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

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Master Thesis

for

Christoph Heinz Nickl

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

Varmefordeling i oppvarmingssystem og energifleksibilitet av norske boliger

Background and objective

In the current electricity supply structure, power generation follows demand. As the grid itself has a limited ability to compensate differences between demand and production, power plants traditionally have to adjust to these fluctuations. The ongoing integration of intermittent renewable energy sources into the power grid in Europe is therefore a challenge for grid stability and the economical operation of the existing power plant mix.

The control of the heating load to match the instantaneous production may be one key to solve this problem. This is usually done by shifting loads using storages. For example, the constructions used in buildings can be considered as thermal storage, which enables postponing active cooling and heating without violating thermal comfort. The storage potential is largely depending on the type of construction, the heat distribution system and user specific comfort criteria. In combination with electric heating, buildings can therefore offer different services to the grid, such as demand side management (DSM). Flexibility can also be obtained by using storage tanks, managing onsite generation or by batteries.

The objective of this Master Thesis is to evaluate how much energy flexibility residential buildings can provide to the grid. The main focus is on the influence of the space-heating distribution systems. The ZEB Living Laboratory (Living Lab), which is a residential zero emission building (ZEB) at the Gløshaugen Campus in Trondheim, is chosen as a test case.

The following tasks are to be considered:

1. Literature review of studies investigating the energy flexibility potential of residential buildings (especially in the context of thermal mass activation). The main focus of this review should be set on the influence of the space-heating distribution.
2. Set up models of the ZEB Living Lab in IDA ICE with three different heat distribution systems, namely water-based floor heating, a water-based radiator and air heating.
3. Evaluation of key performance indicators quantifying the energy flexibility potential for the three different systems (e.g. energy use, operational costs, self-consumption, load shifting)
4. Write a final report

The thesis comprises 30 ECTS credits.

The work shall be edited as a scientific report, including a table of contents, a summary in Norwegian, conclusion, an index of literature etc. When writing the report, the candidate must emphasise a clearly arranged and well-written text. To facilitate the reading of the report, it is important that references for corresponding text, tables and figures are clearly stated both places.
By the evaluation of the work the following will be greatly emphasised: The results should be thoroughly treated, presented in clearly arranged tables and/or graphics and discussed in detail.

The candidate is responsible for keeping contact with the subject teacher and teaching supervisors.

Risk assessment of the candidate's work shall be carried out according to the department's procedures. The risk assessment must be documented and included as part of the final report. Events related to the candidate's work adversely affecting the health, safety or security, must be documented and included as part of the final report. If the documentation on risk assessment represents a large number of pages, the full version is to be submitted electronically to the supervisor and an excerpt is included in the report.

According to "Utfyllende regler til studieforskriften for teknologistudiet/sivilingeniørstudiet ved NTNU" § 20, the Department of Energy and Process Engineering reserves all rights to use the results and data for lectures, research and future publications.

The report shall be submitted to the department via Blackboard.

Submission deadline: 1. February 2018.

☐ Work to be done in lab (Water power lab, Fluids engineering lab, Thermal engineering lab)
☐ Field work

Department for Energy and Process Engineering, *31.08.2017*

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Preface

This master thesis presents 27 ECTS in the Master of Engineering Program "Energiesysteme und Energiemangement" at the University of applied sciences Esslingen. However, large parts of this work were done at the Norwegian University of Science and Technology Engineering. I would like to thank my supervisor Laurent Georges and especially my co-supervisor John Clauß. For the warm welcome and the support, as well as sharing large parts of his IDA ICE models.

I also would like to thank Thomas Rohrbach for his encouragement to write the thesis abroad.

Stuttgart, 14.04.2018

Abstract

Demand side flexibility gained more and more research interest over the last years, as the generation of renewable power grows and challenges economical operation of power plants as well as grid stability. Several studies were already conducted and showed a large potential in the flexible use of plug loads as well as heating devices. However, there is a vast amount of parameters that influence this potential and need further investigation.

This thesis tries to evaluate the influence of the heating distribution system on the energy flexibility of residential buildings. Different building performance models were created for air heating, radiator heating, and floor heating. The case study building was a nearly zero emission building called "Living Lab", located in Trondheim. The energy system consists in each case of a heat pump, domestic hot water and space heating tank, as well as solar thermal collectors and photovoltaic.

The behavior of the different systems was assessed for a rule based control based on a schedule to shift electricity to off-peak hours as well as a price based signal which uses data from the day-head spot market.

For the radiator system the consumption in peak hours was strongly decreased (up to 20%) when domestic hot water and space heating tank set points were included. When only activating the thermal mass, reductions of 10% were found. In contrast, the consumption in peak hours did not decrease or even grew for the floor heating case. The air heating cases showed little to no shifting potential.

The total consumption and operational costs increased in each case, most pronounced with the schedule based set point variations for hot water and space heating tank.

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1   Introduction

The world's total final energy consumption more than doubled from 4244 Mtoe (million tons of oil equivalent; 1 toe = 11.63 MWh) in 1971 to 9385 Mtoe in 2015. In that time, the distribution of consumption between the three major sectors transport, industry, and buildings did not change considerably. Industry still holds the biggest share with 37%, which represents an incline of 1 %. The share of the transport sector increased from 23% to 29%. The building sector, which comprises of the residential sector, commerce and public services is accountable for 30 % of the total final energy consumption (2 % decrease). [1]

While the agriculture and forestry sector only accounts for 2% of the total final energy consumption, the greenhouse gas emissions associated with the sector make up almost one quarter of the world's GHG in 2010 (10 – 12 $GtCO_2eq/yr$), which results mainly from agricultural emissions from livestock, land use change and forestry. [2]

The Industry sector is still the largest contributor with 30% (15.4 $GtCO_2eq/yr$). The emissions mainly result from the production of just steel, iron and cement. [3]

The greenhouse gas emissions from the building sector therefore represent only energy consumption. They make up about 19% of all global GHG emissions (9.18 $GtCO_2eq/yr$). Nevertheless, about half of the world's steel production and almost all cement are used in construction, but are not accounted to the building sector. The share of the sector would than rise to about 25 %. [4]

A reduction of CO_2 can be realized in three ways. Firstly, by increasing the energy efficiency of the HVAC systems, appliances and the buildings envelop (high insulation, high air tightness etc.). Secondly, by choosing construction materials in a life cycle approach, meaning to evaluate the CO_2 – emissions from cradle to gate/grave and or the life expectancy. Thirdly, a change in the power supply mix, which differs greatly throughout Europe and the world.

For example, in Germany 48% of residential houses are heated by gas and 29% by oil. [5] In contrast, almost 96% of Norwegian households are heating with electricity-based devices, either directly or by using heat pumps. These systems are mostly combined with wood ovens, as they make up nearly 52% of the installed heating systems. [6] Even though the specific CO_2 – emissions for fossil gas (210 gCO2 eq/kWh) and for fossil oil (285 gCO2 eq/kWh) can be considered equal for both countries, there is a major difference in the electricity mix. In

Norway, due to a 96% share of hydro-power, the specific emissions only amount to $10 - 15$ gCO2 eq/kWh, where as the specific emissions of the German electricity mix account to 564 gCO2 eq/kWh in 2014. [7] This shows that there is plenty of room for improvement and that a decarbonisation of the building sector is possible through renewable electricity. Nevertheless, this goal poses some challenges.

In the current electricity supply structure, power generation follows demand. As the grid itself has a limited ability to compensate differences between demand and production, power plants have to adjust to these fluctuations. The ongoing integration of intermittent renewable energy sources into the power grid in Europe is therefore a challenge for grid stability and the economical operation of the existing power plant mix. The control of consumption to match the instantaneous production may be one key to solve this problem.[8] This is usually done by shifting loads using storages. For example, the constructions used in buildings can be considered as thermal storage, which enables postponing active cooling and heating without violating thermal comfort. [9] The storage potential is largely depending on the type of construction, the heat distribution system and user specific comfort criteria. [10] In combination with electricity-based heating, buildings can therefore offer different services for the grid, such as demand side management (DSM) and load control.[11] Flexibility can also be obtained by using storage tanks, or in different form, by managing onsite generation and batteries.

The objective of this Master Thesis is to evaluate how much energy flexibility residential buildings can provide to the grid. The focus is on the influence of the space-heating distribution system. The ZEB Living Laboratory (Living Lab), which is a residential zero emission building (ZEB) at the Gløshaugen Campus in Trondheim, is chosen as a test case.

The research method is based on detailed building performance simulations using the software IDA ICE 4.7.1. The chosen building is modeled with three different heat-distribution systems, namely air heating, water-based radiators, and floor heating. The sizing was done according to NS-EN 12831-1:2007. Different control strategies were implemented. Results are evaluated based on the key performance indicators energy use, operational costs, self-consumption and load shifting.

2 Background Information

2.1 Residential buildings in Norway

2.1.1 Current situation

The residential sector in Norway comprises of 52% detached or farmhouses, followed by 23% of flat-blocks and 20.3% semidetached or terraced houses. In total there are approximately 2.5 million dwellings. In recent years, the trend to smaller houses resulted in an average utility floor space area of 110 m² for newly built dwellings in 2013. That is a decrease of almost 25% compared to 1980. On the other hand, the average living area per person increased from 37 m² to 58 m² in the same time. This development is only possible because of a change in the number of persons per household, which decreased strongly from 2.7 in 1980 to 2.1 in 2013. Consequently, around 80% of Norwegian households are small houses with around 120 m² and two inhabitants. [12] The building stock mostly comprises of buildings from the 1971 – 1990, followed by buildings constructed before 1956. Between 1991 and 2010, the share of multi-unit housing increased. This trend continued even stronger since 2011, as a result of stronger urbanization.
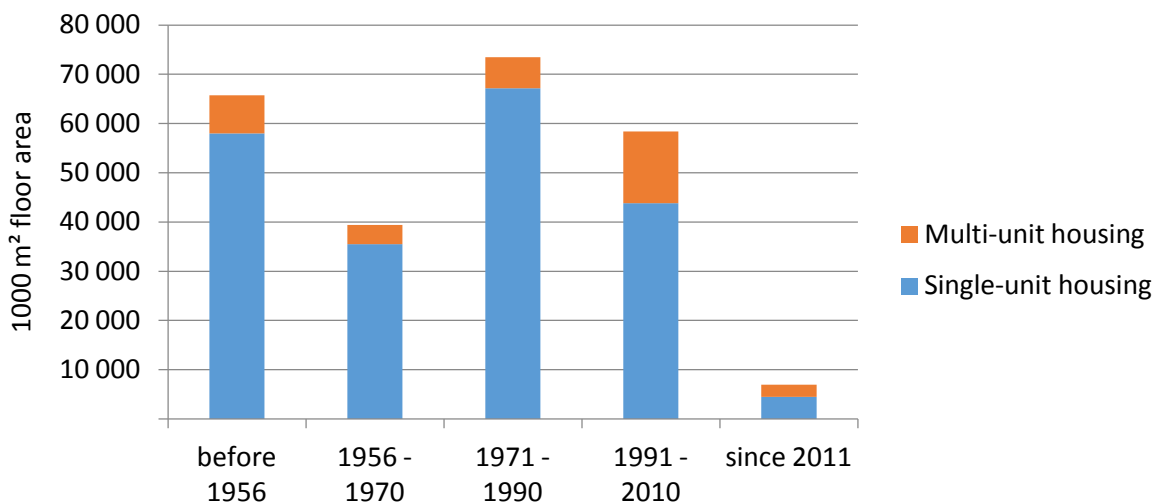

Figure 2-1: Distribution of living space between single-unit and multi-unit housing and age; made with data from [13]

2.1.2 Heat generation and heat distribution systems

In 2012, private households accounted for 27% of final energy consumption in Norway. The average final energy consumption was 20230 kWh per household or 185 kWh per m² dwelling area. The most important commodity was electricity with a share of 79%, followed by wood/biomass with 17%. Oil and kerosene make up 3.4 %. [14] The predominance of electricity consumption is due to the fact, that almost 96 % of Norwegian households are heating with electricity-based devices, either directly or/and by using heat pumps. [6]
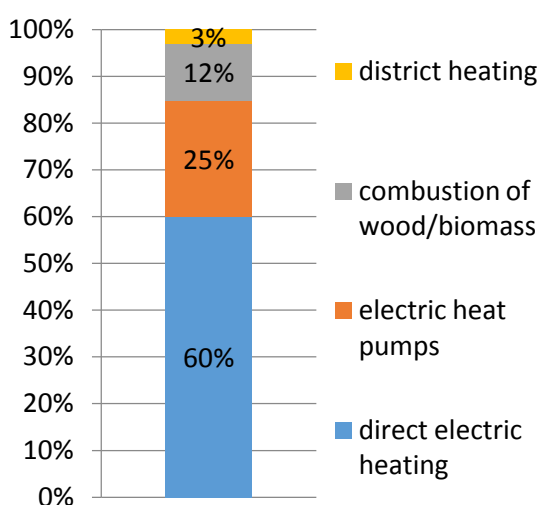
Figure 2-2: main heat generation system data from [9]
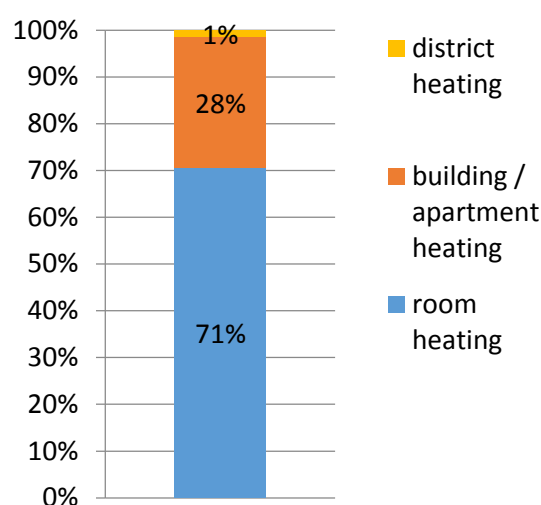
Figure 2-3: centralization of space heating system, data from [9]

The most common main generation system for space heating is direct electric heating. 60% of the Norwegian households use electrical space heaters as a main source for space heating. Electrical heat pumps represent a share of 25%, followed by combustion of wood and biomass. The share of district heating (3%) is insignificant but is expected to grow in the next decades.

