *et al.*, 2013).

Heat distribution system

Besides building-specific and time-varying external parameters, the heat distribution system is expected to have significant influence on the energy flexibility potential, as floor heating (FH), air heating (AH), and radiator (RAD) heating show different dynamics.

Air heating is very dynamic and reacts directly to the heat demand needed in the room. The heat transfer can be considered completely convective. For radiator systems, the heat transfer is usually (around 70%) convective. The air volume is heated directly without considerable delay, where the heat-up time is in the range of a few minutes. The warmer air then activates all surrounding surfaces in the room. The amount of heat that can be stored is largely depending on the material properties of the outermost layer of the construction. Regarding water-based FH, several system specifications are possible. In general, pipes containing water or other media are embedded in the construction. A distinction is made between dry systems, usually using a panel of dry screed above the pipes and wet systems, with pipes completely covered by concrete. In case heating is needed, the slab or the construction is heated and heat is conducted to the floor covering. The warmer surface then heats up the air, and the other surfaces via radiation. As all the layers have different properties, the dynamic behavior is strongly dependent on the chosen system. Capillary systems can heat up almost as fast as radiator systems when parquet flooring is chosen but cool down more slowly. For conventional systems, the heat-up and cool down times are in the range of several hours.

Research question

This work evaluates the influence of the SH distribution system on the energy flexibility of highly insulated single-family residential buildings by investigating AH, RAD heating and FH. Compared to previous studies in literature, this work provides detailed information on the design procedure of the investigated heat emission systems. In this work, heat distribution system refers to the emission, distribution and control system for each of the three systems studied.

Methods

To evaluate the influence of the SH distribution system on the energy flexibility, detailed dynamic simulations are carried out. The modelling procedure applied in this work is presented in Figure 1.

Simulation procedure

Building performance simulations are performed using the software IDA ICE 4.7.1. The building is modelled with the previously mentioned heat distribution systems. The sizing of these systems is done according to NS-EN 12831-1:2007. Four rule-based control strategies are implemented, which aim to activate the thermal mass in the rooms only or additionally also the SH and DHW tanks. Results are evaluated based on the key performance indicators energy use, operational costs, and load shifting.

Case study description

The case study building is the Living Laboratory at the Gløshaugen Campus of the Norwegian University of Science and Technology (NTNU). It is a single-family residential building, which comprises of two bedrooms, a bathroom and a combined area for cooking and living. The building has a total heated floor area of 105 m^2. A floor plan of the building is presented in Figure 2. As the building is designed as a Zero Emission Building (ZEB), the building envelope is highly insulated and airtight, almost in accordance with the Norwegian passive house standard NS 3700:2013 (Standard Norge). The building has a lightweight wooden construction.

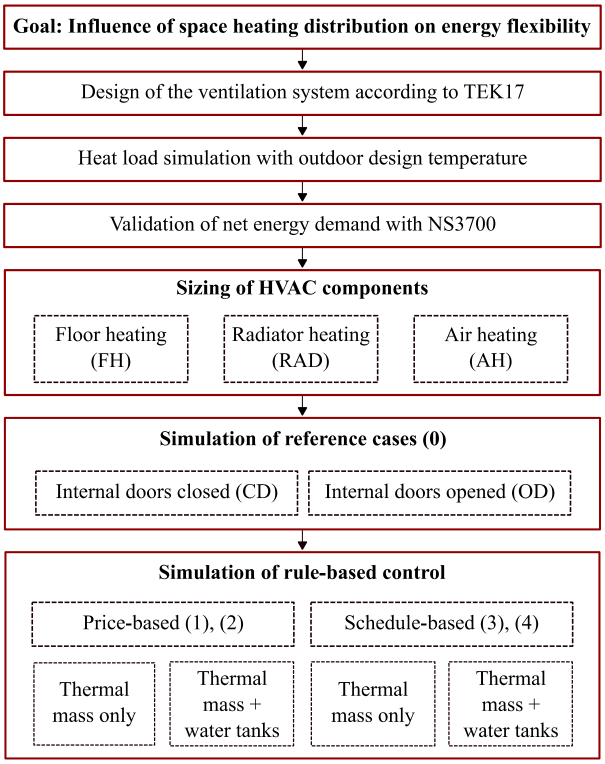

Figure 1. Overview of the modelling procedure.

