Master's thesis

NTNU
Norwegian University of Science and Technology
Faculty of Engineering
Department of Energy and Process Engineering

Andrine Fardal, Inga Volle Sørensen and Synne Mo Samuelsen

Energy and climate concept for the development of a zero emission residential area - Determination of energy demands in the area

Master's thesis in Energy and Environmental Engineering
Supervisor: Natasa Nord
June 2023

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MASTEROPPGAVE

for

Andrine Fardal, Inga Volle Sørensen, Synne Mo Samuelsen

Vår 2023

Energi- og klimakonsept for utviklingen av et nullutslippsboligområde – analyse av energibehov for området

Energy and climate concept for the development of a zero emission residential area - determination of energy demands in the area

Bakgrunn

Framtidens energikrav til bygninger kommer til å bli strengere både når det gjelder energieffektivisering og krav til fornybare energikilder. I tillegg er det viktig å ha høye ambisjoner ved utviklingen av bygnings- og boligområder. Det skal bygges et nullutslippsboligområde på Tanberghøgda, som omfatter 600 nye boliger i en ny bydel i Hønefoss i Ringerike kommune. Fossen Utvikling AS utvikler all infrastruktur og alle uteområdene, helt frem til bygningskroppen. Målet med oppgaven er å definere passende bygningskonstruksjoner og tilhørende oppvarmingsløsninger for tre ulike bygningstyper, for å oppnå minimalt energiforbruk i nullutslippsboligområdet. Oppgaven fokuserer på energibehov og muligheter for reduksjon av energi- og effektbehov i det gitte området. Det skal defineres mulige og relevante energieffektiviseringstiltak for de ulike bygningstypene som analyseres. Programmet IDA ICE skal benyttes i oppgaven. Tidsprofiler for varme og elektrisitet skal analyseres. Det er viktig å finne både teknisk- og økonomisk optimal balanse mellom bruk og forsyning av varme og elektrisitet. Alle resultatene skal oppsummeres og analyseres. Masteroppgaven baseres på tidligere arbeid utført i prosjektoppgaven.

Mål

Målet med oppgaven er å definere passende bygningskonstruksjoner og tilhørende oppvarmingsløsninger for tre ulike bygningstyper, for å oppnå minimalt energiforbruk i nullutslippsboligområdet.

Oppgaven utarbeides fra følgende punkter:

1. Litteraturstudie med fokus på energibehov, ulike oppvarmingsløsninger, tekniske krav og installasjoner i bygninger og muligheter for reduksjon av energi- og effektbehov.
2. Samle informasjon om boligområdet på Tanberghøgda, inkludert hvilke bygningstyper som skal bygges, og definere et forslag til ulike bygningskonstruksjoner og oppvarmingssystemer.
3. Utvikle ulike modeller i simuleringsprogrammet IDA ICE for minst tre bygningstyper som skal bygges i området.
4. Analysere effekten av passivhus tiltak med fokus på reduksjon av energi- og effektbehov.
5. Analysere alle resultatene med hensyn på energieffektivitet, termisk komfort og økonomisk lønnsomhet, og foreslå passende anbefalinger basert på analysen.

Belastningen på masteroppgaven utgjør 30 studiepoeng.

Besvarelsen redigeres mest mulig som en forskningsrapport med innholdsfortegnelse, et sammendrag på norsk, konklusjon, litteraturliste, etc. Ved utarbeidelsen av teksten skal kandidaten legge vekt på å gjøre teksten oversiktlig og velskrevet. Med henblikk på lesing av besvarelsen er det viktig at de nødvendige henvisninger for korresponderende steder i tekst, tabeller og figurer anføres på begge steder. Ved bedømmelsen legges det stor vekt på at resultatene er grundig bearbeidet, og at de oppstilles tabellarisk og/eller grafisk på en oversiktlig måte og diskuteres utførlig.

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Leveringsfrist: *11.juni 2023*

☐ Arbeid i laboratorium (vannkraftlaboratoriet, strømningsteknisk, varmeteknisk)
☐ Feltarbeid

NTNU, Institutt for energi- og prosessteknikk, 15. januar 2023

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Prephase

This master's thesis was developed during the spring of 2023 at the Norwegian University of Science and Technology (NTNU) in Trondheim. The thesis was written for the Department of Energy and Process Engineering (EPT) in relation with the study program Energy and Environmental Engineering.

We would like to thank our supervisor, Natasa Nord, for the guidance and educational support during the execution of the thesis. Your academic proficiency and dedication have been crucial during this process, and the completion of this thesis would not have been possible without your help. Your valuable insight and constructive feedback have made an appreciated impact on our professional development.

Furthermore, we would like to express our appreciation to Fossen Utvikling AS for your support and academic input, in addition to your exceptional dedication to the development of the zero emission residential area at Tanberghøgda. Your commitment was truly inspirational.

Lastly, we would like to address a big appreciation to our families and friends who have always supported and motivated us.

Department of Energy and Process Engineering, NTNU Trondheim

7th of June 2023

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Abstract

In line with the significant consequences caused by climate change and global warming, the world is facing severe effects such as sea level rise, drought, and a higher frequency of global natural disasters. These effects are related to the increased greenhouse gas emissions, where the building sector accounts for approximately 40% of the energy-related carbon dioxide emissions. As a result, the green energy transition is a necessity to cope with the current climate crisis. Hence, measures reducing the energy demand in the building sector are essential to overcome this complex problem.

In an effort to reduce emissions from the building sector, zero emission neighborhoods have become a popular approach when new areas are developed. A zero emission neighborhood is a group of interconnected buildings with associated infrastructure located within a confined geographically defined area. The aim is to reduce the direct and indirect greenhouse gas emissions towards zero. To achieve this goal, building constructions and materials, as well as energy efficient heating solutions for a building, have to be carefully selected. This selection has to take the Norwegian regulatory framework "Byggteknisk forskrift" (TEK17), and standards like "Kriterier for passivhus og lavenergibygninger - Boligbygninger" (NS3700) into consideration. TEK17 defines regulations and technical requirements for construction work to ensure that projects comply with the technical standards for safety, environmental health and energy. NS3700 is a Norwegian standard that is used when passive houses and low energy buildings are developed.

This master's thesis explores a zero emission neighborhood, currently being developed at Tanberghøgda in Hønefoss. The residential area is the largest development area planned in the region in the last 50 years, where Fossen Utvikling AS is the responsible party for managing this project. The aim of this thesis was to define appropriate types of building constructions and respective heating solutions for three different building types, to achieve minimal energy consumption of the zero emission residential area.

The simulation tool IDA Indoor Climate and Energy (IDA ICE) was used to construct and simulate three different types of buildings; a single family house, a row house and an apartment building. The models were constructed to satisfy the energy requirements defined by TEK17 and NS3700. In addition, different heating solutions were considered, providing the basis for three different scenarios for space heating. Initially, ideal heaters were used to determine the size of potential heating systems, representing scenario 0. Further, two suitable systems, radiators and floor heating, were thoroughly explored to decide the most energy efficient heating solution. These represented scenario 1 and 2, respectively. Finally, the TEK17 and passive house models were compared to evaluate the impact of implementing passive house measures.

After analyzing the simulated results, it was found that all of the buildings experienced a decrease in energy demand of less than 10% when passive house measures were implemented. For building a passive house, the investment cost is approximately 300 000 - 367 000 NOK higher than for building a TEK17 house. In relation to the simulated results, saved costs between 500 - 3000 NOK/(unit year) were obtained with an electricity price of 1.888 NOK/kWh.

The payback period was calculated to be between 124 - 720 years for all the buildings analyzed. As a result, it was not possible to recoup the passive house investment costs within the building's expected lifetime of approximately 60 years. Considering the relatively low percentage reduction and the significant investment required, it is not advisable to invest in passive house measures in the project at Tanberghøgda.

The evaluated heating systems were compared with regard to high energy efficiency and thermal comfort. By replacing the radiators with floor heating, an increased heating demand of 60% and 72% occurred for the single family house and the row house, respectively. When a heat pump was implemented to the models with floor heating, a reduction of 51% for the single family house and 63% for the row house was obtained, compared to the floor heating models without a heat pump. Finally, the scenario with floor heating and a heat pump resulted in a reduction of 22% for the single family house and 36% for the row house, compared to the scenario with radiators. Based on these results, the scenario with floor heating and a heat pump was the most favorable, and is therefore the recommended heating solution for the buildings at Tanberghøgda.

Sammendrag

I tråd med de betydelige konsekvensene forårsaket av klimaendringer og global oppvarming, står verden ovenfor en alvorlig situasjon preget av blant annet havnivåstigning, tørke og en økende trend av globale naturkatastrofer. Disse hendelsene er knyttet til økte klimagassutslipp, hvor byggsektoren står for ca. 40% av de energirelaterte karbondioksidutslippene. Som et resultat er det grønne skiftet nødvendig for å takle den pågående klimakrisen. Derfor er tiltak som reduserer energibruken i byggsektoren avgjørende for å løse dette komplekse problemet.

I et forsøk på å redusere utslippene fra byggsektoren, har nullutslippsboligområder blitt en populær tilnærming når nye områder skal bygges. Et nullutslippsboligområde er en gruppe sammenkoblede bygninger med tilhørende infrastruktur som ligger innenfor et avgrenset geografisk definert område. Målet i dette området er å redusere de direkte og indirekte klimagassutslippene mot null. For å nå dette målet må bygningskonstruksjoner og materialer, samt energieffektive oppvarmingsløsninger for et bygg, velges nøye. Da må det norske regelverket "Byggteknisk forskrift" (TEK17), samt standarder som "Kriterier for passivhus og lavenergibygninger — Boligbygninger" (NS3700), bli tatt hensyn til. TEK17 definerer forskrifter og tekniske krav til byggverk for å sikre at prosjekter overholder de tekniske standardene for sikkerhet, miljøhelse og energi. NS3700 er den norske standarden som brukes når passivhus og lavenergibygg skal bygges.

Denne masteroppgaven er basert på et nullutslippsboligområde som skal utvikles på Tanberghøgda i Hønefoss. Dette boligområdet er det største utbyggingsområdet som er planlagt i regionen de siste 50 årene, hvor Fossen Utvikling AS er ansvarlig for dette prosjektet. Målet med denne oppgaven var å definere hensiktsmessige bygningskonstruksjoner og respektive oppvarmingsløsninger for tre ulike bygningstyper, for å oppnå lavest mulig energiforbruk i nullutslippsboligområdet.

Simuleringsverktøyet IDA Indoor Climate and Energy (IDA ICE) ble brukt til å konstruere og simulere modeller for hver bygningstype; en enebolig, et rekkehus og en boligblokk. Modellene er konstruert for å tilfredsstille energikravene definert i TEK17 og NS3700. I tillegg ble ulike oppvarmingsløsninger vurdert, hvilket la grunnlaget for tre ulike scenarioer for romoppvarming. I utgangspunktet ble ideelle varmeovner brukt for å bestemme størrelsen på potensielle varmesystemer, og dette representerte scenario 0. Videre ble to egnede systemer, radiatorer og gulvvarme, grundig utforsket for å bestemme den mest energieffektive oppvarmingsløsningen. Disse representerte henholdsvis scenario 1 og 2. Til slutt ble TEK17 og passivhusmodellene sammenlignet for å evaluere effekten av å implementere passivhustiltak.

Etter å ha analysert de simulerte resultatene, ble det funnet at alle bygningstypene opplevde en reduksjon i energibehovet på mindre enn 10% når passivhustiltak ble implementert. For et passivhus er investeringskostnadene omtrent 300 000 - 367 000 NOK høyere enn for et hus som tilfredsstiller TEK17 kravene. I de simulerte resultatene ble det oppnådd kostnadsbesparelser mellom 500 - 3000 NOK/(enhet år), med en strømpris på 1.888 NOK/kWh.

Den beregnede tilbakebetalingstiden var mellom 124 - 720 år for alle de analyserte bygningene. Som et resultat var det ikke mulig å tjene inn passivhusets ekstra investeringskostnader i løpet av bygningens forventede levetid på omtrent 60 år. Derfor kan ikke de lave energibesparelsene som ble oppnådd rettferdiggjøre de høye investeringskostnadene forbundet med å bygge passivhus. Med tanke på den relativt lave prosentvise reduksjonen og den betydelige investeringen som kreves, er det dermed ikke anbefalt å investere i passivhustiltak i prosjektet på Tanberghøgda.

De vurderte oppvarmingsløsningene ble sammenlignet med hensyn til høy energieffektivitet og termisk komfort. Ved å erstatte radiatorer med gulvvarme økte oppvarmingsbehovet med 60% og 72% for henholdsvis eneboligen og rekkehuset. Når en varmepumpe ble implementert i modellene med gulvvarme, oppnådde man en reduksjon på 51% og 63% sammenlignet med modellene med gulvvarme uten varmepumpe. Dette gjaldt for henholdsvis eneboligen og rekkehuset. Til slutt førte scenariet med gulvvarme og varmepumpe til en reduksjon på 22% for eneboligen og 36% for rekkehuset, sammenlignet med scenariet med radiatorer. Basert på disse resultatene var scenariet med gulvvarme og varmepumpe det mest gunstige, og er derfor den anbefalte oppvarmingsløsningen i bygningene på Tanberghøgda.