Almost every single unit house is heated by room heating (94%). Only 5% use a central heating system and only 1% use district heating. In multi unit houses, the share of building and apartment heating is bigger (15%), district heating plays also a larger role, mainly due to the fact that multi unit houses are more common in urban areas. Nevertheless, room heating is still dominant (71%). [13]

2.1.3 Future developments

In 2011, the European Union issued the Directive on Energy Performance of Buildings (EPBD), which requires all new non-residential buildings to be nearly zero energy buildings by 2018 as well as all new residential buildings by 2020. The directive itself has left some room for interpretation, which lead to multiple definitions and standards throughout Europe. [15]

Even though Norway is not part of the EU, the country is taking large measures towards energy efficiency in buildings in accordance to the directive. Consequently, the current building regulation includes technical requirements (TEK17) for U-values of the building envelop as well as HVAC Parameters and maxima of annual total net energy needs for different usages. These already strict requirements are topped by the Norwegian Standard (NS3700) for low energy and passive houses. [16] Additionally, a concept called Zero Emission Building (ZEB) was developed. In contrast to other EU-countries, it focuses on the CO_2 - balance of the building rather than on energy consumption and generation. [17] According to the Norwegian Research Center on Zero Emission Buildings there are five ambition levels, ranging from "Energy use during operation excluding equipment" to a whole life cycle analysis including emissions associated to energy use inclusive equipment, embodied material emissions, the construction process and end-of-life scenarios (demolition, incarnation or possible reuse). Depending on the ambition level, the produced greenhouse gas equivalent emissions shall be compensated by on site generation of renewable power. [18] The goals of ZEB are most likely not achievable without using water based systems or/and storages.

Besides regulation, economic incentives and financing instruments by the state enterprise Enova and the Norwegian State Housing bank are strengthening the development towards higher energy efficiency. Heating solutions like heat pumps and water based heating systems are therefore partially sponsored for renovation. [19]

3 Literature review on energy flexibility potential of residential buildings

3.1 Definition of energy flexibility

There is currently no general acknowledged definition of energy flexibility, as it may vary with different energy systems and their different prerequisites. Regardless it is always possible to differentiate between the supply side and the demand side. In case of electricity, residential buildings are always seen as consumers even if they can produce a significant amount of energy during the year.

Lopes et al. [20] described several different definitions and methodologies to quantify energy flexibility in buildings in their literature review of various independent studies. Most of the research for energy flexible buildings is carried out under the framework of the IEA Annex 67, their current working definition is the following:

"The Energy Flexibility of a building is the ability to manage its demand and generation according to local climate conditions, user needs, and energy network requirements. Energy Flexibility of buildings will thus allow for demand side management/load control and thereby demand response based on the requirements of the surrounding energy networks." [21]

Demand side management and demand response

In general, demand side management (DSM) describes the change of consumption in magnitude and/or time. In the industrial sector this is already a common part of the energy management systems, as large consumers of electricity also have to pay a load component on top of the delivered energy. The cost of that component is often calculated from the highest peak of the year. Therefore, it is economically interesting to cut peaks and flatten the demand profile. For small consumers, such as households, there is currently no load component but these tariff options are discussed by Distribution System Operators (DSO) [22].

Nevertheless, there are already tariffs in Norway, which incentivize the adjustment of the demand. These are:

- Time-of-use (TOU)

  Different prices at predefined periods of time

- Real-Time-Pricing

  Prices are tied to events in the energy-supply network. Most often the Spot market price is the decisive factor. Price building mechanisms are normally based on operational costs, therefore times of low prices usually correspond to a high share of renewable energy in the generation mix. (Merit-order-effect)

Besides these tariffs, it is also common to use the magnitude of the onsite power generation from photovoltaic or other sources as a signal, because the electricity cost avoided is in general higher than the feed-in price. There are several categories of DSM:

- Peak shaving

  The magnitude of load is down regulated

- Valley filling, load growth

  The load is increased in times of low demand/generation

- Load shifting

  Loads are shifted from peak hours to low demand/generation hours

3.2 Quantifying energy flexibility

Economic indicators such as operational costs are well known and relatively easy to quantify during monitoring or simulation. On the other hand, indicators quantifying the services provided to the grid often differ from study to study and from the involved energy systems. Clauß et al [23] provided a review of 22 key performance indicators (KPIs) used to assess energy flexibility.

Grid interaction KPIs can be used to analyze the electricity consumption and production profile. For grid operation, peak demand and peak production are most important, as the feeders and electrical lines are designed for a certain power. The relation between peak power consumption/production and the designed connecting capacity was presented by Salom et al. [24]

Load matching KPIs describe the relation between onsite production and consumption. This is mostly done in an hourly resolution. It can be distinguished between self-consumption, also known as supply cover factor, which describes the proportion of on-site generation consumed by the building, and the proportion of electrical demand met by on-site generation, which is called self - generation or load cover factor. They are important, as more and more buildings are equipped with electricity generating devices.

As there are already electricity tariffs with changing prices in time, like time-of-use tariffs, the shifting of consumption from high price times to low price times can be analyzed with the amount of energy shifted and their avoided associated costs.

The shifting of loads is only possible by using a form of storage, for heating or cooling purposes that is mostly water tanks or building inertia. These processes of charging and discharging are always associated with losses. Le Dréau and Heiselberg introduced the KPI "shifting efficiency" [29] which shows the relation between the amount of heat discharged and heat charged, compared to a reference case. For charging processes the KPI "storage efficiency" presented by Reynders et al. [30] is similar and results can be compared. The same applies for the KPIs " available storage capacity" in [30] and "charged heat" in [29], as both describe the amount of energy that can be stored during heat up.

3.3 Energy flexibility potential of residential buildings

Even though heating flexibility of buildings might also play an important role for district heating, most studies target the interaction between the electricity network and buildings. Naturally, the focus is on power generation from photovoltaic or combined heat and power and the main consumers. In residential buildings, these are namely white goods, cooling appliances, air handling units and in case of electrified heating, heat pumps or resistance heaters.

The flexibility of smart appliances such as dishwasher or tumbler were assessed in the Netherlands and Belgium with extensive monitoring. D'Hulst et al. [31] analyzed measurements from 186 households with 418 smart appliances over three years. They concluded an average maximum increase at midnight of 430 Watt and a decrease of 65W in the evening. Klaassen et al. [32] did similar monitoring but also with manual demand response. Even though these studies show that there also is a flexibility potential in postponable loads, the focus is on the electricity consumption for heating and cooling, as they often have higher nominal power and the processes can more easily be interrupted and scaled in power. [11]

Thus, heat pump systems with thermal storages are the most evaluated energy system for cold climates. As a heat distribution system most studies focus only on floor heating. However, radiator systems were studied in [26, 29, 30, 33, 34].

It is a common approach to design heating systems by calculating the overall heat loss of a building at a design outdoor temperature (DOT). Regardless the operation mode, the size of the heat pump is therefore always depended on the thermal properties of the building and the climate it is located. [29] The size of water tanks for space heating and domestic hot water is also often influenced by the design power of the heat pump. Fischer et al. [35] showed that current sizing practices already lead to sufficiently large tanks for the use of DSM.

The flexibility potential of domestic hot water tanks were assessed in [27, 36]. Clauß et al. [27] pre-heated the DHW tank in defined hours and could reduce the electricity consumption in peak hours by almost 14 %. Coninck et al. [36] successfully reduced curtailment losses of photovoltaic systems by 74% with using DHW tanks as a storage.

3.4   Energy flexibility and structural thermal storage

In contrast to other storage options, like hot water tanks, the available energy storage potential in building structure is depending on a larger number of factors. First of all, the set points for room temperature can only be lowered or raised in the boundaries of thermal comfort. According to ISO 7730:2005 [37] the operative temperature can vary about +/- 2 K around 21°C for a common level of clothing as well as of activity, and still be in an acceptable range of thermal comfort. Besides that, building specific parameters as distribution thermal mass, insulation level and heat distribution system but also time varying factors like solar radiation and outside temperature strongly influence the behavior of structural thermal storage.

As described in chapter 3.2. the KPIs storage capacity and storage efficiency can be used to express the performance of thermal mass activation.

3.4.1 Building specific parameters

In general, studies [29, 34, 38, 39] showed that with an increase in insulation, the storage capacity decreases. This is mainly due to the fact, that in less insulated buildings the nominal power of the heating system is larger than in well-insulated houses. In contrast, storage efficiency decreases with insulation. As it is strongly dependent on the heat loss of the building, efficiency also decreases with an increase of activation time, as air temperatures are higher. The differences in efficiency between the building types are therefore larger for longer durations of the heat up event. [30, 39]

Le Dréau et al.[29] showed that the ability to shift power from high price times to low price times is lower for less insulated buildings compared to new buildings. For a house from the 80s they found a two hours heat up/cool down period optimal, whereas they could use 12 hours could down periods for buildings from 2014 without observing temperature variations higher than 1°C. Reynders et al. [34] also evaluated the influence of different insulation levels on the grid interaction action KPIs load cover and supply cover factor. They showed that both factors are generally higher for low energy buildings, nevertheless the increase due to DSM controls is higher for the less insulated buildings. This is explained by a shorter heating period in the low energy buildings. Differences in the construction weight were also assessed in this study. The cover factors increased stronger in heavy weight buildings than the light weight building for all insulation levels.

3.4.2 Time varying parameters

Wolisz et al. [40] studied charging/discharging of thermal mass by hydronic radiators in a three apartment house made of massive brick. A simulation was carried out for constant outdoor temperatures of -5°C, 0°C and 5°C. The results show a decrease in storage capacity from 51.5 kWh in the warmest to 36.5 kWh in the coldest case. The storage efficiency also decreases from 93 % in the warmest to 80% in the coldest.

Similar results were found in [29] where the influence of different climate files on the achieved flexibility were examined. The variations compared to the reference cases were in the range of 12% to 4%.

Reynders et al. [30] also showed that the available capacity changes on a seasonal level. They found a substantial decrease in capacity and storage efficiency when the heating demand in the reference cases is low due to solar gains and warm outside temperatures. In times were the indoor temperature is higher than the upper comfort threshold the available capacity is zero.

On a daily basis, the schedules of occupancy showed to have strong impact as well. In the discussed cases, this is mainly due to a night set back control. In the times after the night set back the available capacity is close to zero as the heating system is already operating at nominal power. This also illustrates also the importance of the applied heating control.

3.4.3 Influence of heat distribution system

Besides the parameters described above, the heat distribution system is also expected to have significant influence on the energy flexibility potential of structural thermal storage, as the dynamics of floor heating, air heating, and radiator heating differ from each other. Air heating is very dynamic and reacts directly to the heat demand needed in the zone. The heat transfer can be considered completely convective.