Climate and location

For improved coherence of weather and spot prices, measured weather data of the year 2015 are used, retrieved from shinyweatherdata (Lukas Lundström).

Internal heat gains

As it is a highly insulated building, the hourly profiles for internal gains from lighting, electric appliances and occupants have a great impact on the thermal demand of the building. In this study, schedules for occupancy and lighting follow hourly profiles for the ISO/FDIS 17772-1 standard developed by (Ahmed *et al.*, 2017). The number of occupants and the nominal power of the light bulbs are adjusted to fit the yearly specific use of 13.1 kWh/m² and 11.4 kWh/m² for occupants and lighting given in NS/TS 3031:2016 (Standard Norge, 2016). The hourly schedule and heat gains from appliances are in accordance with NS/TS 3031:2016. All internal gains are assumed equally distributed within the building. Windows and outer doors are closed at all times.

Ventilation system

The ventilation system is designed according to the installed system in the case building, and the current building regulation TEK17. The ventilation system comprises of a central air handling unit with heat recovery (efficiency 85%) and an electrical heating coil with a nominal power of 1200 W in the FH and RAD heating cases. In the AH cases the electrical heating coil is replaced by a water-based coil. The specific fan power is set to 1.5 kW/(m^3/s) for both fans. The efficiency of the fans is set to 0.7. The air flow rates are determined by using the pre-accepted minimum values according to TEK17, leading to a total ventilation rate of 154 m^3/h.

In heating mode for the FH and RAD cases, the supply air temperature is constant at 19°C, and since there is no cooling coil, the supply air temperature is close to the outdoor air temperature for ambient temperatures above 19 °C. Further details for the air heating cases are discussed in the next section.

Heat generation system

The core of the heating setup of the Living Lab is a water storage tank which consists of two tanks in one shell. The upper part consists of the domestic hot water (DHW) tank and the lower part is for SH. In the SH tank there are two heat exchangers, one for the solar thermal circuit and one for pre-heating DHW. This way the solar thermal panels mounted on the south facade of the building can support both SH and DHW. Primarily, the heat demand is covered by a ground source heat pump (GSHP) which is connected to a horizontal surface collector. The geothermal collector supplies the SH tank directly whereas it is connected to the DHW tank via a heat exchanger. Both tanks can also be heated with electric resistance heaters, with a power of 3 kW (DHW) and 9 kW (SH) respectively. To reach the ZEB balance, the building is equipped with a 12 kWp photovoltaic system.

Sizing and implementation in IDA ICE

It is a common approach to design heating systems by calculating the overall heat loss of a building at design outdoor temperature (DOT). Regardless of the operation mode, the size of the heat pump is therefore always dependent on the thermal properties of the building and the climate (Le Dréau and Heiselberg, 2016). Water storage tank volumes are dependent on the nominal power of the heat pump. Fischer et al. (Fischer *et al.*, 2016) showed that current sizing practices already lead to sufficiently large tanks for the use of DSM.

A heat load calculation is carried out in accordance to NS:EN 12831-1:2017 (Standard Norge, 2017). The proposed internal design temperature is constant at 24°C for the bathroom and 20°C for all other rooms. The DOT is -22 °C for Trondheim (Sintef Byggforsk). Solar radiation and internal heat gains are neglected for the heat load calculation. The ventilation system has a constant supply air temperature set point of 19°C. The calculation is done using an ideal heater in each room. These room units have no mass and react directly to the heat power need. The required zone heating is 3.58 kW.

Heat generation system

Heat pump

The operating mode of the heat pump was chosen monovalent/mono-energetic. The chosen GSHP, a "Calorex WW3500", has a nominal power of 3.5 kW and a COP of 4.0 at rating conditions 0/35°C. For higher temperatures, e.g. a RAD or AH system, the available power will decrease to 2.6 kW at 0/55°C. The maximum supply temperature for DHW is 65°C. The compressor power can modulate between 30% and 100% of the nominal capacity.