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1 Introduction

The introduction will include a description of the background, motivation and goal, framework and scope, as well as the structure of the master's thesis.

1.1 Background

Today the world is facing severe effects due to human caused climate change. It is anticipated that greenhouse gases produced by humans will continue to increase the global temperature. As a result, consequences such as sea level rise and more extreme weather events will occur. According to the report "2018 Global Status Report" made by International Energy Agency (IEA) for the Global Alliance for Buildings and Construction[1], building construction and operations accounted for 36% of global final energy use and nearly 40% of energy related carbon dioxide (CO_2) emissions in 2017. This means that a significant share of the total greenhouse gas emissions comes from the building sector. Therefore, improvements and measures in this sector are crucial for the clean energy transition. This has resulted in increased awareness of energy efficiency in buildings, with the necessity for a comprehensive approach.

This master's thesis is related to the concept study "Energi- og klimakonsept for Tanberghøgda, Hønefoss, 31.januar 2022" performed by COWI[2]. The project at Tanberghøgda is directed by Fossen Utvikling AS, which will be the developer of all infrastructure in this residential area[3]. Based on this study, models for a single family house, a row house and an apartment building were developed for the zero emission neighborhood. In addition, solutions for building constructions, materials, schedules and setpoints were defined and evaluated. Further, three different scenarios for space and domestic hot water heating were studied and compared.

The thesis is based on earlier work conducted in the project assignment[4]. It serves as a continuation and expansion of the previous findings, providing a more comprehensive analysis of the subject matter.

1.2 Motivation and goal

The aim of this thesis was to define appropriate types of building constructions and respective heating solutions for three different building types, to achieve minimal energy consumption of the zero emission residential area. The motivation behind this master's thesis was the energy and environmental crisis the world is facing today, involving the ongoing global energy poverty and climate change.

Further, this study had a particular focus on the impact from the building sector. The goal was to construct three different types of buildings; a single family house, a row house and an apartment building. The aim was to analyze the total energy demand for these building types and evaluate how different building constructions and heating solutions would influence the demand. Furthermore, ensuring a satisfactory indoor environment was prioritized. Due to the goal defined by Fossen Utvikling AS of developing a zero emission neighborhood, the models were constructed to satisfy the requirements defined by the regulatory framework "Byggteknisk forskrift" (TEK17), as well as passive house requirements defined in the standard "Kriterier for passivhus og lavenergibygninger - Boligbygninger" (NS3700).

1.3 Framework and scope

The construction project planned at Tanberghøgda is large and complex, encompassing many different elements. As this master's thesis involved limitations in relation to time, a suitable framework and scope had to be determined. Firstly, the project was narrowed down to three types of buildings; a single family house, a row house and an apartment building. Since Fossen Utvikling AS was still in the preconstruction phase when this thesis was conducted, the building constructions at Tanberghøgda were not yet developed. It was therefore decided that the scope should include a suggested solution for specific building designs and constructions for the three building types considered. An analysis of the energy and power demands for the buildings was also included in the scope. This analysis was used to reduce the total energy demands by implementing different measures.

1.4 Structure

This thesis is divided into 8 main sections, as described below.

Section 1 - Introduction
Description of the background, motivation and goal, framework and scope, and the structure of the thesis.

Section 2 - Literature review
A literature review was carried out to obtain relevant theory.

Section 3 - Method
Description of the simulation tool, the model development, and the theoretical background used.

Section 4 - Building site
Description of the studied building area as well as information and illustrations of the three building types.

Section 5 - Building construction
Description of standard principles for constructing the opaque walls, roof, floor, and windows based on TEK17 and NS3700.

Section 6 - Simulation background
Presents the general input parameters for the IDA ICE models, as well as the chosen building structure for the TEK17, the Hunton and the passive house models.

Section 7 - Results and discussion
Presents and analyzes the simulation results to determine suitable recommendations.

Section 8 - Conclusion
Presents the conclusion of the thesis.

2 Literature review

The literature review contains relevant theory based on research, creating the basis for the execution of the thesis.

2.1 Byggteknisk forskrift

The regulatory framework ”Byggteknisk forskrift” (TEK17) defines regulations and technical requirements for construction work[5]. According to Direktoratet for byggkvalitet[6], the purpose of the regulation is intended to ensure that projects are planned, designed, and executed based on good visual aesthetics, universal design, and in a manner that ensures that the project complies with the technical standards for safety, environmental health and energy.

2.2 Hunton

Fossen Utvikling AS has developed a collaboration with Hunton for the construction materials of the buildings at Tanberghøgda. Hunton is a manufacturer of building materials mainly based on wood and wood fibers, with a strong focus on sustainability[7]. Wood and wood fibers have a low carbon footprint, as the products are made of renewable raw materials. Hunton suggests building solutions for opaque walls, floors and roofs that satisfy the regulations and technical requirements defined in TEK17. Further, Hunton specifically chooses construction materials that correspond to the building's expected lifetime of 60 years[8].

2.3 Passive houses

A passive house is an energy efficient building with a particular construction that typically features well insulated walls, improved airtightness to prevent air leakage, and reduction of thermal bridges[9]. Passive houses are acknowledged as high quality structures with comfortable indoor environments and low energy consumption. Passive measures are used to lower the energy consumption of the building, which is the reason for the name ”passive house”. Norway has its own standards for passive houses, and these requirements have been modified to fit the Norwegian climate. Passive house requirements for residential buildings are covered by the standard ”Kriterier for passivhus og lavenergibygninger — Boligbygninger” (NS3700)[10].

The construction of passive houses can present a challenge in terms of investment costs. Consequently, these high costs may make building a passive house excessively expensive. According to a study performed by ZEN Research Centre[11], the investment cost for a passive house is approximately 300 000 - 367 000 NOK higher than for a TEK17 house. In this particular study, the implementation of passive house measures led to a cost saving of 5 700 - 6 000 NOK each year, when an electricity price of 1.888 NOK/kWh was used. With this, it was not possible to recoup the investment costs during the buildings' expected lifetime of approximately 60 years.

2.4 Zero Emission Buildings

A definition of Zero Emission Buildings (ZEB) has been created by the Norwegian Research Centre on Zero Emission Buildings based on earlier and ongoing work carried out by the International Energy Agency (IEA) and the revised Energy Performance Building Directive (EPBD)[12]. According to the Research Centre on Zero Emission Buildings, ZEB is defined as a building that produces enough renewable energy to compensate for the building's greenhouse gas emissions over its lifetime.

2.5 Zero Emission Neighborhoods

According to The Research Centre on Zero Emission Neighborhoods (FME ZEN) the definition of a Zero Emission Neighborhood (ZEN) is a group of interconnected buildings with associated infrastructure located within a confined geographically defined area, aiming at reducing its direct and indirect greenhouse gas emissions towards zero[13]. NTNU is the host of FME ZEN and cooperated with SINTEF in their research on environmentally friendly energy and innovative development[14]. The research center is established by the Research Council of Norway.

2.6 The concept study by COWI

The concept study for Tanberghøgda was carried out by COWI in 2022. It contains an energy and climate concept for the neighborhood, including ambitious goals to reduce the power and energy demand in addition to reducing greenhouse gas emissions. The energy and climate concept for the development of this residential area can be found in the report "Energi- og klimakonsept for Tanberghøgda, Hønefoss, 31.januar 2022"[2]. The zero emission neighborhood will consist of 600 new buildings. The planned building types are displayed in Table 2.1. According to this study, all of the buildings at Tanberghøgda should have hydronic heating as space heating. For the single family houses, heat is planned to be supplied by air-to-water heat pumps, while district heating is considered for the rest of the building types.

Table 2.1: Building types and their corresponding areas.

Type of building	**Number of units**	**Number of buildings**	**Total area [m^2]**	**Area per unit [m^2/unit]**
Single family house	17	17	2 890	170
Row house	29	8	2 610	90
Apartment building	251	30	17 570	70
Kindergarten	1	1	1 000	1 000
Attached house	183	37	16 470	90

2.7 Air Handling Unit

An air handling unit, also called AHU, is a device that conditions and distributes air within a building[15]. Higher requirements for the building's airtightness and envelope have introduced the necessity to maintain an adequate indoor environment by the use of an AHU[16]. Therefore, this is important to consider in a construction with high airtightness, like a passive house.

Typical components in an AHU are supply and exhaust fans, a heat recovery unit, filters, a heating coil, a cooling coil and a silencer. The supply fan expels the air from the AHU to the ducts in order to distribute the air throughout the rooms. The exhaust fan extracts the polluted air from inside the rooms and then transfers it through the heat recovery unit, before it is discharged to the atmosphere. The heat recovery unit, which is a heat exchanger, transfers heat between the extracted air and the outside air. According to TEK17 "§ 14-2. Krav til energieffektivitet", the efficiency of a heat exchanger should be larger than 80%[5].

2.8 Airflow

Minimum requirements for airflow rates in residential buildings are defined in TEK17 "§ 13-2. Ventilasjon i boligbygning"[5]. Residential buildings during occupancy hours must supply an average minimum airflow rate of 1.2 m^3/h per m^2 gross floor area, while rooms that are not intended for permanent occupancy must have a minimum airflow rate of 0.7 m^3/h per m^2 gross floor area. The minimum requirement for the airflow rate in a bedroom is 26 m^3/h per bed. The minimum airflow rates for a kitchen and a bathroom are 36 m^3/h and 54 m^3/h, respectively.

2.9 Indoor temperatures

A sufficient indoor temperature is important for both the indoor environment in a building, and for the health of the occupants. By controlling the indoor temperature, the energy consumption can be reduced. There are different recommended temperature levels that can be implemented. According to Folkehelseinstituttet (FHI)[17], the indoor temperature is recommended to be at a level between 20 - 24°C during the winter season and 23 - 26°C during the summer season. However, it is usually preferred to have a colder indoor temperature in specific rooms of a building, like the bedrooms and corridors. Fjordkraft (FK) has recommended certain temperature levels for various zones in a building[18]. These temperature levels are presented in Table 2.2.

Table 2.2: Recommended indoor temperatures by FK.

Room	**Temperature [°C]**
Bedroom	16 - 18
Corridor	16 - 18
Bathroom	22 - 24
Kitchen/Living room	20 - 22

2.10 Pollution level

According to FHI[19], there are several connections between high pollution levels of CO_2 and health problems. To ensure a comfortable and safe indoor environment, the level of CO_2 must not exceed the recommended limit of 1000 ppm.

2.11 Relative humidity

Relative humidity is defined as the ratio between the absolute humidity of the air and the humidity required to achieve saturation at a given temperature. It is therefore a measure of the amount of water vapor in the air[20]. Too high or low humidity is a severe problem for the indoor environment, and can cause health problems. According to Nemitek[21], it is recommended to have a relative humidity between 30 - 70% in residential buildings. This is the same as 5 - 12 g of water per kg dry air with an indoor air temperature of 22°C.

2.12 Domestic hot water

A domestic hot water system is a system that delivers hot water to different appliances, like for instance a sink, a bathtub or a shower[22]. A domestic hot water system usually consists of a centralized storage tank separate from the water used for space heating. According to Table A.10 in the standard ”Bygningers energiytelse” (NS3031)[23], the total annual energy demand for domestic hot water is 25 kWh/(m^2year). This applies to buildings in the category ”småhus” and ”boligblokk”.

2.13 Thermal bridges

A thermal bridge is defined as an area with increased heat loss due to connections between two or more building parts. The construction and the materials included in the connections are factors that affect heat loss through a thermal bridge[24]. To reduce the heat loss, minimal thermal bridges are necessary in order to get an energy efficient building. A solution is to have a thermal break, which is to insulate the outside of the building part that causes the thermal bridge[25].

Thermal bridges can have different consequences, such as increased heat loss and energy demand, low surface temperatures, condensation, reduced thermal comfort, downdraft effect, and temperature differences[24]. The maximum normalized thermal bridge value that satisfies TEK17 is 0.05 W/(m^2K). For passive houses, the maximum normalized thermal bridge value is 0.03 W/(m^2K)[10].

2.14 Hydronic heating systems

According to Enova[26], hydronic heating systems are systems where water is used as an energy carrier. Heat is distributed through pipes from a heat source to a heating unit. Two commonly considered heating units when constructing a new building are radiators and a hydronic radiant floor system. Therefore, these two systems were reviewed.

Radiators

A radiator is a water based heat exchanger, transferring heat from the water to the room. In other words, it combines natural convection and radiation[27]. Radiators have a shut-off valve to interrupt the water flow, a vent and a manual control valve or a thermostatic valve. As a consequence of their small heat emitter area, radiators require higher water temperatures. The design temperature levels are either 80/60°C, 70/50°C, or 60/40°C.