When a radiator system is chosen, the heat transfer is mostly (around 70%) convective. The air volume is also heated directly without considerable delay but 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 therefore largely depending on the material properties of the outermost layer of the construction. Nevertheless, depending on the chosen comfort range, the maximum operative temperature is reached rather fast, which results in a limitation of the heating power, the activation time and finally the stored heat. Depending on the size and model, the weight is around 30 kg/m² to 90 kg/m², which together with the water content slows down the cool down process. Thus the cool down time is also in the range of a few minutes for commonly used panel radiators but can be significantly higher for older steel radiators.

Figure 3-1: Heating power depending on time for different floor heating systems and coverings, the dotted line indicates systems with capillary mats, the solid line indicates conventional wet systems. Comparable are 1 and 4, 2 and 5, 3 and 6 (heat up), Ohne Belag = without flooring; Parkett = parquet, Fliesen = tiles [41]

There are a lot of different systems who can be named water based floor heating. In general, pipes containing water or other media are embedded in the construction or placed inside it. A distinction is made between dry systems, which usually use a panel of dry screed above the pipes and wet systems, where the pipes are completely covered by concrete. In case heating is needed, the slab or the construction is heated first and the 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 depending on the chosen system. Figure 3-1 and 3-2 show the heat up and cool down time of different system and floor coverings. They show that 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.
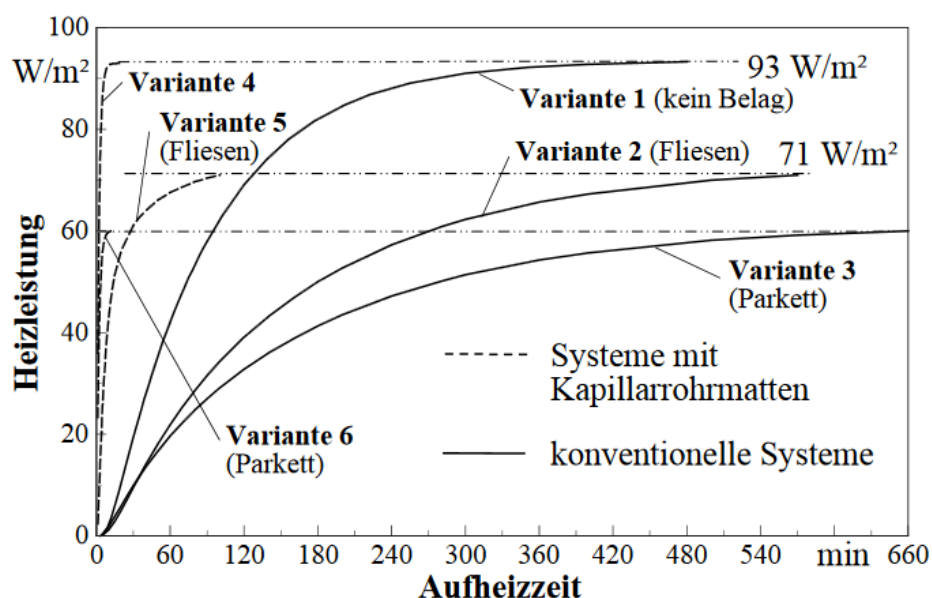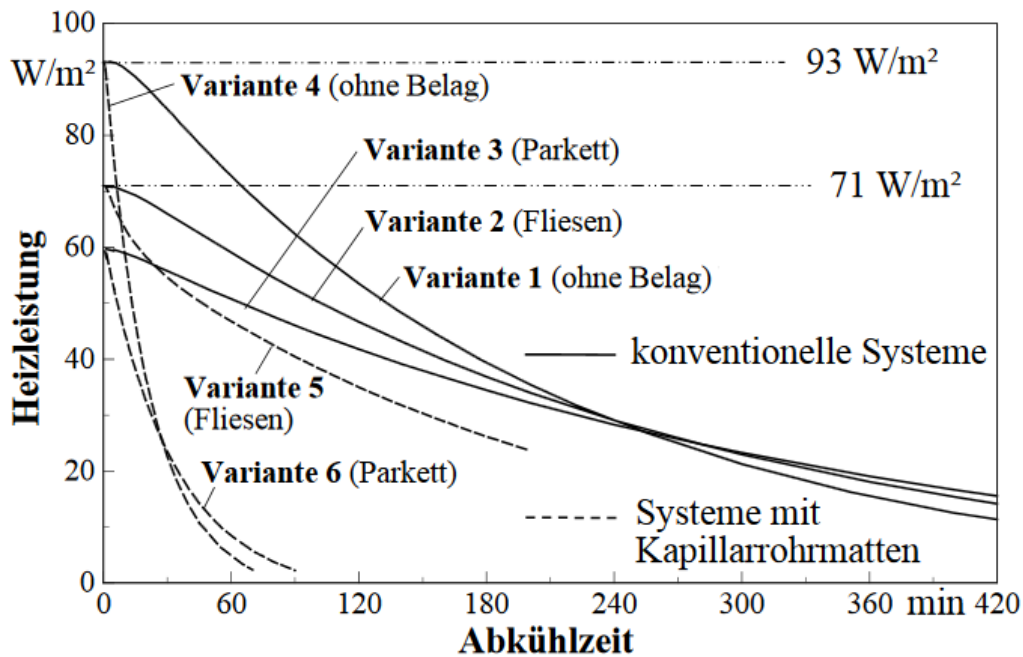

Figure 3-2: Heating power depending on time for different floor heating systems and coverings, the dotted line indicates systems with capillary mats, the solid line indicates conventional wet systems. Comparable are 1 and 4, 2 and 5, 3 and 6 (cool down), Ohne Belag = without flooring; Parkett = parquet, Fliesen = tiles [41]

Storage capacity and storage efficiency

Le Dréau et al. [29] investigated the modulation potential of a passive house and a poorly insulated building in Denmark. The heat distribution system was varied between radiators and floor heating. Both were oversized with a factor of 25%. They simulated 365 days independently and compared upward and downward modulations with different durations and starting points. The modulations were performed with an in- or decrease of the temperature set point of +/- 2K around 22 °C. For a storage event of 2h in a house from the 80s, the median amount of stored heat for the radiator system was around 70 Wh/m². The storage efficiency was approximately 0.9. In the case of floor heating the results were around 50 Wh/m² and 0.96, respectively. These results correspond well with the findings of other studies.[30, 40]

For longer activation periods the maximum operative temperature is reached and the heating power is adjusted. This limits the available storage capacity. The study showed that this is especially the case for the radiator version. In average, an operative temperature of 23.5°C was reached after 2 hours of activation and the upper threshold after 4 hours.

In the case of the floor heating system the operative temperature almost does not change for an activation of 2h, after 4 hours the median operative temperature is 22.5°C. The differences between the two systems only vanish for activation periods longer than 12 hours. In the consequence, the storage capacity of the floor heating is larger for longer periods. In this case of 12 hours activation a storage capacity of 300 Wh/m² for floor heating and 150 Wh/m² for radiators, and an efficiency of 0.85 and 0.75 was found, respectively.

Reynders et al. [30] showed that the efficiency of radiator systems varied between 65% and 90% for different building types and insulation levels, whereas the values for floor heating were above 90%. They concluded that the lower efficiencies are due to higher heat losses caused by higher air temperatures. Consequently, radiator heating is more sensitive to ventilation rates. [42]

Supply cover factor and demand cover factor

As described above, nearly zero energy buildings will be the future. One solution is that the produced on-site electricity production by building integrated photovoltaic (BPIV) equals the electricity demand on annual basis. Nevertheless, the usual demand profile does not match the instantaneous profile of BPIV generation. For example, electricity demand is highest for heating and lighting in winter times, when generation is low. The influence of the heat distribution system on cover factors was assessed by two studies [26, 34].

Baetens et al. [26] investigated the impact of the type of heat emission system on the self-consumption and grid-interaction of a BIPV system in a highly insulated Belgian residential house. The dwelling was modeled in TRNSYS using a compression heat pump for both space heating and domestic hot water production as well as domestic consumers and on-site photovoltaic generation. The highest cover factor was reached by the floor heating with 0.30, followed by a combination of both systems with 0.24 and radiators with 0.21. For the floor heating electricity consumption was also highest, which resulted in a much larger BIPV system compared to the other two options. Additionally no clear relation was found between peak power demand and heat emission system. They concluded that cover factors are mostly depending on the control strategy applied.

Reynders et al. [34] evaluated the energy flexibility potential of structural thermal mass in a detached house in Belgium equipped with building integrated photovoltaic and an air-to-water heat pump. They compared a low temperature radiator- and a floor heating system for their ability to activate the thermal mass. The heating system was controlled by thermostatic valves in the reference case. For the non-predictive DSM control, they raised the temperature set point in the zones for 1 K, whenever the PV generation exceeded the normal domestic loads and they lowered it when domestic load was 500 W above PV generation. Further, they proposed two model-based control (MPC) approaches, where temperature set points are calculated based on the predicted heat loss and thermal mass of the building. They also varied between three different isolation levels and light and heavy weight constructions.

For comparability with [26] the results for the highest insulated building and for the most sophisticated MPC, the supply cover factor for total electricity use is 0.25 for the radiator heating system and 0.23 for the floor heating system. The demand cover factor is also 0.25 for the radiators and 0.22 for the floor heating. The numbers had to be derived from diagrams, as the authors did not give exact numbers. Heat pump electricity use in peak hours could be reduced

by 68% for the radiator system and by 86% for the floor heating system compared to the reference case for the same model set-up. The heat pump demand during peak supply hours was increased by 129% for the radiator heating and by 165% for floor heating.

Weighted temperature deviation hours with the operative temperature being too low are around 4.5% for the radiator and 3.2% for the floor heating system. For hours above the temperature limit, the radiator system is slightly better with 11.8% compared to 12.3% for the floor heating system. The annual energy use for heating increased between 6.7% and 7.9% for the different isolation levels with radiator heating and between 5.0% and 7.3 % for floor heating.

Shifting electricity use to off-peak hours

Arteconi et al.[43] investigated a detached house from the 1990s located in Northern Ireland, equipped with a heat pump and a radiator or floor heating distribution system. In contrast to the study above, they also investigated the influence of water storage tanks. The goal was to shift electricity consumption in peak hours (16:00 h – 19:00 h) to off-peak hours with lower prices. Therefore, they applied a DSM control, which switched the heat pump off during these hours. In the version without water tanks, the floor heating system could easily maintain thermal comfort in the building during these hours and temperature never dropped below 20°C. The energy consumption decreased about 4% with this control. The lower thermal inertia of the radiator system however led to temperatures lower than 19°C. Consequently, the energy consumption decreased as well. A major drawback of this study is the control of the radiators. They are only considered active at 7:00-9:00, 12:00-14:00 and 18:00-22:00, which means that comfort temperatures could have been violated even before or outside times of the DSM event. In contrast, the floor heating was active 24/7.

Le Dréau et al. [39] used the price signal of the French sport market and divided it into low, medium and high prices. They showed that floor heating was more useful for shifting loads than the radiators. They also presented a "flexibility factor". When factor is 0, the same amount of energy was consumed in high and low price times. When the factor is 1, there is no heating in high price periods. For an activation time of four hours in a state of the art residential house, the flexibility factor was 0.82 for radiators and 0.87 for floor heating.