Space heating tank

The recommendations for sizing the SH-tank vary widely and are depended on blocking times, the chosen heat emission system and the used heat pump. According to manufacturer data, 20-25 l/kW are used to optimize the duration of heat pump cycles, whereas 30-60 l/kW are advised when blocking hours are considered (Viessmann Deutschland GmbH, 2011). Other references also distinguish between FH and RAD heating. The advised volume is doubled for radiators, due to the smaller inertia of the system and smaller amount of water in the circuits (Stiebel Eltron, 2017). As the heat generation setup should be similar for all versions, a volume of 200 l was chosen corresponding to 57 l/kW.

Domestic hot water tank

The tapping profile for DHW is decisive for sizing the DHW tank. In the model, the profile from NS/TS 3031:2016 for small houses is implemented. The hourly peak demand is 1.442 kWh and the daily consumption is 7.2 kWh. Assuming cold water at 10 °C and a desired DHW temperature of 60 °C, this leads to a volume of 124 liter. For the model, a 160 l DHW tank was chosen. For the implementation in IDA ICE dimensions of a commercially available storage tank are used. That way, physical heights of tank-pipe connections are already defined. The volumes of the internal heat exchangers are calculated according to the given pipe diameter and surface area.

Water storage tanks are described in IDA ICE as a piled number of horizontal layers. For each layer the mass and heat balances are computed. Both tank parts consist of six layers with heights of 0.195 m (SH) and 0.181 m (DHW). The DHW tank is equipped with two temperature sensors, which are in the upper part (TM 4) and in the lower part of the tank (TM 3). The charging of the tank begins when the temperature of TM 4 is below 55°C and stops when the measurement from TM 3 is above this set point temperature. The auxiliary heater (AUX 2) switches on/off with a dead band of 0.8 K when the temperature of the upper sensor is 1 K under the threshold. The charging of the SH tank is rather similar; there are also two sensors at different heights (TM1 & TM2). If the measurements of the upper sensor fall short of the value of the outdoor temperature compensation curve (OTCC) of the chosen heat distribution system, the tank is charged until the temperature at the lower sensor is 5 K above the current value of the OTCC. This also ensures a reasonable run time of the heat pump. The auxiliary heater (AUX 1) is switched on when TM2 is 2 K below the current value of the OTCC. A dead band of 6 K was applied here, because of its high nominal power of 9 kW the run time would otherwise be shorter than two minutes. A detailed description of the charging principle is presented in (Clauß and Georges, 2019).

The heat pump has a SH and a DHW operation mode. The charging of the DHW tank has priority. In DHW mode, a P-controller adjusts the mass flow through the condenser to achieve a temperature of 60°C. The heat pump is then operating at full capacity. In SH-mode, the mass flow is constant and the compressor power is adjusted continuously between 30%-100%.

Water-based radiator

Sizing

A single radiator is placed in the middle of the house. Similar simplified heat distribution systems were assessed in studies with focus on thermal zoning in passive houses (Georges *et al.*, 2016; Georges *et al.*, 2017). The radiator model is based on the commercially available product "Lygnson MC33 2300x900". The power at design conditions (75/65/20°C) is 7590 W. These temperatures are too high to be operated with a heat pump system. At operation conditions (50/45/20°C) the power is 3569 W.

Implementation in IDA ICE

The radiator is placed next to the wall between *Floor* and *Kitchen*. The unweighted average of the mean air temperatures in both rooms is chosen as the input signal. The mass flow is controlled by a PI-controller. The maximum mass flow is calculated by the software automatically based on the design power and exponent (Lygnson: 1.28). It is worth mentioning here that the inertia of a radiator is not represented by this IDA ICE model. In the simulations the surface temperature of the radiator-wall- part drops according to the instantaneous delivered power.

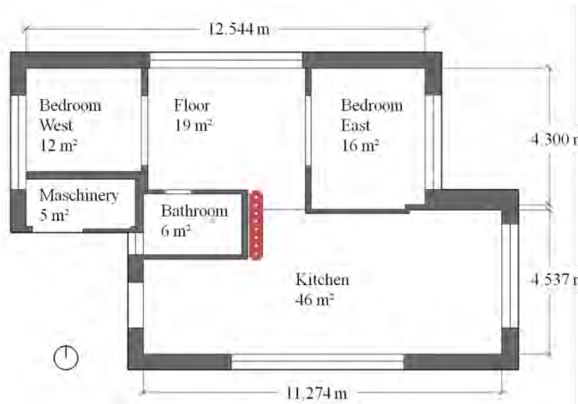

Figure 2. Floor plan and location of the radiator.