Radiators are usually installed below windows to counteract the downdraft effect. This way, the rising hot air will meet the falling cold air, directly counteracting the downdraft. Since there is air circulation from the window, the hot air is evenly mixed and distributed in the room. This makes the air temperature distribution more uniform in the room and the heating more efficient.

Hydronic radiant floor system

A hydronic radiant floor system distributes heat to the rooms in a building through pipes embedded in the floor construction. The water in the pipes is heated by a heat source, before being distributed through the pipes. The heat can be delivered by sources such as district heating, heat pumps, or bio-boilers.

Factors that affect the supply flow temperature are the construction of the floor, the floor's surface temperature and the heat power demand of the building. Uneven surface temperatures can result in local thermal discomfort. To avoid this problem, it is important to choose a correct laying pattern, and to have a temperature drop lower than 5°C between the supply and return temperatures. The heat transfer from a hydronic radiant floor is typically around 20 - 70 W/m^2, where the lower end of this range is adequate for new and well insulated buildings[28]. A floor can emit approximately 10 W/m^2 for each degree difference between the floor's surface temperature and the air temperature. This means that the surface temperature of the floor must be 2 - 3 °C higher than the desired room air temperature in new buildings[29].

According to Byggforskserien[30], two alternatives are considered for a hydronic radiant floor system. The first alternative is a floor system with heating pipes embedded in the insulation layer, which typically has a quick response time. The other alternative is a floor system with heating pipes embedded in the thermal diffusion layer. This option will normally result in better heat distribution, but is known to have a slower response time. In addition, humidity in the floor construction can also occur with this alternative.

The energy consumption of a building might be reduced by the implementation of a hydronic radiant floor system[31]. This is because floor heating provides a more even distribution of heat. A lower indoor air temperature can therefore be allowed, and it is possible to reduce the temperatures in the zones by 2°C and still maintain thermal comfort.

With floor heating, the heat is felt where it is most needed; the lower part of the body. Having warm feet and a cool head is the ideal heat distribution for humans, and can only be achieved by using floor heating[32]. It is preferable to have a temperature of around 18 - 20°C for the head, and between 23 - 24°C for the feet.

2.15 District heating

District heating is a hydronic system that transfers heat in urban areas with high and consistent heat demands[33]. It is a commonly used heating system in many cities in Norway, including Hønefoss. The system is used for space heating and stored heat systems. The heating system consists of a distribution network of pipes that transfers heated supply water from the heat source to the consumers. According to Statkraft[34], the district heating system utilizes surplus renewable energy from local sources such as bio-fuels, waste, and waste heat from industry. For the project at Tanberghøgda, it is considered utilizing district heating from Vardar Varme AS[2]. Another option is to implement a localized district heating system that incorporates a dedicated bio boiler to serve the neighborhood.

2.16 Heat pumps

In the project at Tanberghøgda, it is considered to have air-to-water heat pumps installed in the single family houses[2]. According to Keith E. Harold in the book "Absorption chillers and heat pumps"[35], a heat pump is a technology that transfers heat from a low temperature to a high temperature. To make this happen, heat pumps are powered by electrical energy.

A heat pump consists of four main elements; an evaporator, a compressor, a condenser, and an expansion valve[36]. In the evaporator, the working fluid absorbs heat from the heat source and evaporates at low pressure and temperature. Further, it is compressed to superheated vapor at higher pressure and temperature in the compressor[37]. The heat from the working fluid is rejected to the heating system by condensation in the condenser. The pressure and temperature of the working fluid are then reduced in the expansion valve, where the state of the working fluid is liquid/vapor.

The coefficient of performance, COP, is a measurement of the energy utilization of the heat pump[38]. It is defined as the ratio of rejected heat from the condenser, Q, to the supplied electric power into the compressor, W. The equation for COP is given in Equation 2.1.

$$COP = \frac{Q}{W} \tag{2.1}$$

The efficiency of an air-to-water heat pump increases as the required water flow temperature decreases. In other words, the operation of the heat pump is more efficient when the heating system has low temperatures. Floor heating systems have a large heat exchange surface, which makes it possible to run at low temperatures. Floor heating and air-to-water heat pumps are therefore considered a good combination. Radiators, on the other hand, have a smaller heat emitter area, and consequently require higher water temperatures. Radiators and air-to-water heat pumps are therefore not as energy efficient as the combination with floor heating[39].

3 Method

This section contains a description of the simulation tool, the model development, and the theoretical background used to determine the energy demands in the residential area.

3.1 IDA Indoor Climate and Energy

The simulation tool used in this study is a simulation application called IDA Indoor Climate and Energy (IDA ICE). This is a simulation program used to examine the indoor thermal climate and the energy consumption of complete building structures. IDA ICE is modified to meet local requirements such as climate data, standards, special systems, special reports, products, and material data[40]. The program is well suited for transferring data to Excel in order to create figures and tables that represent the results in a clear way.

3.2 Model development

Since the building constructions for the zero emission neighborhood at Tanberghøgda were not yet established, a model for a single family house, a row house and an apartment building had to be developed. First of all, a proposal for the design of the three building types with associated floor plans was created. Further, the construction of the opaque walls, roof, floors, and windows was defined with regard to satisfying the requirements in TEK17. A suggestion for models satisfying the requirements for a passive house was also defined. The final models were then implemented in IDA ICE.

The models were simulated using an ideal heater with an efficiency of 1 in each zone. The annual energy demands, as well as the indoor temperature distributions for the different zones, were established. Further, the ideal heater for each zone was replaced by the chosen heating unit for the specific building.

According to the report performed by COWI[2], all of the buildings at Tanberghøgda should have a hydronic radiant floor system. However, radiators were initially introduced in order to evaluate their performance in comparison to a hydronic radiant floor. The radiators were first sized based on the peak power demands for heating found from the models with ideal heaters. Further, the models were simulated several times with the purpose of finding the optimal heat rate for each radiator. This resulted in reduced heat rates and the removal of radiators in some rooms, and was performed to avoid over-dimensioning of the radiators.

The radiators were then removed, and a hydronic floor was implemented in specific zones in the models. The hydronic radiant floor was sized according to Byggforskserien, as described in the section "Hydronic heating systems". An air-to-water heat pump was also implemented in combination with the floor heating to reduce the energy consumption for heating.

Finally, the models with radiators and with floor heating were compared to find the most optimal heating solution. The results from the simulations of the TEK17 and the passive house models were also compared. The aim was to establish the reduction in energy demand after passive house measures were implemented.

3.3 Theoretical background

The following section contains the theoretical background and equations relevant to the execution of the thesis.

U-value

According to Byggforskserien[41], the U-value is defined as the amount of heat transferred per time unit through an area of 1 m^2 at a constant temperature difference of 1K between the surroundings on the hot and cold side of the construction. The U-value therefore specifies the ability a building component has to transfer heat. The unit associated with the U-value is $W/(m^2K)$.

To calculate the U-value for a construction, the total thermal resistance must be determined. According to Byggforskserien[41], thermal resistance is defined as the measure of how well a material insulates against heat transfer. The thermal resistance of construction layer i is calculated by using Equation 3.1, where d_i is the thickness and λ_i is the thermal conductivity of construction layer i. Thermal conductivity is measured by a material's ability to conduct heat. The material has good thermal insulation properties if the thermal resistance is high or the thermal conductivity is low. The total U-value can be calculated by using Equation 3.3, where R_{Tot} is the total thermal resistance calculated by using Equation 3.2. R_{si} and R_{se} is respectively the internal and external thermal surface resistances.

$$R_i = \frac{d_i}{\lambda_i} \quad [(\mathrm{m}^2\mathrm{K})/\mathrm{W}] \tag{3.1}$$

$$R_{Tot} = \sum_i \frac{d_i}{\lambda_i} + R_{si} + R_{se} \quad [(\mathrm{m}^2\mathrm{K})/\mathrm{W}] \tag{3.2}$$

$$U_{Tot} = \frac{1}{R_{Tot}} \quad [\mathrm{W}/(\mathrm{m}^2\mathrm{K})] \tag{3.3}$$

Surface resistances

The conventional surface resistances for plane surfaces were selected based on the standard "Building components and building elements — Thermal resistance and thermal transmittance — Calculation methods"[42]. These surface resistances apply to surfaces that are in contact with air. Surfaces that are in contact with other materials, such as soil for the ground floor, do not have a surface resistance that applies. According to the standard, the internal surface resistances are calculated with regard to an indoor temperature of 20°C and an epsilon, ϵ, equal to 0.9. For the external surface resistances, the values are calculated with regard to an external temperature of 10°C, a velocity of 0.4 m/s, in addition to the same value for epsilon, ϵ. In Table 3.1, the conventional surface resistances are displayed.

Table 3.1: The conventional surface resistances.

Surface resistance $[(\mathrm{m}^2\mathrm{K})/\mathrm{W}]$	**Upwards**	**Horizontal**	**Downwards**
Internal: $\mathbf{R_{si}}$	0.10	0.13	0.17
External: $\mathbf{R_{se}}$	0.04	0.04	0.04

Requirements for energy efficiency

Requirements for energy efficiency are given in TEK17 ”§14-2. Krav til energieffektivitet”[5]. For apartment buildings, the maximum allowed energy demand is 95 kWh/(m^{2}year). For the category ”småhus”, which includes building types such as single family houses and row houses, the maximum allowed energy demand, Q_E, is calculated with Equation 3.4, where GFA is the heated gross floor area.

$$Q_E = 100 + \frac{1600}{\text{GFA}} \quad [\text{kWh/(m}^2\text{year)}] \tag{3.4}$$

According to Table 3 in NS3700[10], the highest calculated maximum net energy demand for space heating of a passive residential building is 15 kWh/(m^{2}year). This applies to buildings with a heated gross floor area larger than 250 m^2, and with an annual mean outdoor temperature larger than 6.3°C. According to Table A.1 in NS3700[10], the maximum annual net energy demand for lighting, electrical equipment and domestic hot water is a total of 58.7 kWh/(m^{2}year) for a passive residential building.

Minimum requirements for energy efficiency are defined in TEK17 and NS3700 for TEK17 buildings and passive houses, respectively, and are displayed in Table 3.2 and Table 3.3.

Table 3.2: Minimum energy requirements for TEK17 residential buildings.

Parameter	**Description**	**Minimum requirement ”småhus”**	**Minimum requirement ”boligblokk”**	**Unit**
$\mathbf{U_{opaque}}$	U-value opaque wall	≤0.18	≤0.18	W/(m^{2}K)
$\mathbf{U_{roof}}$	U-value roof	≤0.13	≤0.13	W/(m^{2}K)
$\mathbf{U_{floor}}$	U-value floor	≤0.1	≤0.1	W/(m^{2}K)
$\mathbf{U_{windows/doors}}$	U-value windows and doors	≤0.8	≤0.8	W/(m^{2}K)
$\mathbf{\frac{A_{w/d}}{GFA}}$	Share of window and door area of heated GFA	≤25	≤25	%
$\boldsymbol{\eta_{50}}$	Airtightness at 50 Pa pressure difference	≤0.6	≤0.6	h^{-1}
$\boldsymbol{\psi}$	Normalized thermal bridge value, where m^2 is the heated GFA	≤0.05	≤0.07	W/(m^{2}K)
SFP	Specific fan power	≤1.5	≤1.5	kW/(m^3/s)

Table 3.3: Minimum energy requirements for passive houses.