4 Method

To evaluate the influence of the space heating distribution system on the energy flexibility of residential buildings, detailed dynamic simulations are carried out. Firstly, the ventilation system is designed according to plans of the test case building, the living laboratory in Trondheim, and the current building regulation. Secondly, a heat load simulation is carried out for the design outdoor temperature and the calculated airflow rates. The results are then used to size the heat generation system (heat pump and tanks) as well as the three heat distribution systems. For each of the heat distribution systems simulation models are created. A further specification is then made to evaluate the influence of opened or closed doors. These cases are then simulated with a reference heating control, a rule based control using a fixed schedule and a price based control. The controls affect firstly the heating set point in the rooms and are then extended to the space heating and domestic hot water tank. In total 30 model versions are created.
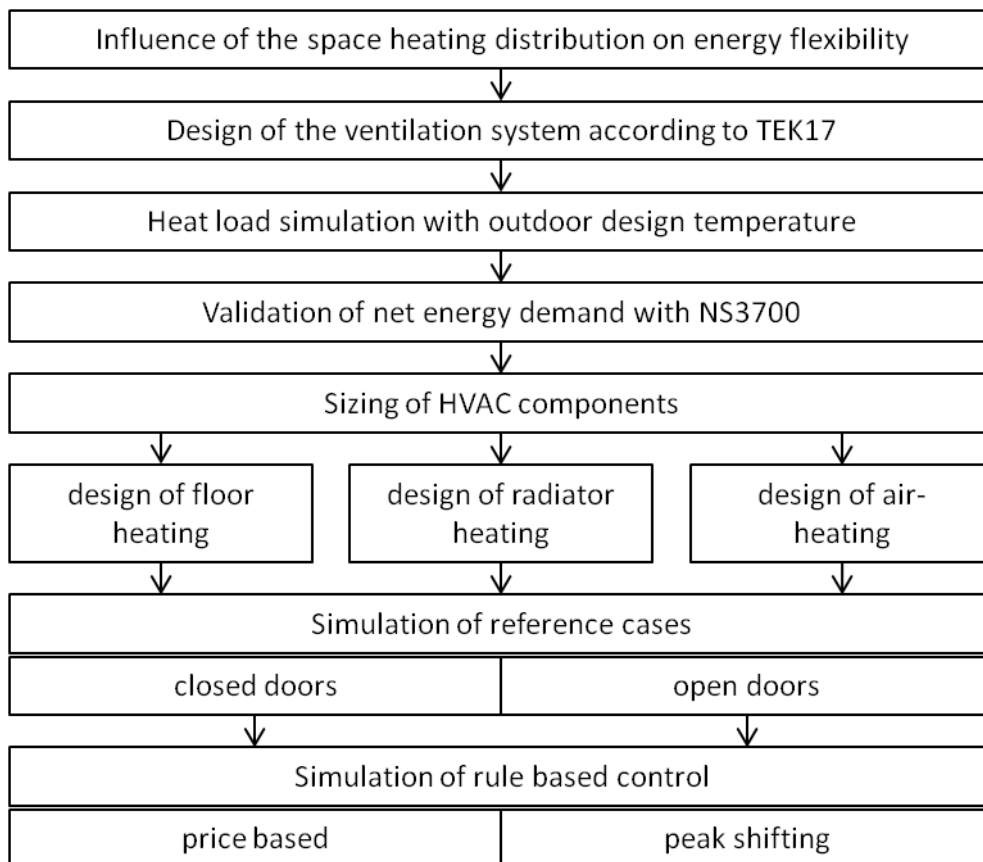
Figure 4-1: Overview of the methodology

4.1   Software

The Software IDA ICE (Indoor Climate and Energy) 4.7.1 was used to model the building and the HVAC system. The Software is common in Scandinavia but has emerged as one of the most used building performance programs in Germany as well in recent years.

4.2   Case Study

The Living laboratory (Living Lab) at the Gløshaugen Campus of the Norwegian University of Science and Technology (NTNU) was chosen as the case study building. It is a single floor residential building, which comprises of two bedrooms, a small bathroom and a combined area for cooking and living. (see Figure 4-3) All together, the building has a 105 m² heated floor area. As it was designed as a Zero Emission Building (ZEB), envelope constructions are highly insulated and airtight. The building can be considered a lightweight building, as the constructions are wooden-frame.
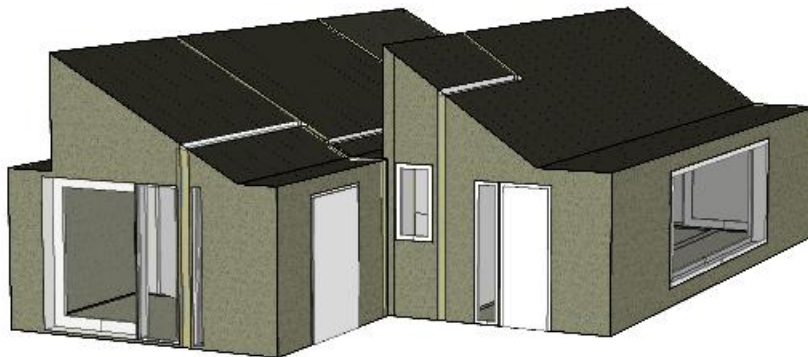
Figure 4-2: Simulation model of the living lab
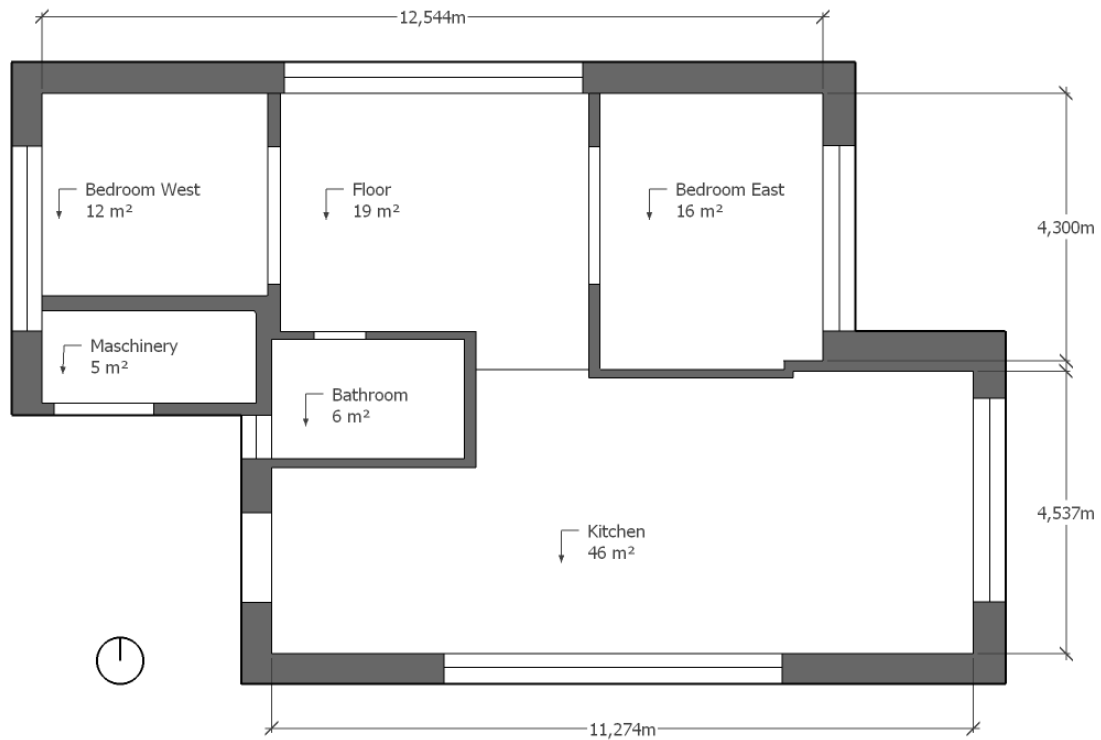
Figure 4-3: Sketch of floor plan of the Living Lab

The building physical parameters are mostly in accordance to the Norwegian passivhouse standard NS 3700:2013 [16]. Table 4-1 gives a brief comparison of values used in the Living Lab and NS3700. The notation in brackets indicates whether a value is mandatory (man.) or informative (inf.). The Living Lab is therefore not a passive house.

Table 4-1: building physical parameters of the Living Lab

	Living Lab	NS 3700		Unit
U-value wall	0.16	0.10 - 0.12	(inf.)	[W/m²K]
U-value floor	0.11	0.08	(inf.)	[W/m²K]
U-value roof	0.11	0.08 - 0.09	(inf.)	[W/m²K]
U-value windows (south)	0.65/0.69	0.8	(man.)	[W/m²K]
U-value windows (north)	0.97	0.8	(man.)	[W/m²K]
U-value Windows (east/west)	0.80	0.8	(man.)	[W/m²K]
g-value	0.5	-		[-]
Infiltration n50	0.7	0.6	(man.)	[ach]
Normalized thermal bridge	0.03	0.03	(man.)	[W/m²K]

4.3   Climate and Location

In building performance simulation typical meteorological years are often used to represent the climate at a specific location. These years are created from measurements made in a time span up to 30 years. This means that a typical meteorological consists out of weeks from different years. In this work, this approach does not fit, as the control of the heating system is in some versions defined by real time spot market price data from 2015. It should be noted, that the behavior of the spot market is also influenced by the weather.

For the sake of consistency, a climate file based on measured data from 2015 was chosen. The file provides hourly values for dry-bulb temperature, relative humidity, wind-speed and wind-direction as well as direct and diffuse solar radiation on a horizontal pane. The file was created using shinyweatherdata [44] based on data from the Swedish Meteorological and Hydrological Institut as well as Copernicus Atmospheric Monitoring service.

Figure 4-4 shows the dry-bulb outdoor temperature throughout the year. It is coldest in January and December where temperatures range from a minimum of -12°C to a maximum of 26°C in August. The mean temperature over the year is 6.78°C. Compared to the mean temperature for Trondheim that is used for energy calculations according to NS-EN ISO 15927-5:2004 it was a rather warm year, as the temperature was given as 5.8°C in [45].
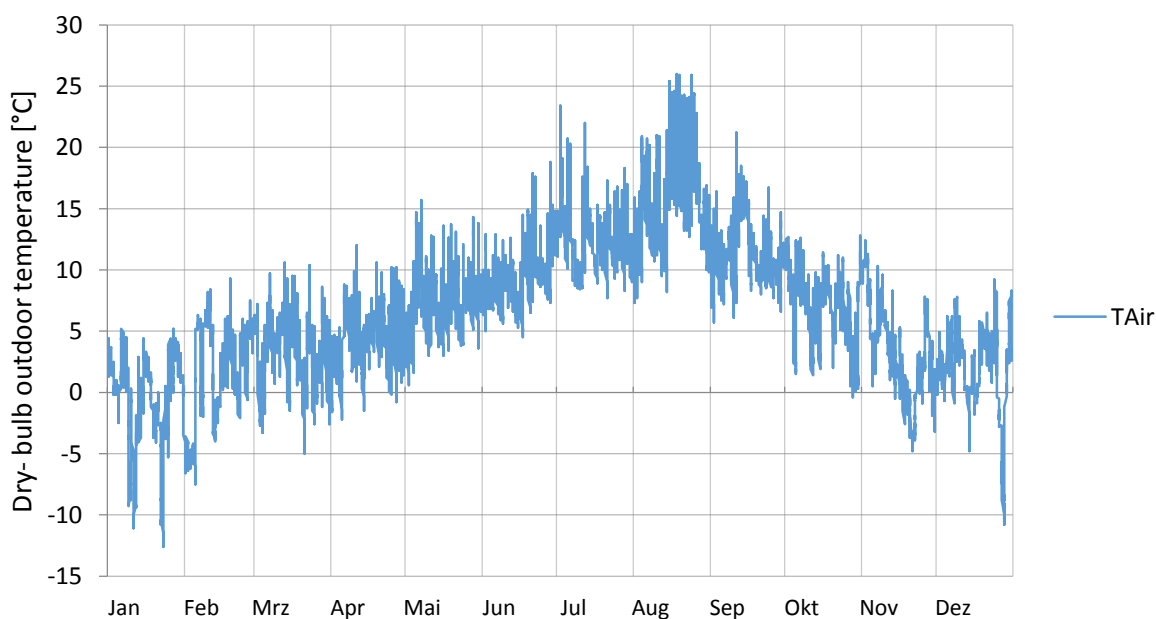
Figure 4-4: Dry-bulb outdoor temperature for 2015 used in the simulations

4.4   Internal gains and human behavior

As it is a highly insulated building, the definition of internal gains and occupant behavior has a great impact of the dynamics of the building. In fact, it can be one of the greatest sources of errors when comparing measurements to simulation data. [46]

In this study schedules for occupancy and lighting were taken from Ahmed et al. [47], who developed them for the new ISO/FDIS 17772-1 standard. The number of occupants and the nominal power of the light bulbs were adjusted to suit the daily and yearly sum of 13.1 kWh/m² and 11.4 kWh/m² for occupants and lighting given in NS/TS 3031:2016 [48].
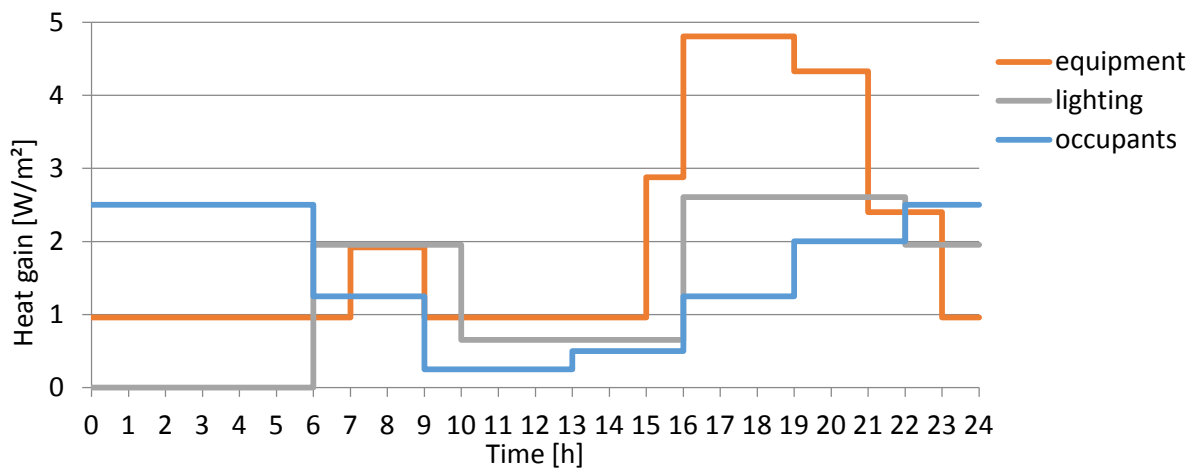
Figure 4-5: applied daily profile of internal gains in simulation

This was chosen because gains from occupant and lighting were constant in NS/TS 3031:2016 and the timly distribution of SO/FDIS 17772-1 was considered more realistic. Schedule and heat gain from equipment were directly taken from NS/TS 3031:2016. All internal gains where assumed equally distributed throughout the building and are therefore uniform. Windows and outer doors are closed at all times, whereas inner doors are either closed or open the entire simulation time.