Water-based floor heating

Sizing

The FH is implemented as a dry screed system, "Roth Clima Comfort TBS" is used for design and calculation according to EN 1264-3:2009 (European Commitee for Standardization, 2009). The construction on top of the pipes consists of parquet flooring (22 mm) and dry screed tiles (25mm), underneath there is a wooden frame construction with a U-value of 0.1 W/(m²K). The system can be considered as fast reacting compared to conventional wet systems.

From a practical point of view, the supply temperature is chosen for a distance of 15 cm between pipes and a desired temperature difference of 5 K for the zone with the highest specific heat load (except Bathroom). The supply temperature for all zones is given as 38.2 °C. Based on the FH system of that room, suitable distances between the pipes and thus temperature differences and mass flows are calculated for all other rooms. However, with this system the required heating power for the bathroom cannot be reached. Even with a temperature difference in the flow of 3 K, there is still a margin of around 100 W. For calculating the total mass flow in the circuits at design conditions, the downward heat flux density is approximated to 4.37 W/m², originating from the heat resistance of the construction below the circuits (ca 0.332 m with 0.036 W/(mK)) and a temperature difference of 42 K (difference between DOT and indoor air temperature). The total nominal heating power to the zones is 3445 W, which is 136 W lower than the total heat load in the zones.

Implementation in IDA ICE

FH systems are implemented as a heat exchanger immersed in one layer of the floor construction with uniform layer temperature. The structural component is divided into two parts, with layers above and beneath the floor heating pipes. The maximum mass flow is calculated automatically in IDA ICE based on the given power and temperature difference at design conditions. The heat transfer coefficient between the pipes and the layer they are located in is assumed to be 10 W/m²K. The mass flow in the circuits are controlled by a P-controller which uses a sensor for mean air temperature.

Air heating

Sizing

The third considered heat distribution system is AH. AH uses a temperature control to adjust the emitted power while the RAD and FH use a weather compensation heating curve in combination with mass flow control. Nevertheless, hygienic ventilation rates are not sufficient for times of high heating demand as the maximum inlet air temperature is defined at 55 °C, which is the temperature of dust carbonization and in line with (Georges *et al.*, 2014). Consequently, with the volume rates according to TEK17, only 1.8 kW of heat can be supplied. To cover the heat load of 3.5 kW, the total volume rate has to be increased from 153.7 m³/h to 298 m³/h, which is equivalent to 0.9 ACH

Implementation in IDA ICE

The air is heated by a water-based heating coil, which is implemented as a fixed-size heating coil model with mass flow control. The heat transfer is calculated according to the NTU method. The heating coil is configured according to manufacturer data from “system air VBC 200-3”.

In general, all the discussed AH versions show high temperatures in the Bedrooms, and colder temperatures in the living room. This is conflicting with findings of several studies interviewing occupants of super-insulated building in cold climates. The desired temperatures ranged from 22-24 °C in the living room whereas 16 °C was desired in bedrooms (Georges *et al.*, 2017; Georges *et al.*, 2014). Due to this, the pre-accepted ventilation rates according to TEK 17 (Kommunal- og moderniseringsdepartementet, 2017) might not be suitable for a centralized air heating concept.

Differences between the heat distribution systems

To summarize, all three distribution systems are connected to a water storage tank and thus are dependent on the heat pump operation. For AH, the air is heated up in a water-based heating battery. The two other distribution systems are directly connected to the water storage tank.

All three heat emission systems have a limited thermal inertia. Even the floor heating is relatively fast reacting as it is a lightweight construction: nevertheless, the investigated RAD and AH systems have a shorter reaction time and reach a desired room temperature faster than the FH system. This is due to i) the direct heating of the air for AH, ii) short heat-up times for the surface of the radiator, but iii) a delay of reaching a required surface temperature and thus heating the air for the FH system due to mainly radiative heating.