Parameter	**Description**	**Passive house requirements**	**Unit**
$\mathbf{U_{opaque}}$	U-value opaque wall	0.1 - 0.12	$W/(m^2K)$
$\mathbf{U_{roof}}$	U-value roof	0.08 - 0.09	$W/(m^2K)$
$\mathbf{U_{floor}}$	U-value floor	$\leq$0.08	$W/(m^2K)$
$\mathbf{U_{windows/doors}}$	U-value windows and doors	$\leq$0.8	$W/(m^2K)$
$\boldsymbol{\eta_{50}}$	Airtightness at 50 Pa pressure difference	$\leq$0.6	h^{-1}
$\boldsymbol{\psi}$	Normalized thermal bridge value, where m^2 is the heated GFA	$\leq$0.03	$W/(m^2K)$
SFP	Specific fan power	$\leq$1.5	$kW/(m^3/s)$

Solar transmittance

Solar transmittance is the fraction of incident light that is transmitted through a window[43]. The solar transmittance, τ, can be calculated by using Equation 3.5, where ρ is the solar reflection factor, and α is the solar absorption factor.

$$\tau = 1 - \rho - \alpha \quad [-] \tag{3.5}$$

Daylight requirements

Rooms with continuous occupancy have specific daylight requirements defined in TEK17 "§ 13-7. Lys"[5]. For the different rooms in a building, the daylight requirement can be fulfilled by using Equation 3.6. A_{wp} is the window pane area 0.8 m above the floor level, GFA is the gross floor area and VT is the visible transmittance.

$$A_{wp} \geq 0.07 \cdot \frac{GFA}{VT} \quad [m^2] \tag{3.6}$$

Specific heat capacity

The specific heat capacity, c, is defined as the quantity of heat that is necessary to increase the temperature of the mass with 1 °C[44]. The unit associated with c is J/(kgK). The equation for the specific heat capacity is given in Equation 3.7, where Q is the thermal energy, m is the weight and ΔT is the temperature difference of the mass.

$$c = \frac{Q}{m \cdot \Delta T} \quad [J/(kgK)] \tag{3.7}$$

The thermal energy, Q_R, represents the amount of heat emitted when radiators are used. Equation 3.8 emphasizes the fundamental concept that radiators effectively transmit heat directly to the indoor air.

$$Q_R = (\frac{c \cdot m \cdot \Delta T}{3600})_{air} \quad [Wh] \tag{3.8}$$

The thermal energy, Q_{FH}, represents the amount of heat emitted when floor heating is used, and is given in Equation 3.9. The utilization of floor heating results in direct heating of internal walls and masses, thereby effectively heating the indoor air as well. Due to the term related to internal heat transfer, floor heating can potentially result in a larger amount of heat emitted, compared to the situation with radiators.

$$Q_{FH} = (\frac{c \cdot m \cdot \Delta T}{3600})_{air} + (\frac{c \cdot m \cdot \Delta T}{3600})_{internal} \quad \text{[Wh]} \tag{3.9}$$

Infiltration

Infiltration is defined as the unintentional introduction of outside air into a building, caused by pressure differences between the internal and external environments of a building[45]. The air typically flows through cracks in the building envelope. The infiltration can have a considerable impact on the energy demand of a building, especially on the heating demand. TEK17 requires an airtightness, n_i, below 0.6 h^{-1}[5]. The infiltration heat loss is calculated with Equation 3.10[46]. C is the heat capacity of the air, which is 0.33 $\text{Wh/(m}^3\text{K)}$, V is the room volume, while t_i and t_e are the indoor and outdoor air temperatures.

$$H_i = C \cdot n_i \cdot V \cdot (t_i - te) \quad \text{[W]} \tag{3.10}$$

Transmission heat loss

The transmission heat loss is the total heat loss through the building envelope caused by a temperature difference between the indoor and outdoor air[46]. The heat loss is affected by the area and U-value of the building component, and is proportional to the temperature difference over the building component. The transmission heat loss is calculated with Equation 3.11. A_j and U_j are the area and the U-value of building component j, while t_i and t_e are the indoor and outdoor air temperatures.

$$H_T = \sum_j (A_j \cdot U_j \cdot (t_i - t_e)) \quad \text{[W]} \tag{3.11}$$

Payback period

The payback period, denoted as PBP, represents the duration required to recoup the initial investment costs, and is commonly regarded as the period during which the investment carries a certain level of risk. This parameter can be used as an indicator to evaluate the benefits of various energy systems. Hence, the energy system becomes more economically beneficial when the payback period is shorter. The calculation method for the payback period does not consider the concept of the time value of money[47]. Consequently, a simple equation can be used to determine the payback period, as seen in Equation 3.12. PBP is the payback period, I is the initial investment costs and C_t is the cash inflow or annual savings.

$$PBP = \frac{I}{C_t} \quad \text{[years]} \tag{3.12}$$

4 Building site

This section contains a description of the studied residential area, as well as information of the building types with an overview of the gross floor areas of the different zones.

4.1 Tanberghøgda

Fossen Utvikling AS is developing a zero emission neighborhood at Tanberghøgda in Hønefoss. Tanberghøgda is located in Krakstadmarka, Hønefoss Øst, approximately one hour drive from Gardemoen, Oslo. This area is the largest development area planned in the region in the last 50 years[48]. The zero emission neighborhood will consist of 600 new buildings. The planned building types for the project are displayed in Table 2.1 in the section "The concept study by COWI" in the literature review.

The building site is illustrated in Figure 4.1[49]. Tanberghøgda is located close to the city center of Hønefoss, which has everything a neighborhood needs like a hospital, an arena, and several schools. Since Hønefoss is relatively close to Gardemoen, Oslo, it was assumed that the climatic conditions at Tanberghøgda are similar to those there.

Figure 4.1: The building site[49].

An overview of the residential area with the single family houses marked in blue, the row houses marked in orange and the apartment buildings marked in green is illustrated in Figure 4.2.

Figure 4.2: An overview of the residential area[49].

4.2 Building types

This section presents the three different building types studied in this thesis; a single family house, a row house and an apartment building. The buildings were designed and constructed in the simulation tool IDA ICE.

Single family house

A model from IDA ICE of the single family house is presented in Figure 4.3.

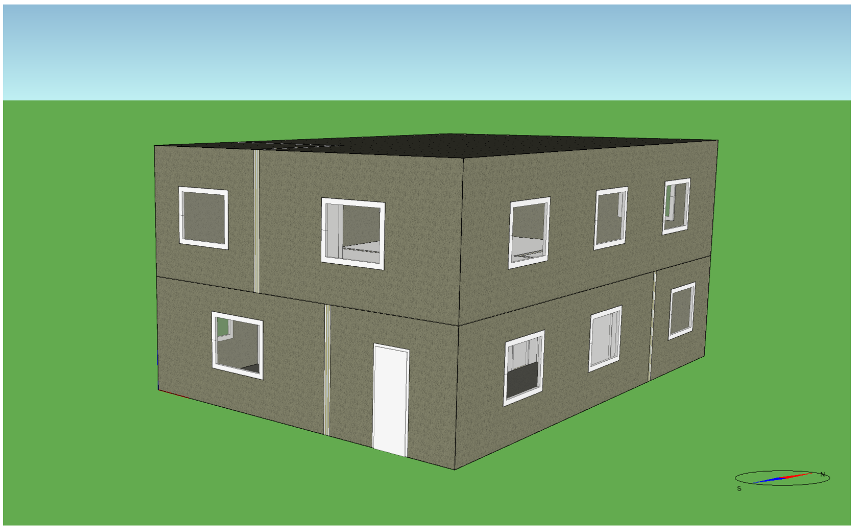


Figure 4.3: Model of the single family house.

The floor plans for the ground and first floor are illustrated in Figure 4.4(a) and Figure 4.4(b), respectively.

((a)) Ground floor. ((b)) First floor.

Figure 4.4: Floor plan for the single family house.

According to the report performed by COWI[2], the single family house will have a total gross floor area of 170 m^2. A simplified building model was therefore developed with a total gross floor area of 174.6 m^2. Table 4.1 displays the gross floor area for the different zones in the singe family house.

Table 4.1: Overview of the gross floor area of the different zones in the single family house.

Type of room	**GFA [m^2]**
Bedroom 1	15.57
Bedroom 2	13.72
Bedroom 3	22.52
Corridor	22.85
Bathroom 1	11.27
Bathroom 2	7.433
Living room/kitchen	81.27
Total	**174.60**

Row house

A model from IDA ICE of the row house is presented in Figure 4.5.

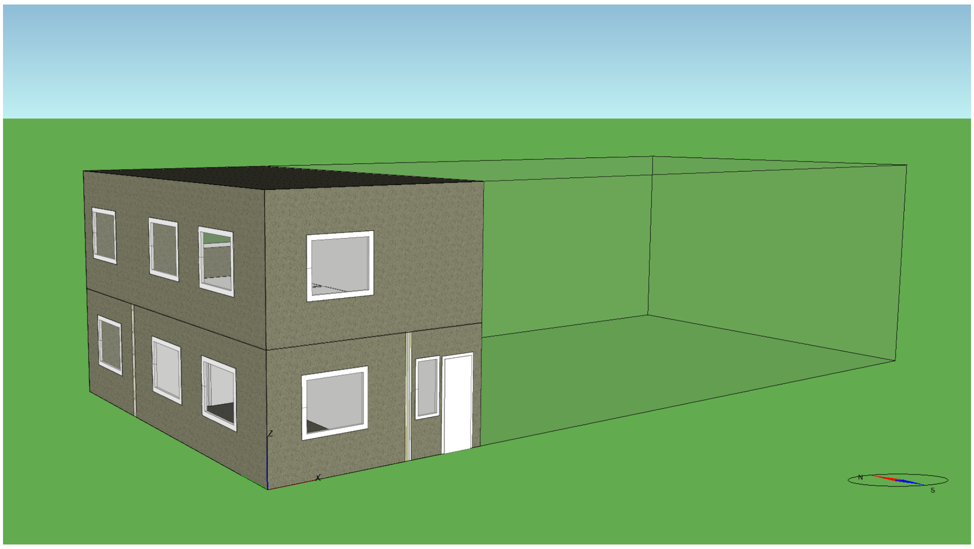
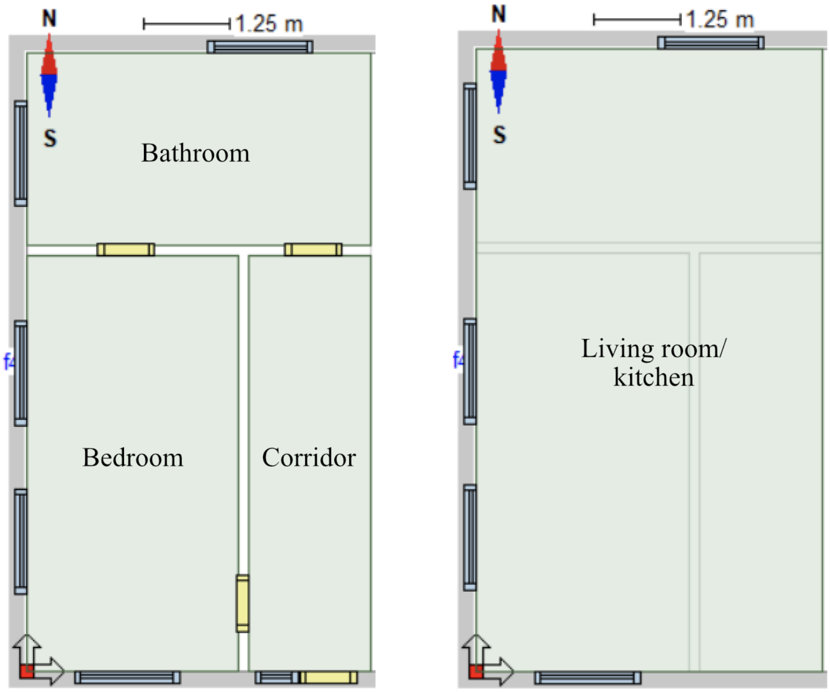


Figure 4.5: Model of the row house.

The floor plans for the ground and first floor are illustrated in Figure 4.6(a) and Figure 4.6(b), respectively.



((a)) Ground floor. ((b)) First floor.

Figure 4.6: Floor plan for the row house.

According to the report performed by COWI[2], one row house unit will have a total gross floor area of 90 m^2. A simplified building model was therefore developed with a total gross floor area of 88.39 m^2 for each unit. Table 4.2 displays the gross floor area for the different zones in one row house unit.

Table 4.2: Overview of the gross floor area of the different zones in one row house unit.

Type of room	**GFA [m^2]**
Bedroom	18.66
Corridor	10.68
Bathroom	14.05
Living room/kitchen	45.00
Total	**88.39**

Apartment building

A model from IDA ICE of the apartment building is presented in Figure 4.7.

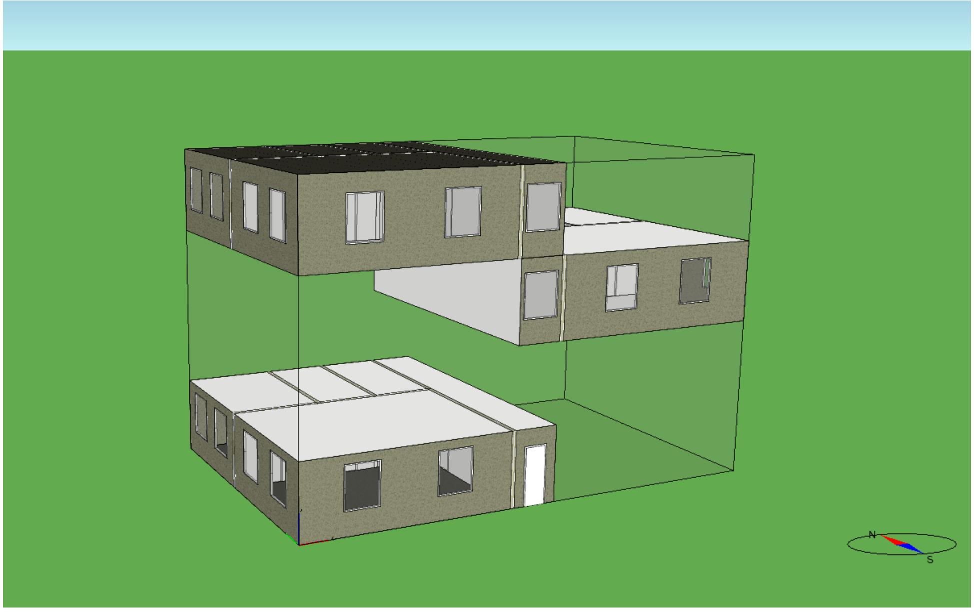


Figure 4.7: Model of the apartment building.