4.5 Ventilation system

As the ventilation concept directly influences heat losses due to infiltration and air flow it is discussed first. It is, besides envelope parameters, the basis for heat load calculation and dimensioning. The ventilation system was designed according to the Norwegian building code (TEK17). In chapter 13.2 of the code, four minimum requirements are described for pre-accepted performance.

Firstly, the overall air flow rate has to be at least 1.2 m³/(h m²) floor area. Secondly, bedrooms must receive 26 m³/h per Person or more specifically, per planned sleeping opportunity, fresh air. Thirdly, rooms not intended for permanent residence shall have ventilation that ensures a minimum of 0.7 m³/(h m²). At last, minimum exhaust ventilation rates are given for wet rooms such as kitchen, baths and laundry rooms according to Table 4-2. [49]

Table 4-2: Ventilation rates for wetrooms according to TEK 17 [49]

Room	minimum ventilation rate [m³/h]	Enhanced ventilation rate [m³/h]
Kitchen	36	108
Bathroom	54	108
Toilet	36	36
Laundry room	36	72

For the bedrooms two beds were assumed, leading to 52 m³/h supply air. The bathroom, floor and kitchen supply was calculated with 0.7 m³/(h m³). These supply rates add up to 153.7 m³/h which is sufficient to fulfill the first criteria of 1.2 m³/(h m²) which would result in 120 m³/h. The exhaust ventilation rates are scaled up minimum ventilation rates to fit the supply rate value. In table 4-3 the distribution of airflow rates in the building is given.

Basic Air handling unit (AHU)

Ventilation is provided by a balanced mechanical system with constant flow. The central air handling unit (AHU) is equipped with a rotary heat exchanger with a recovery rate of 85%. The supply air temperature is constant 19°C throughout the year. An electrical heating coil with a maximum power of 1.2 kW power assists the heat recovery. The air temperature rise due to the fan motor was assumed to be a constant 1 K. That means, the set point temperature for the heating coil is 18 °C.

A specific fan power (SFP) of 1.5 kW/(m³/s), as this is also the minimum requirement in NS3700:2013[16], and a efficiency of 0.7 for both the fans was assumed. IDA ICE uses both of these parameters to calculate the pressure head automatically. The efficiency is constant by default and therefore the pressure head as well.

Table 4-3: Supply- and return airflows

Room	Supply air [m³/h]	Return air [m³/h]	Supply air [(m³/h m²)]	Return air [m³/(h m²)]
Bathroom	4.2	92.2	0.7	15.5
Bedroom East	52.0	0.0	3.1	0.0
Bedroom West	52.0	0.0	4.3	0.0
Floor	14.0	0.0	0.7	0.0
Kitchen	31.5	61.5	0.7	1.4
total	153.7	153.7	1.5	1.5

4.6   Heat generation

The core of the heating set up for the Living Lab consists of a two storage tanks in one shell. The upper part consists of the domestic hot water (DHW) tank and the lower part is for space heating (SH). In the space heating tank there are two heat exchangers, one for the solar thermal circuit and one for domestic hot water, which is thereby pre-heated before entering the DHW-tank. This way the solar thermal panels mounted on the south facade can support SH and DHW without a second heat exchanger. Primarily, heat demand is covered by a ground source heat pump (GSHP) which uses a horizontal surface collector as an energy source. It supplies the space-heating tank directly whereas the DHW tank via a heat exchanger. Both tanks can also be heated with electrical resistance heaters, with a power of 3 kW in the DHW part (AUX 2) and 9 kW in the SH part (AUX 1) respectively.

To reach the ZEB goal, the building is also equipped with a 12 kWp photovoltaic system. The used components, their sizing and implementation are described in detail in the following part.
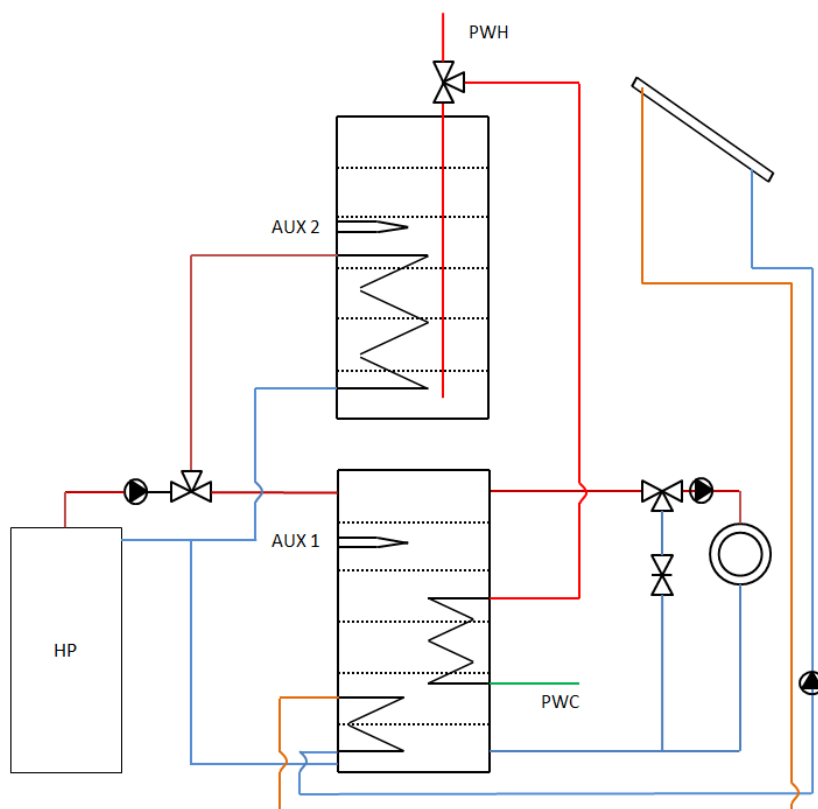
Figure 4-6: simplified description of the buildings energy system

4.6.1 Sizing of the heating system

The heat load calculation was carried out in accordance to NS:EN 12831-1:2017 [50]. The proposed internal design temperature is 24°C for the bathroom and 20°C for all other rooms. The design outdoor temperature (DOT) is -22°C for Trondheim [45]. Solar radiation and internal gains were neglected.

The calculation was done in IDA ICE using the described AHU above and ideal heaters in every room. These room units have no mass and react directly to the heat power need. They were implemented to release convective power only, which means they directly affect the air node of the zone model. The results (table 4-4) show that the bathroom has the highest specific heating demand, which is due to the higher set point temperature. The adjacency of Bedroom West to the lower-heated (19°C) machine room is also noticeable.

Table 4-4: Heating demand in zones

Room	heating demand [W/m²]	heating demand [W]
Bathroom	66.03	393.5
Bedroom East	36.37	606.2
Bedroom West	44.83	539.3
Floor	25.37	506.4
Kitchen	34.1	1536
total		3581.4

4.6.2 Heat pump

The operating mode of the heat pump was chosen monovalent or more specifically mono-energetic, because of the auxiliary heaters. Therefore, the ground source heat pump (GSHP) has a nominal power of 3.5 kW and a COP of 4.0 at the rating conditions of 0/35°C. That also indicates that for higher temperatures, e.g. the radiator system or the air heating system, the available power will decrease to 2.6 kW at 0/55°C.

The maximum leaving temperature is 65°C for domestic hot water. The compressor power can modulate between 30% and 100% of the nominal capacity.

It is therefore necessary to model the part load performance of the heat pump. The model in IDA ICE relies hereby on four coefficients, which should be calibrated with manufacturer data for different operating points (0/35°C, 15/35°C, 0/55°C, 15/55°C). This can be done by setting up four or more (one for each operating point available) heat pump models and calculating the errors between computed values and the given data. Using the parametric runs tool in IDA ICE and GenOpt optimization software, several simulations are carried out and the error is subsequently minimized.

4.6.3 Water storage tanks

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, in case of blocking times 30 - 60 l/kW are advised. [51] [52] Others also make a distinction between floor heating and radiator heating. The advised volume is doubled for radiators, because of the smaller inertia of the system and smaller amount of water in the circuits. [53]

As the heat generation set-up should stay the same for all versions, a volume of 200 l was chosen which corresponds to 57 l/kW.

Domestic hot water tank

Manufacturers [51, 53] suggest sizing according to hourly peak demand. The tapping profile for domestic hot water is therefore decisive for sizing the DHW tank. In the model, the profile from NS/TS 3031:2016 (see figure 4-7) for small houses was implemented. The hourly peak demand is 1.442 kWh and the daily consumption is 7.2 kWh. Assuming coldwater at 10°C and a desired hot water temperature of 60°C, this equals 124 liter.
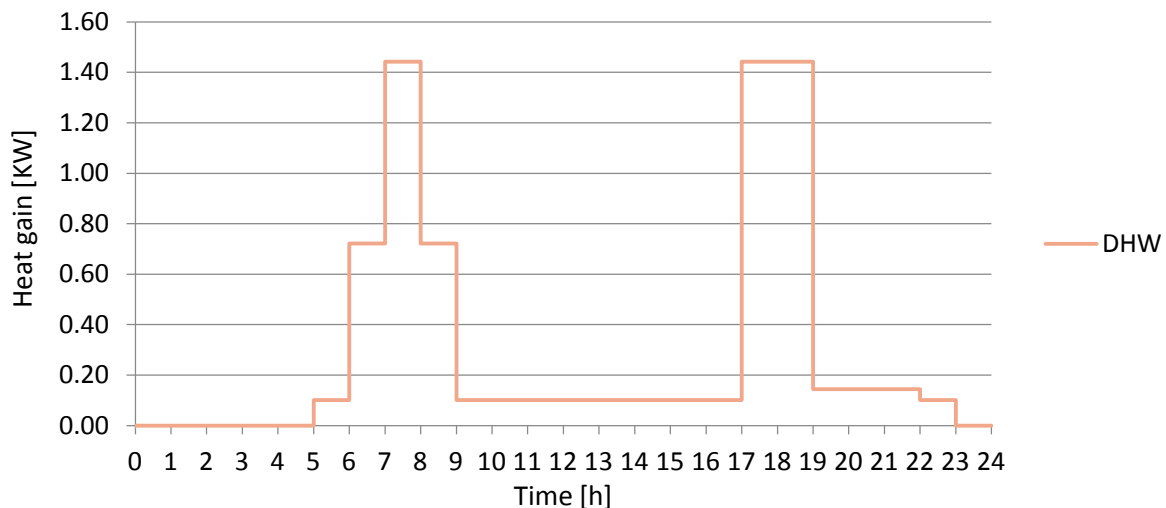
Figure 4-7: Distribution of domestic hot water use according to NS/TS 3031:2016

This is in line with the tapping profile in EN 15450 for a family with shower use (100 liter). Nevertheless, the hourly peak demand is higher with 2.24 kWh. Because of the second daily peak in the NS/TS 3031:2016 profile lasting two hours, it seems reasonably to choose 2.88 kWh as the decisive value. For single family houses there is also the possibility to use a simplified approach. [51, 53, 54] The volume of the DHW-tank is then estimated with daily demand of 25 l (60°C) per person and doubled. A second general estimation is given in [55].

As there were multiple ways for dimensioning the DHW tank, a comparison of the approaches can be seen in table 4-5. It also shows that there are great differences. For the model, a 160l DHW tank was chosen. For even smaller units, manufacturer data is rare.