As shown, there are slight differences among the three heat emission systems regarding their nominal power: 3500 W for AH, 3445 W for FH and 3569 W for RAD.

Differences in the thermal behavior of the heat distribution system can be attributed to the differences in thermal inertia of each of the systems as well as differences in the system-specific control.

Controls for energy flexibility

Price-based control

Predictive price-based control 1

In this control approach, the set points in the zones are changed according to a price signal. This control is aiming at reducing operational costs by reducing the energy use during hours with high spot prices, based on the principle presented in (Clauß *et al.*, 2019). The spot price evolution is divided into three segments: low, medium and high. The upper threshold is 75% of the maximum spot price in the next 24 h and the lower threshold is 25% of the maximum spot price. When the current value is between the thresholds, temperature set points are kept. If the current hourly spot price is considered high, the set point will be decreased by 2 K; if it is low, the set point will be increased by 2 K. The comparison is done for each hour and its respective succeeding 24 hours. The analysis is based on data from 2015 for the Trondheim bidding area at Nordpool market (Nordpool).

Predictive price-based control 2

The price-based control 1 is extended to the DHW and SH tanks. These set points in the tanks are raised or lowered by 3 K depending on the price signal.

Schedule-based control

Peak-shaving control 3

Based on a typical energy use profile for Norwegian households (Bergesen *et al.*, 2013), the heating set points in the zones are adjusted depending on a schedule. The schedule aims to reduce the electricity need in peak hours 7–9a.m. and 5–7p.m. Consequently, the set point is decreased from 21°C to 19°C in these hours. In the time from 5–7a.m. and 4–5p.m. the SH set-points are increased to 23°C. The remaining hours of the day, the set point is 21°C.

Peak-shaving control 4

Control approach 3 is expanded to the DHW and the SH tank. These set points are increased by 3 K in the hours before the peak and decreased by 3 K during the peak hours.

Results

Results are evaluated based on the following performance indicators:

- *Heating use for DHW and SH:*
  The sum of energy delivered to the heat distribution system or used for DHW.
- *Electricity delivered in peak hours*
  The hourly values of total electricity use (heating and other electricity consumers) in peak hours 7-9a.m. and 5-7p.m. are summed up and presented in kWh/m²a.
- *Energy costs during operation without feed-in*
  For each hour, total electricity use is multiplied with the current spot prices used in the controls above. In average, these are 0.189 NOK/kWh, a constant grid fee incl. tax of 0.493 NOK/kWh and taxes for electricity use of 0.139 NOK/kWh were added. Consequently, the total average electricity price is 0.817 NOK/kWh. The hourly values are then summed up and presented.
- *Energy costs during operation with feed-in*
  The surplus electricity generated by the building integrated PV is multiplied by the current spot price and subtracted from the current costs due to consumption. This is also done with hourly resolution. Prices are similar for imported and exported electricity.

Evaluation reference scenarios

As shown in Figure 1, there are two separate reference scenarios for the open doors and closed doors cases respectively. Both reference scenarios have constant heating temperature set-points of 21 °C for all three heat distribution systems.

The annual heating needs for SH and DHW is 73.0 kWh/m², 84.1 kWh/m² and 72.5 kWh/m² for the open door (OD) cases for AH, FH and RAD heating, respectively. The FH versions stand out, because of higher transmission losses caused by the tempered slab. Nevertheless, the corresponding electricity use is lowest for FH, as the maximum supply water temperature is in general lower (38.2°C) compared to air heating (58°C) and radiator heating (50°C). FH also leads to the highest COP of the heat pump.

The closed door (CD) cases of FH and AH show only small deviations in heating energy use from the OD versions as each zone is provided with the needed amount of heat.

The RAD cases clearly show that closed doors significantly reduce the transport of heat to the zones without heating device. Similar findings are presented in (Johnsen *et al.*, 2019). For the closed door RAD cases, the room temperature set-point of 21°C is reached faster. In contrast, the closed-door AH version has a slightly higher heating demand, as the heat supplied in the bedrooms is prevented from direct exchange with the other zones. AH with closed doors leads to higher volume-averaged indoor temperatures to enable the right temperature in the living areas.