The floor plan for one floor is illustrated in Figure 4.8. All the four floors in one apartment building have the same layout.

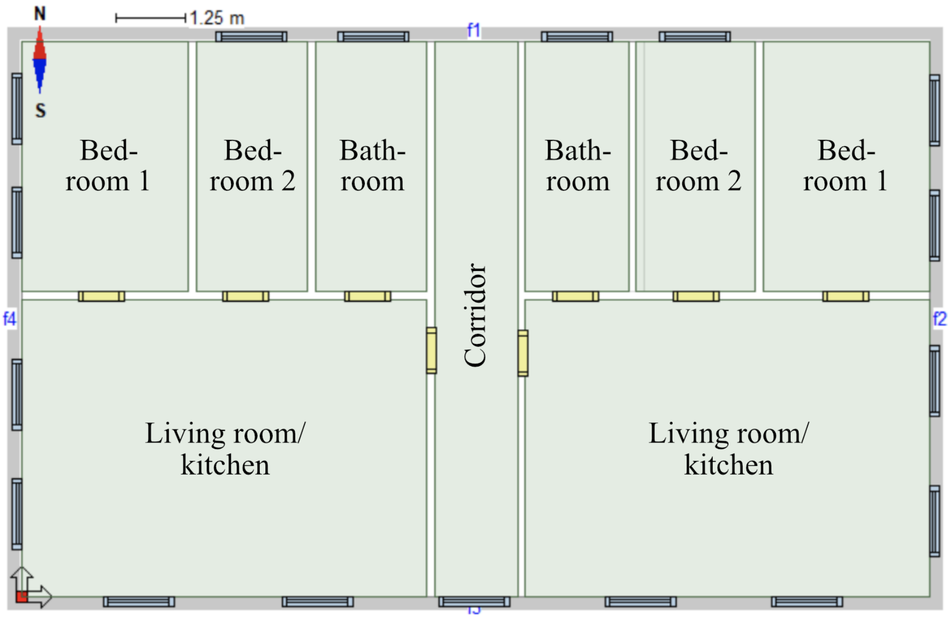


Figure 4.8: Floor plan for one floor in the apartment building.

According to the report performed by COWI[2], each apartment unit in the apartment building will have a total gross floor area of 70 m^2. A simplified building model was therefore developed with a total gross floor area of 70.50 m^2 for each unit. There is also one corridor per floor with an area of 15 m^2. The total gross floor area per floor unit, including the corridor, was therefore 85.5 m^2. Table 4.3 displays the gross floor area for the different zones in one apartment unit.

Table 4.3: Overview of the gross floor area of the different zones in one unit of the apartment building.

Type of room	**GFA [m^2]**
Bedroom 1	13.50
Bedroom 2	9.00
Bathroom	9.00
Living room/kitchen	39.00
Corridor	15.00
Total	**85.50**

5 Building construction

This section describes standard principles mainly based on Byggforskserien for the construction of the windows, roof, floors, and opaque walls satisfying the TEK17 and the passive house requirements.

5.1 Construction of the windows

The construction of a window requires careful consideration of multiple factors. A window's primary function is to provide daylight, view and aeration. In addition, the property of the thermal insulation and the ability to shield from or pass through solar radiation are important factors. A typical window has a height of 1.23 m and a width of 1.48 m[50]. The resulting window area is 1.82 m^2. According to TEK17 "§14-2. Krav til energieffektivitet", the total maximum U-value for a window, including both the window pane and the frame, is 0.8 W/(m^{2}K), as seen in Table 3.2[5].

Construction of the window pane

A type of glazing for the window pane is insulating panes[51]. This is a common term for double or multi-glazed window panes. The common type of glazing for residential purposes is energy saving glass. With this type of glass, the inside of the inner glass layer is coated with a low emission coating of metal. This results in a low emissivity value reducing the heat transfer by radiation in the cavity and gives a lower U-value for the window. Typically, the cavity between the glass layers is filled with argon or another gas known for its superior insulation properties compared to air. This is to reduce the U-value even further.

Today, there is a wide selection of insulating window panes which can be divided into four categories; sun shielding panes, insulating two-layer panes, sun shielding panes with improved thermal insulation, and high insulating three-layer panes. It is common for the high insulating three-layer panes to have a low emission coating on the second and fifth glass surfaces. This is illustrated in Figure 5.1, which is inspired by Byggforskserien[43].

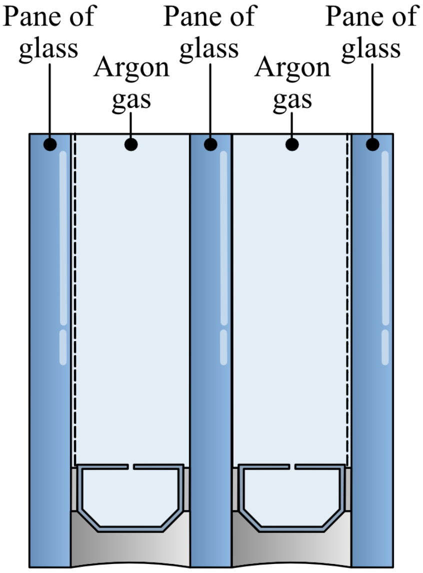


Figure 5.1: The structure of a high insulating three-layer pane.

The solar heat gain coefficient, called the g-factor, is defined as an expression for the percentage of the incident solar radiation that transmits through a window and ends up in the building as heat[43]. It is usually desired with a high g-factor in residential buildings, as solar energy can be used to reduce the heating demand. High insulating three-layer panes have a g-factor between 40 - 60%. For a window pane filled with argon gas and with a construction of 4E-16Ar-4-16Ar-E4, the g-factor is between 36 - 54%. The visible transmittance is between 58 - 69%, the solar absorption factor is between 25 - 35%, the solar reflection factor is between 23 - 46%, and the emissivity is between 0.01 - 0.05. The center U-value for this window pane is between 0.65 - 0.72 W/(m^{2}K).

Construction of the window frame

Three different types of materials are typically used in window frames; wood, aluminum, and PVC[50]. Wood is normally used in Norwegian residential houses. However, this solution requires maintenance regularly. On the other hand, PVC and aluminum require almost no maintenance. PVC has the same thermal insulation capacity as wood, whereas aluminum has a low thermal insulation capacity and requires special thermal bridge breakers that are placed into the profiles.

To be able to utilize the best properties of the different materials, a combination of the three materials can be used. It is possible to use wood as the main material and apply a profile of PVC or aluminum to the outside of the frame with an air gap in between. This will give the window frame a thermal insulation as high as an ordinary wooden frame, while the exterior PVC or aluminum profiles will work as a climate shield and reduce the need for maintenance. For a typical three-layer wooden window, the frame accounts for 29% of the total window area[50].

5.2 Construction of the opaque walls

A standard principle of the construction of opaque walls, influenced by Byggforskserien[52], is displayed in Figure 5.2.

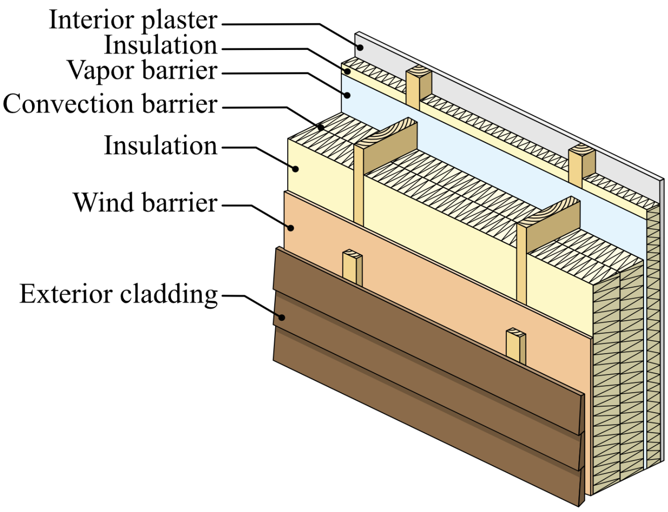


Figure 5.2: Illustration of the construction of the opaque walls.

Exterior cladding

The first layer of the opaque wall is the exterior cladding. The exterior cladding aims to protect the wall construction from mechanical damage and climatic impacts. In addition, the exterior cladding also works as UV protection for the wind barrier[52].

To provide aeration and drainage for the half-timbered walls, lathing is necessary to create a ventilated cavity. The principle of a ventilated cavity is to get a drying effect inside the wall by letting air into and out of the wall[53]. Weep vents are located at lower and higher levels of the wall, ensuring air motion through the wall. This is a good solution for buildings located in a wet climate as it reduces problems related to moisture. The typical thickness of a lath is 25 mm[54]. The thermal conductivity of stagnant air is 0.025 W/(mK)[41].

The exterior cladding works as a two-stage seal against rain. There are different types of relevant cladding for half-timbered walls, such as timber cladding, brick cladding, air-plastered cladding, and various plate claddings. Hardwood and softwood are typical types of wood that are used for timber cladding[52]. The thermal conductivity of hardwood and softwood is 0.16 W/(mK) and 0.12 W/(mK), respectively[55]. The exterior timber cladding typically has a thickness of 19 or 22 mm, and can be placed either vertically or horizontally[56].

Wind barrier

There are two possible wind barriers that can be applied in the structure of a wall[52]. Either a wind barrier in roll form or a wind barrier made of plate materials. The wind barrier in roll form provides large areas with minimal joints. This type of wind barrier has a good resistance against moisture and a low water vapor resistance.

Further, the wind barrier made of plate materials has many advantages, such as high resistance against damage during construction. In addition, the material is stiffer compared to the other option, and has therefore an enhanced ability to secure the insulation in position. This particular wind barrier design prevents it from being displaced into the ventilated cavity, thereby ensuring that the ventilation behind the exterior cladding remains unaffected. A disadvantage of this type of wind barrier, on the other hand, is the many joints between the plates that must be sealed to provide sufficient tightness. The most common types of wind barriers are 12 mm asphalt-impregnated porous wood fiber boards with windproof coating, or 9.5 mm thick gypsum plates with impregnated cardboard. The thermal conductivity of gypsum plates is 0.17 W/(mK)[55].

Insulation

The opaque wall can be insulated with mineral wool, wood fiber insulation or different types of blow-in insulation. According to TEK17 "§14-2. Krav til energieffektivitet"[5], the maximum U-value requirement for opaque walls is 0.18 W/(m^{2}K). To satisfy this requirement, a thickness of 200 - 250 mm is necessary. In a passive house, the maximum U-value requirement is 0.1 - 0.12 W/(m^{2}K). Therefore, it is necessary with an insulation thickness of 300 - 350 mm in a passive house[57].

The thermal conductivity of typical insulation materials is between 0.032 - 0.037 W/(mK)[52]. For mineral wool, the associated thermal conductivity is 0.036 W/(mK)[41]. Splitting up the insulation layer with a convection barrier is recommended when the insulation thickness is over 200 mm. This is to prevent convection in the insulation layer.

Vapor barrier

The primary purpose of a vapor barrier is to establish a moisture resistant and airtight layer within the opaque wall. The purpose of the barrier is to prevent water vapor diffusion and air leaks through the wall. A 0.15 mm thick polyethylene foil is typically used as a vapor barrier[52]. The thermal conductivity of a polyethylene foil is 0.25 W/(mK)[41].

Interior cladding

The type of interior cladding is of great significance in relation to acoustic properties and fire security. Typical choices for interior cladding on half-timbered walls can be wooden panels or plate cladding. Gypsum boards are a good alternative for plate cladding as they have many advantages[52]. The boards do not contain substances that can cause health risks, and they are also a good alternative for the indoor environment as the boards do not emit any gases. Further, due to the chemically bound water in the gypsum boards, the interior surface will have a high level of fire resistance[58]. Another advantage of gypsum boards is that the material is easy to recycle into new raw material for the production of new gypsum boards[59]. This is a good basis for a sustainable and circular solution. A typical thickness of gypsum boards is 12.5 mm[58]. The thermal conductivity of gypsum boards is 0.17 W/(mK)[55].

5.3 Construction of the roof

There are three main types of roofs; compact roofs, roofs with insulated surfaces and ventilated roofing, or roofs with cold attics[60]. The construction of a compact roof is considered for the project at Tanberghødga. Compact roofs are made of multiple layers that are placed close together with a minimal distance between each other. The roof construction illustrated in Figure 5.3 is an upright roof, a specific type of compact roof, which is inspired by Byggforskserien[61]. An upright roof consists of a vapor barrier above the structural deck, thermal insulation, and roofing[61].