Table 4-5: DHW tank sizes for different sizing methods

Profile	Hourly peak demand [kWh]	Minimum volume [l]
3 Pers. shower (EN 15450)	2.24	48.45
3 Pers. bath (EN 15450)	4.45	87.91
NS/TS 3031:2016	1.44	28.53
NS/TS 3031:2016 x2	2.88	57.06
estimation manufacturers[51, 53]	-	187.50
estimation literature [55]	-	175.31

Implementation in IDA ICE

For the implementation in the simulation environment measurements of a commercially available storage tank were used. That way, heights of inlets, outlet and heat exchangers were set. The volumes of the internal heat exchangers were calculated according to the given pipe diameter and surface area. The heat transfer coefficient of the heat exchangers was determined with an average overall heat transfer coefficient of 450 W/m² K. This is the average value given for helical coils in [56].

Water storage tanks are described in IDA ICE as a piled number of horizontal layers. For each layer the mass and heat balance is computed. Both of the tanks consist of six layers with a height of 0.195 m (SH) and 0.181 m (DHW).

Besides the set up of inlet and outlets, there are two parameters, which can alter the heat balance. These are "mixfac" for heat exchange due to mixing processes and "stratfac" for heat exchange due to stratification phenomena. Both of these factors were set to zero, as these factors are highly specific to a certain set up. One example of a calibrated IDA ICE tank model can be found in [57], there a mixing factor of twelve showed the best agreement with the measurements of a 0.5 m³ tank.

4.6.4 Control of the heating system

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) (see figure 4-8). 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 space-heating tank is rather similar; there are also two sensors at different heights (TM 1/ TM 2). If the measurements of the higher one fall short to the value from out-door temperature compensation curve (OTCC) of the chosen heat distribution system, the tank is charged until the temperature of lower sensor is 5 K above the current value of OTCC. This also ensures a reasonable run time of the heat pump. The auxiliary heater (AUX 1) is switched on when TM 2 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 about two minutes.

The heat pump has a space heating and a domestic hot water 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%. That indicates that when switched on, the smallest power is 30% of the nominal power.
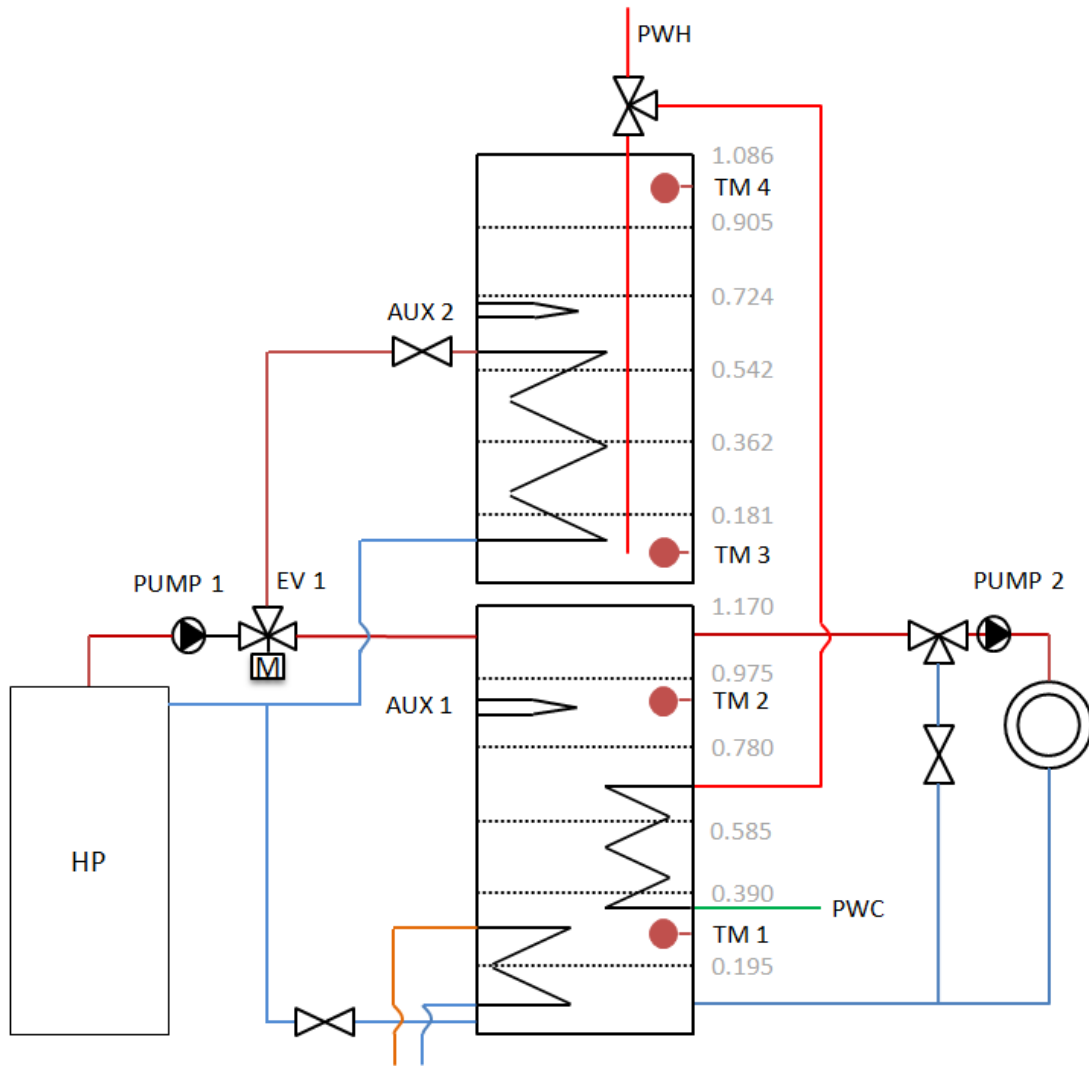
Figure 4-8: simplified description of the heating system set up

4.7 Heat distribution systems

All heat distribution systems are controlled by an outdoor compensation curve. To determine the curve, a whole year simulation was carried out with weather data from 2015 and ideal heaters. Figure 4-9 shows the result of a simulation without internal gains. This was then translated to supply temperatures for the different systems.
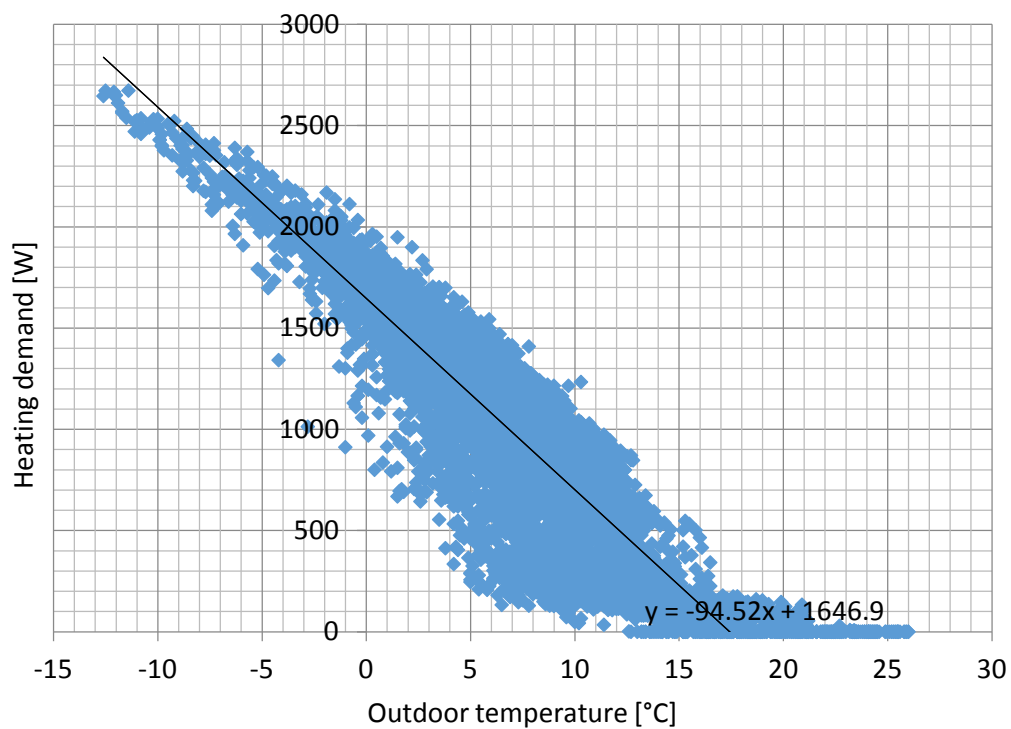
Figure 4-9: Heating demand depending on outdoor temperature

4.7.1 Water based radiator

Sizing

In the Radiator version, a single radiator is placed in the middle of the house, between floor and living room. Similar simplified heat distribution systems were assessed in recent studies with focus on thermal zoning in passive houses. [58–60]

The MC33 2300x900 from Lygnson was chosen. The power at norm conditions (75/65 / 20°C) is given with 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

In the model, the radiator had to be split up because of zone boundary between "Floor" and "Kitchen". This poses some problems to the control of the radiators, as the measurement signal is the mean air temperature of the zone the radiator is located in by default. It was therefore possible that both radiator parts were not operating at the same time. To avoid this, the unweighted average of the two mean air temperatures was chosen as the input signal. The mass flow is controlled by a PI-controller. In reality, a thermostatic valve is the most common solution, but hard on/off switches slow down simulations. The maximum mass flow is calculated by the software automatically when design power and exponent are given. But it is also possible to adjust it in the advanced level manually.

Additionally, radiators have to be placed at/in walls in IDA ICE, because the model creates a wall part the size of the radiator whose temperature is calculated and represents the radiator surface. Unfortunately, the available space was smaller than in reality. To keep the area of the radiator the same, the height of it had to grow bigger. This is necessary, to ensure that the calculation of the mean radiant temperature and therefore mean operative temperature is not compromised in the zone model. It should also be mentioned, that the inertia of a radiator is not represented by this model. In the simulations the surface temperature of the radiator- wall-part drops exactly in the same way as the delivered power.
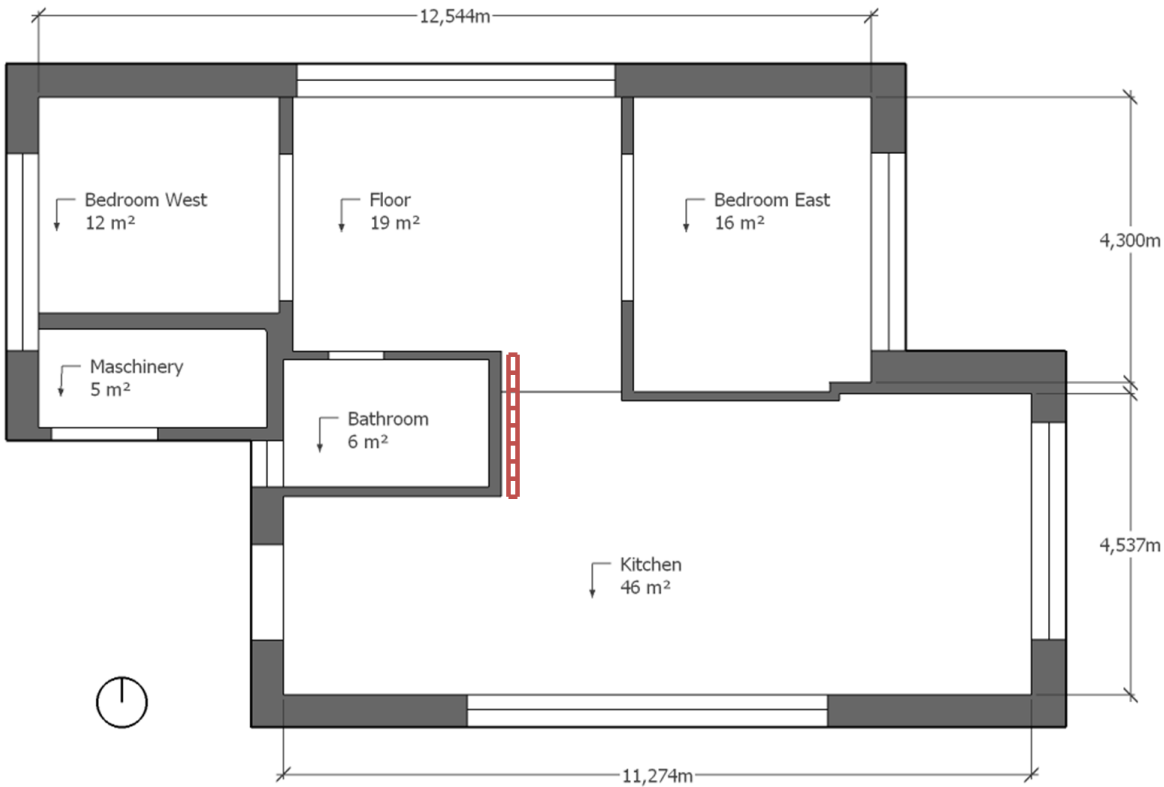
Figure 4-10: Location of the radiator

4.7.2 Water based floor heating

Sizing

The floor heating was implemented as a dry screed system, manufacturer data for the system "Roth Clima Comfort TBS" was used for design and calculation according to DIN EN 1264-3:2009 [61]. 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 U-value of around 0.1 W/(m²K). The system can be considered as lightweight and fast reacting compared to conventional wet systems. Each room has its own floor heating circuit except the kitchen, where it is divided into three circuits.