The amount of electricity delivered during peak hours in the OD versions is highest in the AH case followed by RAD and FH with 15.9, 15.8 and 13.8 kWh/(m²a), respectively. Again, electricity use of domestic appliances is dominant with 8.6 kWh/(m²a) in all versions. Consequently, the amount of electricity delivered during peak hours for heating only differs strongly for the different heat emission systems. In the FH cases it is only 5.2 kWh/(m²a) representing ca 24% of the annual heating energy use. In the RAD and AH cases this share is between 33 and 34%, thus leading to a higher shiftable load. This difference is due to the higher supply water temperatures for AH and RAD heating leading to a lower COP of the heat pump and higher average temperatures in the tank.

Evaluation control strategies open door cases

Figure 3 shows a comparison of the heating energy use for the open door cases for the different control strategies.

The implementation of price-based control 1, e.g. the change of the heating set point in the zones, resulted in higher electricity use for each of the heat distribution systems. Compared to the reference cases, energy use rises 8%, 3% and 4% for AH_1_OD, FH_1_OD and RAD_1_OD respectively.

Peak hour energy use for heating only was reduced by 17% in the RAD version, by 7% for AH and by 27% for FH. Nevertheless, this control approach also resulted in higher operational costs, as the increased temperature set point is kept for long low-price periods, which could not be balanced by cost savings due to lower prices.

The price-based control 2 also includes the DHW and the SH tank. The total annual electricity use and operational costs increase compsared to the reference case and price-based control 1.

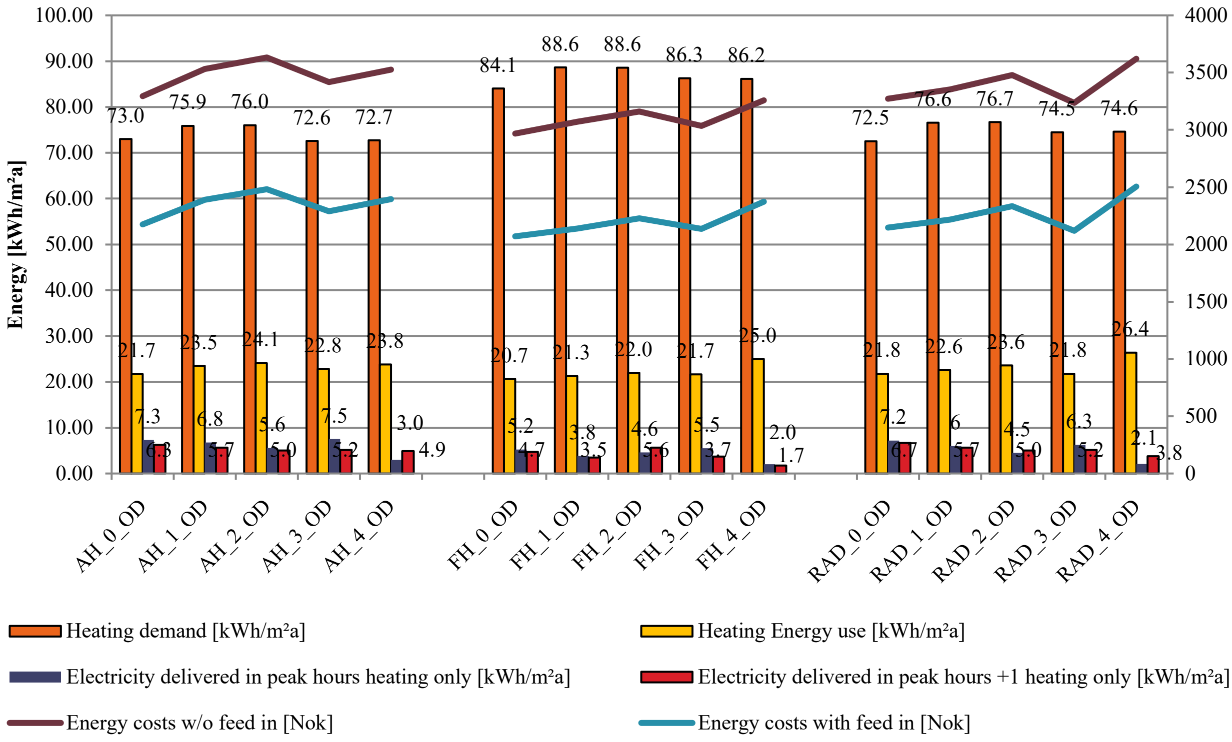

Figure 3. Comparison of the heating energy use for the open door cases for the different control strategies (AH and RAD with PI-controller, FH with P-Controller).