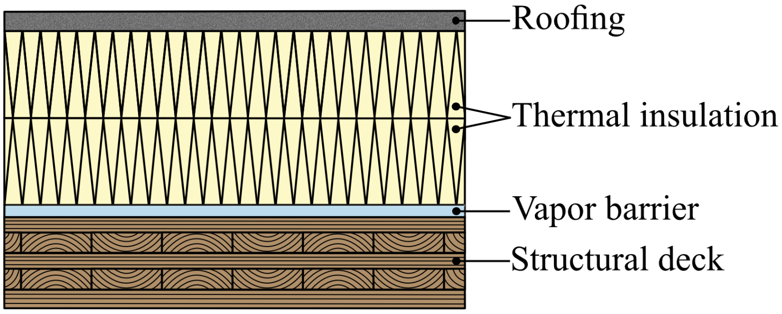


Figure 5.3: Illustration of the construction of the roof.

Roofing

Roofing is the upper layer of the roof construction and is therefore exposed to the outdoor climate[61]. The purpose of roofing is to protect the roof against climatic impacts such as wind and rain. Materials typically used for upright roofs are plastic, rubber, or asphalt with welded joints. Asphalt as roofing for upright roofs has been proven to be a safe alternative. Asphalt-roofing on a roll is typically delivered with a thickness between 2.5 - 5.0 mm[62]. The thermal conductivity of asphalt is 0.0062 W/(mK)[55].

Thermal insulation

For an upright roof, both flammable and non-flammable insulation can be implemented. Mineral wool and foam glass are non-flammable materials that can be used as insulation. The roof will be more resilient to fire by using these materials. It is also necessary with thermal insulation in the roof in order to provide an even surface for the vapor barrier, and at the same time meet fire safety requirements.

A good alternative in this regard is stone wool. This material is not flammable and has a high melting point. It is made of raw materials produced by the earth, making it more eco-friendly. Further, it is well suited for constructions in humid environments as it does not absorb moisture. Stone wool does not lose its effectiveness over time, so it does not need to be replaced during the construction's lifetime. In addition, it provides effective sound insulation properties[63]. The associated thermal conductivity for stone wool is 0.036 W/(mK)[64].

According to TEK17 "§14-2. Krav til energieffektivitet"[5], the maximum U-value for a roof is 0.13 W/(m^{2}K). To satisfy this requirement, an insulation thickness of at least 250 mm is necessary. In a passive house, the maximum U-value is 0.08 - 0.09 W/(m^{2}K). Therefore, it is necessary with an insulation thickness of 400 - 500 mm in a passive house[57].

Vapor barrier

To reduce the transport of moisture by air leaks and diffusion from the inside of the building, a vapor barrier as the next layer in the construction is necessary. Today, the most common type of vapor barrier in upright roofs is a polyethylene foil with a thickness of 0.20 mm[61]. The thermal conductivity associated with polyethylene foils is 0.25 W/(mK)[41].

Structural deck

The structural deck of an upright roof can consist of cast concrete slabs, concrete elements, corrugated steel sheets, wooden constructions, or cross laminated timber[61]. The vapor barrier, thermal insulation, and roofing are then placed above the structural deck.

Cross Laminated Timber (CLT) is a high-quality, renewable, low-carbon and sustainable material that can have a flexible design. CLT emits less than half as much CO_2 as concrete. By taking into account the fact that wood has the ability to absorb CO_2 over time, CLT can actually deliver CO_2 negative solutions[65]. It is therefore more energy efficient to produce and utilize CLT, compared to concrete or steel. The thermal conductivity of CLT is 0.13 W/(mK), and the typical thickness is 160 mm, 200 mm or 240 mm[66].

Ceiling

Several types of ceilings can be applied as lined ceilings; ceiling sheets, metal ceilings, and wood panel ceilings[67]. There are four categories of ceiling sheets, such as mineral wool boards, gypsum boards, wood-wool cement boards, and other plate types. When a fireproof and sound insulating ceiling is desired, dense gypsum boards are applied. Gypsum boards are preferred when the structural deck is made of either corrugated steel sheets or wooden constructions. Standard gypsum boards are delivered with a thickness of 12.5 mm. The thermal conductivity of gypsum boards is 0.17 W/(mK)[55].

5.4 Construction of the floor

According to the report performed by COWI[2], the buildings at Tanberghøgda will have a hydronic radiant floor. The floor was therefore constructed to have the possibility of implementing heating pipes. This is displayed in Figure 5.4, which is inspired by Byggforskserien[30].

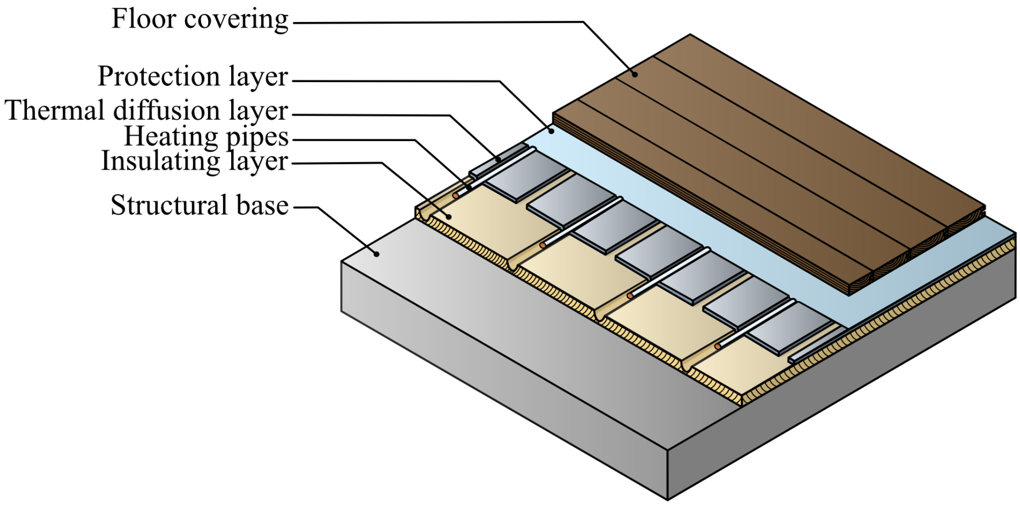


Figure 5.4: Illustration of the construction of the floor.

Floor covering

The floor covering is the top layer of the floor construction, and should be able to withstand the load of normal use, as well as have a high thermal conductivity. In this regard, the selected thickness and type of floor covering are two factors that are very important. For instance, by choosing tiles, the floor will conduct heat better than by choosing wooden materials like parquet.

Ceramic tiles are typically used in rooms like bathrooms and corridors. The advantages of ceramic tiles are that they can withstand heavy mechanical strain and are resistant to most chemicals[68]. Usually, ceramic tiles have a thickness of 9.8 mm[69], and a thermal conductivity of 2.0 W/(mK)[55].

Parquet or other wood floor coverings conduct heat more poorly than tiles. The wooden floor covering must therefore not be thicker than 9 - 15 mm. Parquet has a typical thermal conductivity between 0.11 - 0.15 W/(mK)[70]. The surface temperature for wooden materials should not be higher than 27°C, as wooden materials risk cracking in combination with floor heating[30].

Protection layer

To have a optimal heat transfer to the room, the protection layer should have a low heat resistance[30]. A type of protection layer can therefore be a polyethylene foil, which has a thermal conductivity of 0.25 W/(mK), and a typical thickness of 0.2 mm.

Thermal diffusion layer

In order to transfer heat from the hydronic heating pipes to the room, the thermal diffusion layer should have a high thermal conductivity. The layer can be made of chipboard, expanded polystyrene (EPS), or wood fiber[30]. A thermal diffusion layer made of EPS is typically 25 mm, and has a thermal conductivity between 0.031 - 0.041 W/(mK)[41].

Heating pipes

Heating pipes are generally made of plastic, with a diffusion barrier of PEX, PE-RT or AluPEX[28]. The function of the diffusion barrier is to prevent both bacterial growth and corrosion of steel components. Since the PEX pipes have a relatively low thermal conductivity of 0.36 W/(mK), it is important that the thermal diffusion layer and the heating pipes are installed tight with good contact. Heating pipes usually have an external diameter between 12 - 20 mm, and a wall thickness of 1.5 - 2 mm. The recommended lifetime of the pipes during normal temperature and pressure conditions is 50 years.

Insulating layer

The insulating layer can be made of materials such as mineral wool, wood fiber, or expanded polystyrene (EPS). The purpose of the insulating layer is to ensure that the heat from the heating pipes is transferred upwards to the room, and to prevent heat loss to the ground. Mineral wool is a good alternative, and has a thermal conductivity of 0.036 W/(mK)[61].

According to TEK17 "§14-2. Krav til energieffektivitet", the maximum U-value for a floor construction is 0.1 W/(m^{2}K)[5]. To satisfy this requirement, an insulation thickness between 30 - 70 mm is necessary for floor systems where heating pipes are embedded in the thermal diffusion layer[30]. In a passive house, the maximum U-value is 0.08 W/(m^{2}K). Therefore, it is necessary with an insulation thickness between 300 - 400 mm to satisfy the passive house requirement[57].

Structural base

If pressure-resistant mineral wool is chosen for the insulating layer, the mineral wool will work as a capillary-breaking layer. Thereby, it will be sufficient to have a draining layer as the structural base[71]. The structural base should be at least 200 mm thick, consisting of crushed stone[72]. The thermal conductivity for crushed stone is between 0.5 - 0.7 W/(mK)[73].

The structural base in the intermediate floors can be made of concrete or a layer of wooden beams[30]. It is typical to use lightweight concrete blocks if the structural base is made of concrete[74]. The thickness of a lightweight concrete block is normally between 150 - 250 mm. The benefit of this structure is that it contributes to good sound absorption. The thermal conductivity of lightweight concrete blocks is 0.23 W/(mK)[75].

6 Simulation input

In order to accurately simulate and analyze the building performance of the residential area at Tanberghøgda, it is essential to utilize appropriate input parameters in the simulation tool IDA ICE.

This section provides an overview of the general input parameters, as well as a description of the selected building constructions for the TEK17, Hunton, and passive house models. The presented parameters were used as simulation input for the models.

6.1 General input parameters

Simulation input parameters are presented in the following section. These general input parameters encompass various aspects of a building, such as key parameters regarding internal gains and HVAC systems. The performance of the air handling unit, selected setpoints and the relevant heating units are presented as well.

Schedule of the internal gains

It is considered four distinct sources of internal gains in the building; domestic hot water, technical equipment, lighting and occupants. The schedule for domestic hot water was based on Table A.2 in the standard ”Bygningers energiytelse” (NS3031)[23], and is presented in Figure 6.1. The percentage of energy demand supplied as heat to the zones from domestic hot water is 0%.

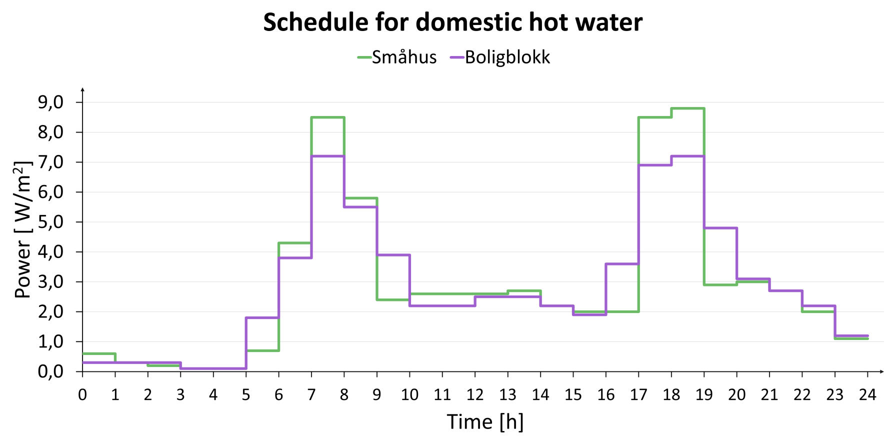


Figure 6.1: Schedule for domestic hot water.

The schedule for technical equipment was based on Table A.3 in the standard ”Bygningers energiytelse” (NS3031)[23], and is presented in Figure 6.2. The percentage of energy demand supplied as heat to the zones from technical equipment is 60%.