Implementation in IDA ICE

Floor heating systems are implemented as a tempered layer in the floor construction. Therefore the structural component is divided in two parts, one above and one beneath the floor heating. The maximum mass flow is calculated automatically in IDA ICE from the given power and temperature difference at design conditions. Thus, it is important to include the expected downward heat loss. A calculation method for this heat loss is also given in [61]. The heat transfer coefficient was left at the default parameter of 10 W/m²K, as no data was given by the manufacturer. The circuits are controlled by a PI-controller which uses a sensor for mean air temperature.

4.7.3 Air heating

Sizing

The third considered heat distribution system is air heating. The air is heated by a water based heating coil in the central unit. In contrast to the other hydronic distribution systems, where the needed mass flows are calculated during simulation and adjusted continuously until a certain threshold, this air heating system adjusts the supply air temperature for the basic ventilation rates as defined in 4.5 according to the current heating demand. Nevertheless, these ventilation rates are not sufficient for times of high heating demand as the maximum inlet air temperature is defined at 50°C which is in line with [62] where the maximum temperature was set to 55°C, the temperature of dust carbonization.

If the system is designed to cover the entire heat load of 4.03 kW at the outdoor temperature of -22°C, an airflow rate of 397 m³/h would be necessary. This is around two air changes per hour or 2.5 times bigger than the needed air flow according to building regulation.

The coldest outdoor temperature in the used weather data is -12°C, corresponding to a needed airflow of 298 m³/h. The nominal airflow of 154 m³/h can only provide around 1.5 kW heating power, which is needed until temperatures up to 0°C. Additionally, the distribution of airflow rates throughout the zones does not reflect the distribution of heating demand. For example, the kitchen only has a supply rate of 0.7 m³/hm² but 35.1W/m² heating demand compared to 3.1 m³/hm² in the Bedroom West with 36.4 W/m² heating demand. Therefore, air-heating control should take the nominal flow rates according to building regulation and the heating demand into account.

Preliminary simulations

To test this assumption, three airflow distribution concepts were simulated for the coldest week in the dataset, 19.01. – 25.01.2015, with open and closed inner doors to evaluate the balancing effects of air exchange between the zones.

- Air flow rates according to TEK17 (154 m³/h)
- Air flow rates of TEK 17 possible boost to 298 m³/h (scaled TEK 17)
- Air flow rates of TEK 17 possible boost to 298 m³/h (distributed according to heating demand)

In the test cases the water based heating coil, was implemented as a free size coil in the central unit with an assumed water-to-air efficiency of 0.9. This corresponds to a finned tube cross flow heat exchanger and an air velocity of 1 m/s. [55] The air flow rates for each zone can be seen in table 4-6.

Control

The supply air temperature is defined by a PI controller, using the unweighted average of the kitchen and the floor temperature as measurement. In the basic version, the set point is constant 21°C. In the versions with boost flow rates are enhanced according to table 4-6, when the supply air temperature reaches 50°C, and lowered to default when the supply air temperature has dropped to 43°C.

Table 4-6: Air flow distribution for different air heating concepts

Room	Supply Tek 17 [l/s]	Return Tek 17 [l/s]	Supply boost scaled [l/s]	Return boost scaled [l/s]	Supply boost distrib. [l/s]	Return boost distrib. [l/s]
Bathroom	1.2	25.6	2.2	49.7	8.6	49.7
Bedroom East	14.4	0.0	28.0	0.0	14.4	0.0
Bedroom West	14.4	0.0	28.0	0.0	14.4	0.0
Floor	3.9	0.0	7.5	0.0	11.1	0.0
Kitchen	8.8	17.1	17.0	33.1	34.2	33.1
total	42.7	42.7	82.8	82.8	82.8	82.8

Results

The results show that for the basic airflow rates heating set points cannot be reached neither in the open door nor in the closed-door version. The kitchen has the lowest values for the operative temperature with 18.4 °C (see table 4-7) in the open door case. Nevertheless, the Floor and especially the Bedrooms are in an acceptable thermal comfort range. The oversupply of heat in the Bedrooms is not enough to heat the kitchen. In the scaled boost version, temperature is in general higher but does not reach the set point for all versions. In the distributed boost case, an increase in the minimum temperature of the Kitchen and Bathroom can be achieved. (See figure 4-11 and 4-12)

The balancing effect of open doors is obvious as the minimum temperatures are 3 - 4 K higher in Bedrooms and 0.6 to 1 K lower in the closed-door cases. The distribution boost option manages to heat up the Bathroom to 20.5°C and the Kitchen to 19.9°C, while the minimum temperature in the Bedrooms can be reduced by 1 – 1.5 K.

In general, all the discussed versions show high temperatures in the Bedrooms, and colder temperatures in the living room. This is quite the opposite to the 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 in the Bedrooms. [59, 63] With this in mind, the pre-accepted ventilation rates according to TEK 17 [49] might not be suitable for a centralized air heating concept. As this is subject to further studies, the distributed boost system was implemented for the evaluation of energy flexibility.

Table 4-7: minimum operative temperatures during the coldest week in 2015

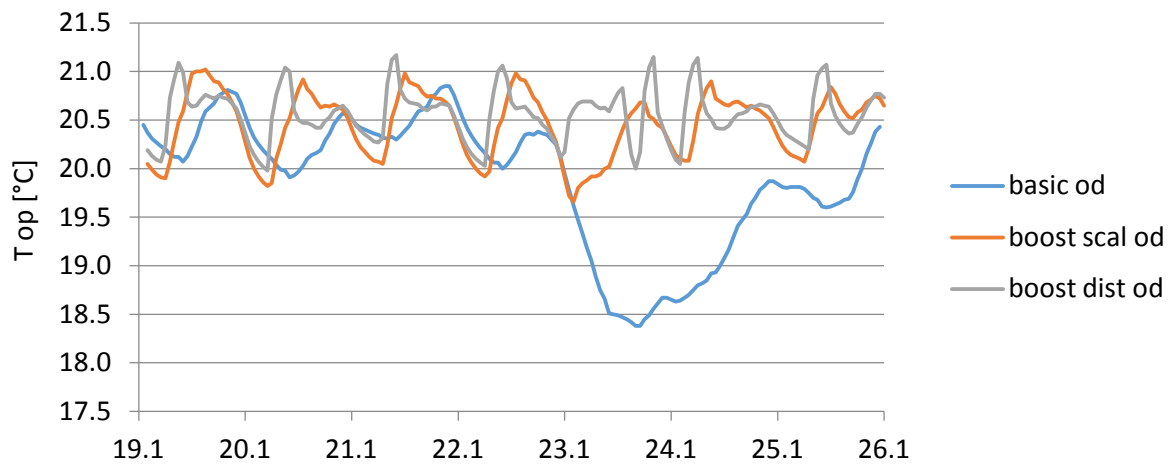| Version	Bedroom West Top [°C]	Bedroom East Top [°C]	Floor Top [°C]	Bath-room Top [°C]	Kitchen Top [°C]
Basic open doors	19.7	19.7	19.3	19.0	18.4
Boost scaled od	20.9	20.9	20.6	20.3	19.7
Boost distributed od	21.0	20.9	20.7	20.6	20.0
Basic closed doors	23.2	24.3	18.7	18.1	17.9
Boost scaled cd	23.6	24.4	20.4	19.8	19.6
Boost distributed cd	22.7	22.9	20.5	20.5	19.9

Figure 4-11: operative temperature in the kitchen, open doors
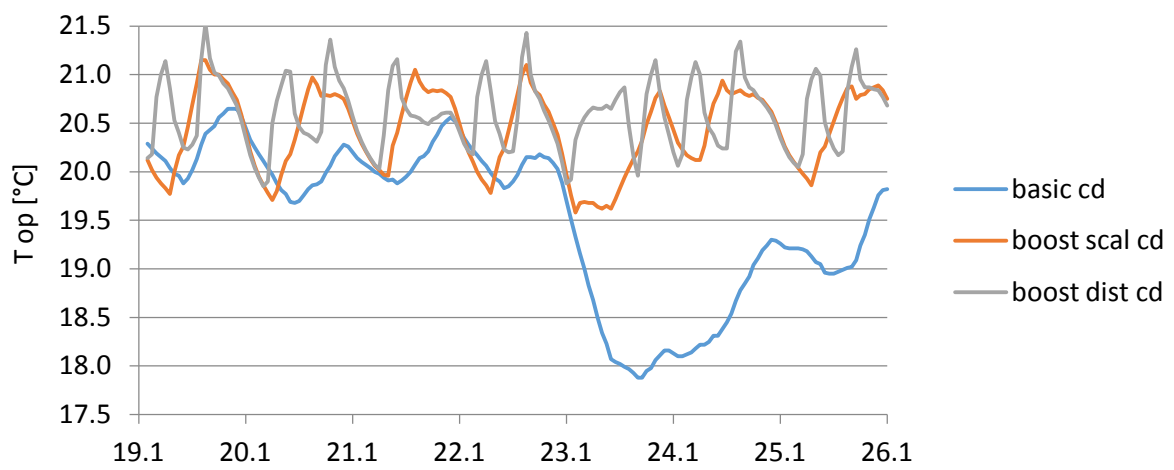

Figure 4-12: operative temperature in the kitchen, closed doors

Implementation of a water based heating coil

There are two possible ways to implement a water based heating coil in IDA ICE. Firstly, a free sized coil, as used in the above simulations, which is defined by a water to air efficiency and a waterside temperature difference. Based on these input parameters the mass flow and maximum achievable leaving air temperature are calculated. A drawback of this option is that the waterside temperature difference always stays at the given value.

The second, more realistic option is a fixed sized heating coil with a mass flow control. The heat transfer is calculated according to the NTU method. There are also different configuration modes: counter flow, cross flow, cross flow both media mixed, cross flow stream 1 unmixed and stream 2 unmixed respectively. Unfortunately, it is not known to the user which stream is water and which is air, thus it has to be tested. The heating coil was configured according to manufacturer data [64] (see also table 4-8). It was possible to compare data from the manufacturer and the simulation at different operation points. The configuration mode 6 of fixed sized model in IDA ICE showed good agreement and was implemented for the evaluation of energy flexibility.

Control

The control of the coil is the same as described in the preliminary simulations. However, the heating coil does not need the same temperature level when operated with the flow rates according to Tek17. In part load, the water supply temperature can be 5 K lower. Therefore, the desired water supply temperature is increased by the same value when the ventilation boost is active as well as the set points in the space-heating tank.

Table 4-8: Data at design conditions, air-heating coil

Air flow rate	300	m³/h
Air velocity	1.02	m/s
Air temperature in/out	8/50	°C
Humidity in/out	20/2	%
Water temperature in/out	58/56.5	°C
Water flow rate	0.7142	l/s

4.8   Energy flexibility controls

4.8.1 Predictive price based control 1

In this control approach, the set points in the zones are changed according to a price signal. Thus, the aim is to reduce consumption in peak hours and at the same time to save costs.

If the current hourly electricity 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 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 in between the thresholds, the set point is kept. 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 Elspot day-ahead market. [65]

4.8.2 Predictive price based control 2

The price-based control 1 is extended to the DHW and SH-tank. The set points there are raised or lowered by 3 K depending on the price signal described in 4.8.1

4.8.3 Rule based control 3

The heat generation system is control as described in chapter 4.6.4, only 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 - 9 am and $17 - 19$ pm. Consequently, the set point is decreased from $21°C$ to $19°C$ in these hours. In the time from $5 - 7$ am and 16 -17 pm the set point is increased to $23°C$. This peak hours present hours of high consumption for the average households in Norway [66]. Between these hours, the set point is $21°C$.