The is due to extensive periods with high temperature set-points, leading to higher heating losses from the tank as well as to prolonged periods of DHW heating by the heat pump. Due to the DHW prioritization of the heat pump, a more frequent use of the electric auxiliary heater in the SH tank is required. The reduction of consumption in peak hours is best for the radiator system (38%), followed by the air heating system (23%). In the floor heating case however, consumption decreased by 12%.

The schedule-based control 3 is able to reduce the energy use during peak hours for the RAD versions. Control 3 does not lead to a reduction of electricity use in peak hours for the FH version, which can be attributed to the combination of four phenomena: i) in the case of control strategy FH_3_OD the heat pump continues running for some time after the zone heating setpoint has been reduced due to the charging strategy of the SH tank. It has been shown that the same control was able to shift energy use, if the period from 8-10a.m. (-22%) instead of 7-9a.m. (+5%) was considered as peak period. The choice of local controller may delay the stop of the heat pump; ii) as stated previously, FH has its own thermal mass and has a higher share of radiant heating, iii) the heating systems use air temperature, not the operative temperature as control signal, and iv) the tuning of the PI-controller parameters of the heat pump control. The chosen PI-controller parameters may lead to integral windup problems that cause an extended heat pump operation until the integral error has come back to 0, especially after set points have been reduced.

When also considering adjusting the set-points for DHW and SH on the heat generation side (control 4), the reduction of peak hour consumption (59% for AH, 61% for FH and 71% for RAD) is the most pronounced, but at the expense of higher costs and total consumption.

Influence door opening

Door opening has little to no influence when the heat distribution is planned according to heat demand of each zone. Consequently, the air heating and floor heating results do not deviate much from the respective open door versions. On the contrary, the simplified heat distribution with one radiator in the floor and kitchen is naturally largely depending on the balancing effects of airflow through internal openings.

Discussion

This work is aiming at evaluating the influence of the heat distribution system on the energy flexibility of residential buildings. However, the case study building only represents a small percentage of the actual building stock. Studies (Reynders *et al.*, 2017; Le Dréau and Heiselberg, 2016) showed that differences between RAD and FH change with the age of the building.

It should be noted that the case study building is not suitable for AH. The heat loss of the envelope constructions can be considered too high. The ventilation rates have to be increased significantly (up to 0.9 ACH) in times of cold outdoor temperatures to ensure thermal comfort. Due to the needed supply air temperatures up to 50 °C the indoor air would be very dry, and humidification would be required to ensure comfortable surroundings. However, local discomfort may occur.

A general concern is the variation of the supply temperature for the heating systems, as this temperature is a trade-off between available power and system losses due to higher temperatures as a function of the outdoor temperature. In the current work, these temperatures are calculated in relation to the needed heat load for an indoor temperature of 23°C as this is the maximum temperature set point for SH in the investigated versions. That means, at any outdoor temperature, there should be enough power to heat up the building to 23°C. Nevertheless, if the heating is supposed to happen in a short period of time, more power may be required. Furthermore, the schedule-based controls only use heat-up and cool-down periods of two hours, whereas longer periods would also be feasible.