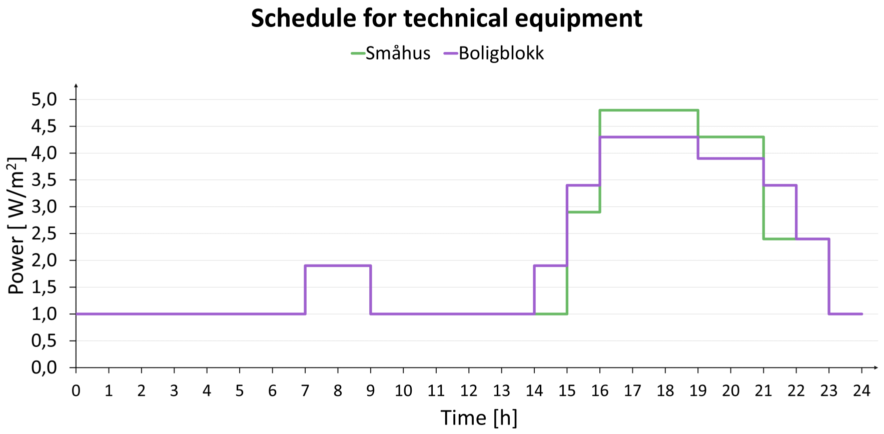


Figure 6.2: Schedule for technical equipment.

The schedule for lighting was based on Table A.6 in the standard ”Bygningers energiytelse” (NS3031)[23], and is presented in Figure 6.3. The percentage of energy demand supplied as heat to the zones from lighting is 100%.

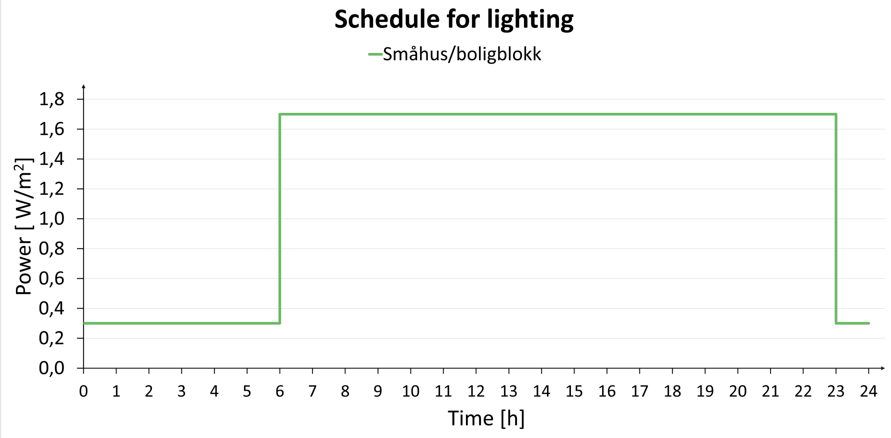


Figure 6.3: Schedule for lighting.

The schedule for occupancy was based on Table A.5 in the standard ”Bygningers energiytelse” (NS3031)[23]. The heat gain from occupants is at a constant level of 1.5 W/m^2 throughout a day. This applies to the single family house, the row house and the apartment building. The percentage of energy demand supplied as heat to the zones from the occupants is 100%.

Air Handling Unit

In relation to the literature review, the air handling unit (AHU) is the device that both conditions and distributes air within a building[15]. Different settings were applied to the AHU in relation to the research provided in the section "Air Handling Unit". For instance, an efficiency of 85% was selected for the heat exchanger. The specific fan power for the air handling unit was set to 1,5 kW/(m^3/s), in order to meet the requirement given in Table 3.2. The supply air temperature from the AHU was set to 18°C to achieve a comfortable indoor environment. The indoor temperatures in the various zones were evaluated in the section "Results and discussion", along with a discussion regarding the necessity of external shading and opening control.

In order to assess the influence of a heating coil within the air handling unit, the heating coil was activated and deactivated during the simulations for evaluation purposes. Since the buildings are located in Hønefoss, a cooling system is unnecessary, and the cooling coils were therefore removed. Furthermore, by avoiding cooling coils, the air handling units will be simplified, and the investment costs can thereby be reduced.

In accordance with the section "Airflow" in the literature review, the minimum airflow rates required in each zone for the single family house, the row house and the apartment building were selected. These are represented in Table 6.1, Table 6.2 and Table 6.3.

Table 6.1: Minimum airflow rates for the single family house.

Room	**GFA [m^2]**	**Minimum airflow [m^3/h]**	**Minimum airflow [L/sm^2]**
Bedroom 1	15.57	26	0.464
Bedroom 2	13.72	26	0.526
Bedroom 3	22.52	52	0.641
Corridor	22.85	27.4	0.333
Bathroom 1	11.27	54	1.331
Bathroom 2	7.43	54	1.345
Kitchen/Living room	81.27	97.5	0.333

Table 6.2: Minimum airflow rates for the row house.

Room	**GFA [m^2]**	**Minimum airflow [m^3/h]**	**Minimum airflow [L/sm^2]**
Bedroom	18.66	52	0.774
Corridor	14.05	16.9	0.333
Bathroom	10.68	54	1.068
Kitchen/Living room	45.00	54	0.333

Table 6.3: Minimum airflow rates for the apartment building.

Room	**GFA [m^2]**	**Minimum airflow [m^3/h]**	**Minimum airflow [L/sm^2]**
Bedroom 1	13.5	52	1.070
Bedroom 2	9	26	0.803
Kitchen/Living room	39	46.8	0.333
Bathroom	9	54	1.667
Corridor	15	10.5	0.194

Zone setpoints

The selected zone setpoints for the IDA ICE models are listed below:

- The location and climate were set to Gardemoen, Oslo, since this alternative was closest to Hønefoss.
- Initially, a temperature level between 22 - 24 °C, defined by FHI, was selected for all of the zones. Further, specific temperature levels for each zone were applied, in order to have lower temperatures in particular zones. These temperature levels are presented in Table 2.2 and are based on recommendations by Fjordkraft.
- To ensure that the level of CO_2 does not exceed the recommended limit of 1000 ppm, the pollution level was set to be between 600 - 900 ppm in each zone[19].
- The relative humidity was set to be between 30 - 70%.
- To fulfill the TEK17 requirements for infiltration, the airtightness at 50 Pa pressure difference was set to 0.6 h^{-1}[5].
- The normalized thermal bridge value per m^2 floor area was set to 0.05 $W/(m^2K)$ in accordance with Table 3.2 to satisfy the TEK17 energy requirements for residential buildings[5].
- The total annual energy demand for domestic hot water per square meter was set to 25 $kWh/(m^2year)$.

Heating units

Initially, scenario 0 involved modeling ideal heaters as a reference scenario to establish a foundation for the sizing of radiators. Subsequently, utilizing the heat rates obtained from scenario 0, the sizing of radiators was determined by selecting peak powers corresponding to each specific zone. The implementation of radiators represented scenario 1. The chosen design temperature level for the radiators was 60/40°C. A PI controller was chosen for the radiators, with an air temperature sensor. The air temperature at maximum power was set to 22°C. The radiators will be supplied with heat from the district heating network in Hønefoss.

Moreover, floor heating was sized according to typical design heat rates defined by Byggforskserien, as described in the section "Hydronic radiant floor system" in the literature review. A heat rate between 20 - 70 W/m^2 was utilized. Since the buildings are categorized as new constructions, the dimensioning heat rate is at the lower end of the range. Floor heating was solely implemented in the bathrooms, and in the kitchen and living room, with heat rates of 40 W/m^2 and 20 W/m^2, respectively. The implementation of a hydronic radiant floor represented scenario 2.

The chosen control unit for the hydronic radiant floor was a thermostat. The thermostat was set to regulate the water temperatures based on the floor surface temperature. The temperature difference between the supply and return water was set to 6K. An air-to-water heat pump with a COP of 3.62 was chosen in combination with the floor heating system. Space and domestic hot water heating would thereby be supplied by the heat pump, covering the base load. The district heating network was set to cover the peak load of the buildings.

6.2 Chosen building structure for the TEK17 models

The chosen building structure based on requirements given in TEK17 is presented in the following section.

Windows

Three-layer 4E-16Ar-4-16Ar-E4 window panes were chosen for the windows, and the solar heat gain coefficient, the g-factor, was therefore set to 0.5. The internal and external emissivity was set to 0.03, and the visible transmittance was set to 0.65[43]. The solar transmittance was calculated to be 0.35 by using Equation 3.5 in the section "Solar transmittance". The applied values for the window pane are given in Table 6.4. The total U-value of the window was set to 0.8 W/(m^{2}K). As external sun shading, a generic markisolette was chosen for all of the windows. These are controlled with regard to sun radiation. For the opening control of the windows, PI temperature control was chosen.

Table 6.4: Applied values for the window pane.

Window pane	Value [-]
g-factor	0.50
Internal/external emissivity	0.03
Visible transmittance	0.65
Solar absorption factor	0.30
Solar reflection factor	0.35
Calculated solar transmittance	0.35

In accordance with the section "Construction of the windows", several parameters were chosen. Firstly, a window area of 1.82 m^2 was used. The frame was then set to account for 29% of the window area. According to TEK17 "§ 13-7. Lys", windows must be placed at least 0.8 m above the floor[5]. By using Equation 3.6 in the section "Daylight requirements with a visible transmittance, VT, of 0.65, the minimum total window pane area, A_{wp}, and the minimum total window area, A_{window}, for each room were calculated. The calculated values are given in Table 6.5, Table 6.6 and Table 6.7 for the single family house, the row house and the apartment building, respectively.

Table 6.5: Window area and the minimum number of windows for each room in the single family house.

Room	GFA [m^2]	A_{wp} [m^2]	A_{window} [m^2]	Minimum number of windows
Bedroom 1	15.57	1.68	2.36	2
Bedroom 2	13.72	1.48	2.08	1.5
Bedroom 3	22.52	2.43	3.42	2
Corridor	22.85	2.46	3.47	2
Bathroom 1	11.27	1.21	1.71	1
Bathroom 2	7.43	0.80	1.13	1
Kitchen/Living room	81.27	8.75	12.33	7
Total	174.6	18.80	26.49	16.5

Table 6.6: Window area and the minimum number of windows for each room in the row house.

Room	GFA [m^2]	A_{wp} [m^2]	A_{window} [m^2]	Minimum number of windows
Bedroom	18.66	2.01	2.83	2
Bathroom	14.05	1.51	2.13	2
Corridor	10.68	1.15	1.61	1
Kitchen/Living room	45.00	4.80	6.82	4
Total	88.39	9.47	13.39	9

Table 6.7: Window area and the minimum number of windows for each room in the apartment building.

Room	GFA [m^2]	A_{wp} [m^2]	A_{window} [m^2]	Minimum number of windows
Bedroom 1	13.5	1.45	2.04	2
Bedroom 2	9.0	0.97	1.37	1
Bathroom	9.0	0.97	1.37	1
Kitchen/Living room	39	4.20	5.92	4
Total	70.5	7.59	10.70	8

Opaque walls

The selected materials, corresponding thicknesses, thermal conductivities, and resistances for the construction of the opaque walls are displayed in Table 6.8. These were carefully selected from the section "Building construction" based on Byggforskserien. The total thermal resistance for the opaque walls was calculated to be 7.02 (m^2K)/W, using Equation 3.1. The respective U-value was calculated to be 0.14 W/(m^2K), using equation Equation 3.3. The TEK17 minimum requirement for opaque walls, $U_{opaque} \leq 0.18$ W/(m^2K), given in Table 3.2 was therefore satisfied.

Table 6.8: The selected construction of the opaque walls.

Construction layer	Selected material	Thickness [mm]	Thermal conductivity [W/(mK)]	Thermal resistance [(m^2K)/W]
External surface resistance	Surface in contact with air			0.04
Exterior cladding	Timber cladding	19.0	0.12	0.16
Ventilated cavity	Air and laths	25.0	0.025	1.00
Wind barrier	Gypsum plate with impregnated cardboard	9.5	0.17	0.056
Insulation	Mineral wool	200	0.036	5.56
Vapor barrier	Polyethylene foil	0.15	0.25	0.0006
Interior cladding	Gypsum board	12.5	0.17	0.074
Internal surface resistance	Surface in contact with air			0.13
Total		**266.15**		**7.02**

Roof

The chosen roof structure is an upright roof, a specific type of compact roof[60]. The selected materials, corresponding thicknesses, thermal conductivities, and resistances for the roof construction are displayed in Table 6.9. These were carefully selected from the section "Building construction" based on Byggforskserien. The total thermal resistance for this roof construction was calculated to be 9.035 $(m^2K)/W$, using Equation 3.1. The respective U-value was calculated to be 0.11 $W/(m^2K$, using Equation 3.3. The TEK17 minimum requirement for roofs, $U_{roof} \leq 0.13$ $W/(m^2K)$, given in Table 3.2 was therefore satisfied.

Table 6.9: The selected construction of the roof.