4.8.4 Rule based control 4

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

4.9 Evaluation criteria

- Heating needs for DHW and SH

  The sum of energy delivered to the heat distribution system, or used for domestic hot water.

- Electricity delivered in peak hours

  The hourly values of total electricity consumption in peak hours 7.00 - 9.00 and 17.00 – 19.00 are summed up and presented in kWh/m²a.

- Energy costs during operation without feed-in

  For each hour, total electricity consumption is multiplied with the current price data 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 consumption of 0.139 NOK/kWh were added. Consequently, the total average electricity price is 0.817 NOK/kWh, which is in line with [67]. 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 substracted from the current costs due to consumption. This is also done in hourly resolution.

- Grid interaction is characterized by the load cover factor and the supply cover factor

$$\gamma supply = \frac{\int_{t2}^{t1} \min(P_{PV}, P_d)dt}{\int_{t2}^{t1} P_{PV}dt}$$

$$\gamma load = \frac{\int_{t2}^{t1} \min(P_{PV}, P_d)dt}{\int_{t2}^{t1} P_d dt}$$

5 Results

The different versions are named according to the following principle:

Table 5-1: explanation of model naming

Heat distribution system	Control of the heating system	Doors open/closed
(AH) Air heating (FH) Floor heating (RAD) Radiator heating	(0) reference control (1)price based control 1 (2)price based control 2 (3)schedule based control 1 (4)schedule based control 2	(CD) Closed (OD)Open

5.1 Domestic electricity use and local PV production

Domestic electricity use comprises of the consumption of equipment, lighting and fans. The consumption of the fans is almost constant throughout the year with a mean value of 123.3 W. Annually, domestic electricity use amounts to around 41 kWh/m², which is about two-thirds of the total energy demand in the references cases.

The profile of equipment and lighting can be seen in chapter 4.4. Even though the peaks of consumption are in the morning (7:00 - 9:00) and in the evening (19:00 − 22:00), a supply cover factor (SCF) of 0.24 and a load cover factor (LCF) of 0.50 was found (domestic electricity use only). This emphasizes the importance of consumption patterns when evaluating the grid dependency. When only heating energy use is considered, both reference cases FH_0_CD and FH_0_OD showed LCFs of 0.26 as well as SCFs 0.06.

5.2 Evaluation of reference scenarios

The annual heating need for space heating and domestic hot water was found to be 73.0 kWh/m², 77.0 kWh/m² and 72.5 kWh/m² for the open door versions for air heating, floor heating and radiator heating, respectively. The floor heating versions stand out, because of higher transmission losses caused by the tempered slab. Nevertheless, the corresponding electricity consumption is lowest for floor heating, as the maximum system temperature is in general lower (38.2 °C) compared to air heating (58°C) and radiator heating (50°C).

The closed-door versions of floor heating and air heating show only small deviations from the open door versions as each zone is provided with the needed amount of heat. The radiator version shows clearly, that closed doors significantly reduce the transport of heat to the zones without heating device. The constant set point of 21°C is then reached faster and the heating power adjusted. In contrast, the closed-door air-heating version has a slightly higher heating demand, as the heat supplied in the Bedrooms is prevented from direct exchange with the other zones.

Table 5-2: results for the reference cases

Version	Heating demand	Heating energy use	Electricity Delivered peak hours	Energy costs during operation		Gird interaction indexes	
	[kWh/m²a]	[kWh/m²a]	[kWh/m²a]	w/o feed in	with feed in	load cover	supply cover
AH_0_OD	73.0	21.7	15.7	3527	2347	0.39	0.28
FH_0_OD	77.0	19.6	13.1	2935	2018	0.39	0.27
RAD_0_OD	72.5	21.8	15.9	3271	2148	0.39	0.28
AH_0_CD	74.8	22.7	15.9	3393	2275	0.38	0.28
FH_0_CD	74.4	19.6	13.0	3545	2399	0.38	0.27
RAD_0_CD	65.3	18.1	14.9	2994	1862	0.40	0.28

5.3   Evaluation of 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 consumption for each of the heat distribution systems. Compared to the reference cases, consumption rises 8%, 10% and 4% for AH, FH and RAD respectively (see table 5-4).

Peak hour consumption was reduced by 10% in the radiator version but only by 3% in the air heating and 6% in the floor-heating version. Nevertheless, this control approach also resulted in higher operational costs, as the increased set point is being kept at high level for long low price periods, which could not be balanced by cost savings due to lower prices.

The second price based control 2 also includes the DHW and the SH tank, consequently consumption and operational cost rise further. The reduction of consumption in peak hours is again best for the radiator system (18%), followed by the air heating system (9%). In the floor heating case however, consumption only decreased by 3%.

The schedule based changing of the zone set point could not successfully reduce electricity use in peak hours for the air-heating version, for the floor heating version the consumption even increases. In both cases, costs rise as well. In contrast, a reduction of 9 % was achieved in the radiator case even with smaller operational costs.

When DHW and SH is included the reduction of peak hour consumption is the most pronounced, but at the expense of higher costs and total consumption.

The effects on the cover factors are in general small as the control strategies did not focus on them. For example, the activation hours of the schedule based control are not in hours of high PV- generation.

Table 5-3: Results in total numbers

Version	Heating demand	Heating energy use	Electricity delivered peak ours	Energy costs during operation		Gird interaction indexes	
				w/o feed in	with feed in	load cover	supply cover
	[kWh/m²a]	[kWh/m²a]	[kWh/m²a]				
AH_0_OD	73.0	21.7	15.7	3294	2175	0.39	0.28
AH_1_OD	75.9	23.5	15.2	3531	2390	0.36	0.28
AH_2_OD	76.0	24.1	14.3	3632	2483	0.35	0.27
AH_3_OD	72.6	22.8	15.5	3416	2290	0.38	0.28
AH_4_OD	72.7	23.8	12.6	3527	2396	0.36	0.28
FH_0_OD	77.0	19.6	13.1	2935	2018	0.39	0.27
FH_1_OD	84.0	21.7	12.3	3321	2173	0.37	0.27
FH_2_OD	84.3	25.2	12.8	3658	2500	0.34	0.27
FH_3_OD	80.3	21.6	13.5	3309	2165	0.38	0.27
FH_4_OD	80.5	29.8	10.5	3990	2844	0.33	0.27
RAD_0_OD	72.5	21.8	15.9	3271	2148	0.39	0.28
RAD_1_OD	76.6	22.6	14.4	3352	2217	0.38	0.28
RAD_2_OD	76.7	23.6	13.1	3478	2333	0.36	0.27
RAD_3_OD	74.5	21.8	14.4	3236	2118	0.39	0.29
RAD_4_OD	74.6	26.4	11.5	3622	2505	0.37	0.29
AH_0_CD	74.8	22.7	15.9	3393	2275	0.38	0.28
AH_1_CD	76.8	23.7	15.4	3528	2171	0.37	0.24
AH_2_CD	77.0	24.3	14.3	3656	2508	0.35	0.27
AH_3_CD	74.1	23.2	15.6	3453	2329	0.37	0.28
AH_4_CD	74.1	24.3	12.6	3570	2443	0.36	0.28
FH_0_CD	74.4	19.6	13.0	3545	2399	0.38	0.27
FH_1_CD	80.4	21.2	12.1	3284	2136	0.37	0.27
FH_2_CD	80.4	26.0	12.8	3724	2565	0.34	0.27
FH_3_CD	77.6	19.5	12.7	3134	1991	0.39	0.27
FH_4_CD	77.6	30.6	10.6	4059	2915	0.33	0.27
RAD_0_CD	65.3	18.1	14.9	2994	1862	0.40	0.28
RAD_1_CD	69.3	17.9	13.8	2998	1854	0.40	0.27
RAD_2_CD	69.3	18.9	12.4	3124	1971	0.38	0.27
RAD_3_CD	67.5	17.9	14.0	2957	1826	0.41	0.28
RAD_4_CD	67.5	20.9	11.5	3209	2080	0.39	0.28

5.4   Influence of door opening

Door opening has little to no influence when the heating 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 area is naturally largely depending on the balancing effects of airflow through inner openings. For each control, heating needs for the closed-door cases are 10% smaller than the corresponding open door cases.

5.5   Discussion

The aim of this thesis was to evaluate 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 [29, 30] showed that differences between radiator and floor heating change with the age class of the building.

It should also be noted, that the building is not suitable for air heating. The heat loss of the envelope constructions can be considered too high. The ventilation rates had 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 will be very dry, humidification would be needed to ensure comfortable surroundings.

In general, it can be argued how the supply temperature for the heating systems should be calculated, as it is a trade-off between available power and system losses due to higher temperatures. In the current work, these temperatures were calculated in relation to the needed heat load for an indoor temperature of 23°C. That means, at any outdoor temperature there should be enough power to heat up the building to 23°C. Nevertheless, when this should happen in a short period of time, more power will be required. On top of that the schedule based controls only used heat-up and cool down periods of two hours, whereas longer periods would also be feasible. The differences between the systems are expected to change with duration.

The set up of the heating system with the 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 a large use of the backup heater. The size of the auxiliary heaters could also be reduced, because of the high nominal power of 9 kW and 3 kW. They are active for only a short time but lead to significant peaks in consumption. This also explains the peaks in consumption.

Table 5-4: Results in relation to the reference version

Version	Heating Demand	Heating energy use	Electricity delivered peak ours	Energy costs during operation w/o feed in	with feed in
	[kWh/m²a]	[kWh/m²a]	[kWh/m²a]		
AH_0_OD	1.00	1.00	1.00	1.00	1.00
AH_1_OD	1.04	1.08	0.97	1.00	1.02
AH_2_OD	1.05	1.11	0.91	1.03	1.06
AH_3_OD	1.00	1.05	0.99	0.97	0.98
AH_4_OD	1.00	1.10	0.80	1.00	1.02
FH_0_OD	1.00	1.00	1.00	1.00	1.00
FH_1_OD	**1.09**	1.10	0.94	1.13	1.08
FH_2_OD	1.09	1.28	0.97	1.25	1.24
FH_3_OD	1.04	1.10	1.03	1.13	1.07
FH_4_OD	1.05	**1.52**	0.81	**1.36**	**1.41**
RAD_0_OD	1.00	1.00	1.00	1.00	1.00
RAD_1_OD	1.06	1.04	0.90	1.02	1.03
RAD_2_OD	1.06	1.08	0.82	1.06	1.09
RAD_3_OD	1.03	1.00	0.91	0.99	0.99
RAD_4_OD	1.03	1.22	**0.72**	1.11	1.17
AH_0_CD	1.00	1.00	1.00	1.00	1.00
AH_1_CD	1.03	1.04	0.96	1.04	0.95
AH_2_CD	1.03	1.07	0.90	1.08	1.10
AH_3_CD	0.99	1.02	0.98	1.02	1.02
AH_4_CD	0.99	1.07	0.79	1.05	1.07
FH_0_CD	1.00	1.00	1.00	1.00	1.00
FH_1_CD	1.08	1.09	0.93	0.93	0.89
FH_2_CD	1.08	1.33	0.99	1.05	1.07
FH_3_CD	1.04	1.00	0.98	0.88	0.83
FH_4_CD	1.04	**1.57**	0.81	1.15	1.22
RAD_0_CD	1.00	1.00	1.00	1.00	1.00
RAD_1_CD	1.06	0.99	0.93	1.00	1.00
RAD_2_CD	1.06	1.04	0.83	1.04	1.06
RAD_3_CD	1.03	0.99	0.94	0.99	0.98
RAD_4_CD	1.03	1.15	0.78	1.07	1.12

6   Conclusion

Several simulation models were set up to evaluate the influence of the space heating distribution on energy flexibility. Two rule base controls were introduced and their effects on energy use and costs evaluated. In the air heating versions, the control strategies focus on charging the thermal mass and show little to no effect. One explanation might be the restriction of heating power due to the outdoor compensation curve, or the already very high system temperatures. The floor heating system shows the highest increases in heating energy use as well as costs. That is especially the case for the schedule based controls and the short heat up times. For strategies focusing on the activation of thermal mass, the consumption in peak hours was increased. The radiator system shows the best performance in terms of shifting loads without significantly increasing cost and energy consumption. However, the simplified distribution is sensitive to closed doors, which reduces the ability to shift loads, as it cannot directly activate the thermal mass in the other rooms.

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. A comparison between different floor heating systems (e.g. wet systems and dry systems) is also a point of interest.

The effect of the systems, when controls focusing on load matching are applied, was also not assessed in this study. However, the strong influence of not shiftable loads on the cover factors was illustrated.

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