The heating system layout, especially pre-heating of DHW in the SH tank, can be seen critically. Whenever DHW is needed the SH tank is cooled down and the heat pump heats the DHW tank first. This causes an increased use of the backup heater in the SH tank. The capacity of the auxiliary heaters could also be reduced. The auxiliary heaters are active for only a short time but lead to significant peaks in energy use. Furthermore, the internal heat exchanger for DHW pre-heating causes problems for the evaluation of the operation of the water-based heat distribution systems:

- i) As soon as SH is required, heat is taken from the tank without operating the heat pump,
- ii) Afterwards, heat is taken from the tank while the heat pump is operating to keep the temperature set point in the SH tank,
- iii) The heat pump continues its operation to charge the SH tank even though no more heating is required in the zones due to three issues:
  - a) DHW is drawn and the internal heat exchanger in the SH tank cools down the SH tank.
  - b) The PI controller has to react to the cool down of the tank that comes from the cold water flow through the heat exchanger.
  - c) Integral windup of the PI controller as it tries to compensate for the positive error from the heating period until the temperature set point is reached.

The RAD system has a lower heating demand (see Figure 3) as it mainly supplies heat to the *floor* and *kitchen*, whereas the bedrooms are mainly heated by the ventilation system. A temperature set point of 21 °C is not sufficient for the RAD system, if also the other rooms are supposed to reach 21 °C.

Conclusion

Several cases were set up to evaluate the influence of the space heating distribution on energy flexibility. Four rule-based controls were introduced and their effects on energy use and costs evaluated.

All systems have been sized to have a similar nominal power. The performance of the three emission systems is rather similar. The performance is mostly influenced by the quality of the control rather than the properties of the heat emission system. The small differences come from specific aspects for each of the heat emitters and the way they are modelled.

- The floor heating system shows the highest increase in heating energy use and costs. That is especially the case for the schedule-based controls.
  Floor heating has a lower temperature level which leads to higher COP but it has some additional heat losses through the floor. Among the three systems evaluated, it is the most flexible for temperature zoning as there is at least one FH circuit per room. It is found that the proposed schedule-based control is not suitable for the proposed FH system configuration. It is essential to consider the time constant of the heating system when designing proper control strategies, meaning that change in air temperature set point and the heating hysteresis in the SH tank have to be coordinated Furthermore, it is found that a good demand response measure is not only dependent on a correct selection of the set point at the supervisory control level (like with MPC or RBC), but also a good implementation of the local controllers. This effect is often ignored. Usually, studies on demand response focus on the supervisory control level and do not consider the local controller, which here has proven to be responsible for a delay of the stopping of the heat pump leading to a deteriorated performance with regards to shifting energy use in a defined period.
  Both price-based controls are not able to decrease operational costs. Due to low hourly fluctuations in electricity prices in Norway in combination with the control not always loading the building at the right time makes both controls not very efficient. Furthermore, the heating set points are increased for extended periods.
- The air-heating is not suited for this building as the building nominal heating power is too high. In the air heating versions, the control strategies focus on charging the thermal mass and show little to no effect. In general, the problem of air heating is the temperature zoning with closed internal doors (also shown in (Georges *et al.*, 2014). The average temperature in the building has to increase significantly to ensure the right temperature level in the living room. It is also difficult to get cold bedrooms with warm living areas.
- The radiator system shows the best performance in terms of shifting loads without significantly increasing cost and energy use. The simplified space-heating using one radiator is working well, but ensuring high temperatures in bedrooms with closed internal doors can be challenging as the thermal mass in other rooms cannot directly be activated. In that regard, thermal zoning is a disadvantage. This has also been concluded by (Johnsen *et al.*, 2019).
- Comparing FH and RAD heating for the time period from 8a.m. to 10a.m., the controls show a similar behavior and energy use is in the same order of magnitude for controls 3 and 4. In IDA ICE, the FH has a thermal inertia, and is therefore effected by the delay of stopping the heat pump operation.
- It is shown that a lightweight FH system does not behave very differently from a radiator system, except from a small delay. This is an important conclusion as most residential buildings in Norway can be considered as lightweight.
- Regarding the different control strategies, the rule-based controls show a better performance when also activating the DHW storage as the storage efficiency of the tank is higher than the heat storage efficiency of the thermal mass of the building construction.

For future research, the influence of the sizing of the heat distribution components and the role of the outdoor compensation curve should be further investigated. It should also be tested how the systems behave for longer activation times and periods. Advanced controls like model predictive control (MPC) or model-free soft (or intelligent) control can be tested to operate each system in a better way (i.e. closer to optimal control).

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