Construction layer	**Selected material**	**Thickness [mm]**	**Thermal conductivity [W/(mK)]**	**Thermal resistance [$(m^2K)/W$]**
External surface resistance	Surface in contact with air			0.04
Roofing	Asphalt	4.0	0.0062	0.65
Thermal insulation	Stone wool	250	0.036	6.94
Vapor barrier	Polyethylene foil	0.2	0.25	0.0008
Structural deck	Cross laminated timber	160	0.13	1.23
Ceiling	Gypsum board	12.5	0.17	0.074
Internal surface resistance	Surface in contact with air			0.10
Total		**426.7**		**9.035**

Floor

As explained in the section "Construction of the floor", the floors were constructed to have the possibility of implementing heating pipes to achieve a hydronic radiant floor system. There are two different types of floor coverings; parquet and ceramic tiles. The different types of floor constructions are given below.

Ground floor without heating pipes

Table 6.10 displays the selected materials with the corresponding thicknesses, thermal conductivities, and resistances for the ground floor without heating pipes and with parquet as floor covering. The total thermal resistance for this floor construction was calculated to be 8.97 $(m^2K)/W$, using Equation 3.1. The respective U-value was calculated to be 0.11 $W/(m^2K$, using Equation 3.3, which approximately satisfied the minimum TEK17 requirement for a floor construction of $U_{floor} \leq 0.1\ W/(m^2K)$.

Table 6.10: The selected construction of the ground floor without heating pipes and with parquet as floor covering.

Construction layer	**Selected material**	**Thickness [mm]**	**Thermal conductivity [W/(mK)]**	**Thermal resistance [$(m^2K)/W$]**
Internal surface resistance	Surface in contact with air			0.10
Floor covering	Parquet	15.0	0.11	0.14
Protection layer	Polyethylene foil	0.2	0.25	0.0008
Insulating layer	Mineral wool	300	0.036	8.33
Structural base	Crushed stone	200	0.5	0.40
Total		**515.2**		**8.97**

Table 6.11 displays the selected materials with the corresponding thicknesses, thermal conductivities, and resistances for the ground floor without heating pipes and with ceramic tiles as the floor covering. The total thermal resistance for this floor construction was calculated to be 8.84 $(m^2K)/W$, using Equation 3.1. The respective U-value was calculated to be 0.11 $W/(m^2K)$, using Equation 3.3, which approximately satisfied the minimum TEK17 requirement for a floor construction of $U_{floor} \leq 0.1\ W/(m^2K)$.

Table 6.11: The selected construction of the ground floor without heating pipes and with ceramic tiles as floor covering.

Construction layer	**Selected material**	**Thickness [mm]**	**Thermal conductivity [W/(mK)]**	**Thermal resistance [$(m^2K)/W$]**
Internal surface resistance	Surface in contact with air			0.10
Floor covering	Ceramic tiles	9.8	2.0	0.005
Protection layer	Polyethylene foil	0.2	0.25	0.0008
Insulating layer	Mineral wool	300	0.036	8.33
Structural base	Crushed stone	200	0.5	0.40
Total		**510**		**8.84**

Ground floor with heating pipes

Table 6.12 displays the selected materials with the corresponding thicknesses, thermal conductivities, and resistances for the hydronic radiant floor construction with parquet as floor covering. The total thermal resistance for this floor construction was calculated to be 9.85 (m^2K)/W, using Equation 3.1. The respective U-value was calculated to be 0.1 W/(m^2K), using Equation 3.3, which satisfied the minimum TEK17 requirement for a floor construction of $U_{floor} \leq 0.1$ W/(m^2K).

Table 6.12: The selected construction of the hydronic radiant ground floor with parquet as floor covering.

Construction layer	**Selected material**	**Thickness [mm]**	**Thermal conductivity [W/(mK)]**	**Thermal resistance [m^2K/W]**
Internal surface resistance	Surface in contact with air			0.17
Floor covering	Parquet	15	0.11	0.136
Protection layer	Polyethylene foil	0.2	0.25	0.0008
Heating pipes	PEX-pipes	2	0.36	0.0056
Thermal diffusion layer	Expanded polystyrene	25	0.031	0.806
Insulating layer	Mineral wool	300	0.036	8.333
Structural base	Crushed stone	200	0.5	0.4
Total		**542.2**		**9.85**

Table 6.13 displays the selected materials with the corresponding thicknesses, thermal conductivities and resistances for the hydronic radiant floor construction with ceramic tiles as floor covering. The total thermal resistance for this floor construction was calculated to be 9.72 (m^2K)/W, using Equation 3.1. The respective U-value was calculated to be 0.1 W/(m^2K), by using Equation 3.3, which satisfied the minimum TEK17 requirement for a floor construction of $U_{floor} \leq 0.1$ W/(m^2K).

Table 6.13: The selected construction of the hydronic radiant ground floor with ceramic tiles as floor covering.

Construction layer	**Selected material**	**Thickness [mm]**	**Thermal conductivity [W/(mK)]**	**Thermal resistance [m^2K/W]**
Internal surface resistance	Surface in contact with air			0.17
Floor covering	Ceramic tiles	9.8	2	0.0049
Protection layer	Polyethylene foil	0.2	0.25	0.0008
Heating pipes	PEX-pipes	2	0.36	0.0056
Thermal diffusion layer	Expanded polystyrene	25	0.031	0.806
Insulating layer	Mineral wool	300	0.036	8.333
Structural base	Crushed stone	200	0.5	0.4
Total		**537**		**9.72**

Intermediate floor without heating pipes

Table 6.14 displays the selected materials with the corresponding thicknesses, thermal conductivities, and resistances for the intermediate floor without heating pipes and with parquet as floor covering. The total thermal resistance for this floor construction was calculated to be 3.37 $(\mathrm{m^2K})/\mathrm{W}$, using Equation 3.1. The respective U-value was calculated to be 0.3 $\mathrm{W}/(\mathrm{m^2K})$, using Equation 3.3.

Table 6.14: The selected construction of the intermediate floor without heating pipes and with parquet as floor covering.

Construction layer	Selected material	Thickness [mm]	Thermal conductivity [W/(mK)]	Thermal resistance [$(\mathrm{m^2K})/\mathrm{W}$]
Internal surface resistance	Surface in contact with air			0.10
Floor covering	Parquet	15	0.11	0.14
Protection layer	Polyethylene foil	0.2	0.25	0.0008
Insulating layer	Mineral wool	70.0	0.036	1.94
Structural base	Lightweight concrete blocks	250	0.23	1.09
Internal surface resistance	Surface in contact with air			0.10
Total		**335.2**		**3.37**

Table 6.15 displays the selected materials with the corresponding thicknesses, thermal conductivities, and resistances for the intermediate floor without heating pipes and with ceramic tiles as floor covering. The total thermal resistance for this floor construction was calculated to be 3.24 $(\mathrm{m^2K})/\mathrm{W}$, using Equation 3.1. The respective U-value was calculated to be 0.31 $\mathrm{W}/(\mathrm{m^2K})$, using Equation 3.3.

Table 6.15: The selected construction of the intermediate floor without heating pipes and with ceramic tiles as floor covering.

Construction layer	Selected material	Thickness [mm]	Thermal conductivity [W/(mK)]	Thermal resistance [$(\mathrm{m^2K})/\mathrm{W}$]
Internal surface resistance	Surface in contact with air			0.10
Floor covering	Ceramic tiles	9.8	2.0	0.005
Protection layer	Polyethylene foil	0.2	0.25	0.0008
Insulating layer	Mineral wool	70.0	0.036	1.94
Structural base	Lightweight concrete blocks	250	0.23	1.09
Internal surface resistance	Surface in contact with air			0.10
Total		**330**		**3.24**

Hydronic radiant intermediate floor

Table 6.16 displays the selected materials with the corresponding thicknesses, thermal conductivities, and resistances for the hydronic radiant intermediate floor with parquet as floor covering. The total thermal resistance for this floor construction was calculated to be 4.18 (m^2K)/W, using Equation 3.1. The respective U-value was calculated to be 0.24 W/(m^2K), using Equation 3.3.

Table 6.16: The selected construction of the hydronic radiant intermediate floor with parquet as floor covering.

Construction layer	**Selected material**	**Thickness** [mm]	**Thermal conductivity** [W/(mK)]	**Thermal resistance** [m^2K/W]
Internal surface resistance	Surface in contact with air			0.10
Floor covering	Parquet	15	0.11	0.136
Protection layer	Polyethylene foil	0.2	0.25	0.0008
Heating pipes	PEX-pipes	2	0.36	0.0056
Thermal diffusion layer	Expanded polystyrene	25	0.031	0.806
Insulating layer	Mineral wool	70	0.036	1.944
Structural base	Lightweight concrete blocks	250	0.23	1.09
Internal surface resistance	Surface in contact with air			0.10
Total		**362.2**		**4.18**

Table 6.17 displays the selected materials with the corresponding thicknesses, thermal conductivities, and resistances for the hydronic radiant intermediate floor with ceramic tiles as floor covering. The total thermal resistance for this floor construction was calculated to be 4.05 (m^2K)/W, using Equation 3.1. The respective U-value was calculated to be 0.25 W/(m^2K), using Equation 3.3.

Table 6.17: The selected construction of the hydronic radiant intermediate floor with ceramic tiles as floor covering.

Construction layer	**Selected material**	**Thickness** [mm]	**Thermal conductivity** [W/(mK)]	**Thermal resistance** [m^2K/W]
Internal surface resistance	Surface in contact with air			0.10
Floor covering	Ceramic tiles	9.8	2	0.0049
Protection layer	Polyethylene foil	0.2	0.25	0.0008
Heating pipes	PEX-pipes	2	0.36	0.0056
Thermal diffusion layer	Expanded polystyrene	25	0.031	0.806
Insulating layer	Mineral wool	70	0.036	1.944
Structural base	Lightweight concrete blocks	250	0.23	1.09
Internal surface resistance	Surface in contact with air			0.10
Total		**357**		**4.05**

Selected floor constructions for the single family house

An overview of the selected floor constructions for the different zones in the single family house are displayed in Table 6.18.

Table 6.18: The selected floor constructions for the different zones in the single family house.

Room	**Type of floor**
Bedrooms	Ground floor w/o heating pipes and w/parquet
Corridor	Ground floor w/heating pipes and w/ceramic tiles
Bathroom 1	Ground floor w/heating pipes and w/ceramic tiles
Bathroom 2	Hydronic radiant intermediate floor w/ceramic tiles
Kitchen/Living room	Hydronic radiant intermediate floor w/parquet

Selected floor constructions for the row house

An overview of the selected floor constructions for the different zones in the row house are displayed in Table 6.19.

Table 6.19: The selected floor constructions for the different zones in the row house.

Room	**Type of floor**
Bedroom	Ground floor w/o heating pipes and w/parquet
Corridor	Ground floor w/heating pipes and w/ceramic tiles
Bathroom	Ground floor w/heating pipes and w/ceramic tiles
Kitchen/Living room	Hydronic radiant intermediate floor w/parquet

Selected floor constructions for the apartment building

An overview of the selected floor constructions for the different zones on the ground floor in the apartment building are displayed in Table 6.20.

Table 6.20: The selected floor constructions for the different zones on the ground floor in the apartment building.

Room	**Type of floor**
Bedroom	Ground floor w/o heating pipes and w/parquet
Corridor	Ground floor w/heating pipes and w/ceramic tiles
Bathroom	Ground floor w/heating pipes and w/ceramic tiles
Kitchen/Living room	Ground floor w/heating pipes and w/parquet

An overview of the selected floor constructions for the different zones on the first, second and third floors in the apartment building are displayed in Table 6.21.

Table 6.21: The selected floor constructions for the different zones on the 1st, 2nd and 3rd floors in the apartment building.

Room	**Type of floor**
Bedroom	Intermediate floor w/o heating pipes and w/parquet
Corridor	Hydronic radiant intermediate floor w/ceramic tiles
Bathroom	Hydronic radiant intermediate floor w/ceramic tiles
Kitchen/Living room	Hydronic radiant intermediate floor w/parquet

6.3 Chosen building structure for the Hunton model

The buildings at Tanberghøgda are going to have construction materials that are suggested by Hunton. These constructions satisfy the TEK17 requirements. The building materials presented in the following tables for the opaque walls, the floors and the roof were implemented in the model for the single family house.

Opaque walls

The selected materials, corresponding thicknesses, thermal conductivities and resistances for the construction of the opaque walls, defined by Hunton, are displayed in Table 6.22. The total thermal resistance for the opaque walls was calculated to be 8.06 $(m^2K)/W$, using Equation 3.1. The U-value for the opaque walls was calculated to be 0.12 $W/(m^2K)$, using Equation 3.3. The TEK17 minimum requirement for opaque walls, $U_{opaque} \leq 0.18$ $W/(m^2K)$, given in Table 3.2 was therefore satisfied.

Table 6.22: The selected Hunton construction of the opaque walls.

Construction layer	**Selected material**	**Thickness [mm]**	**Thermal conductivity [W/(mK)]**	**Thermal resistance [m^2K/W]**
External surface resistance	Surface in contact with air			0.04
Exterior cladding	Timber cladding	15	0.12	0.125
Ventilated cavity	Air	20	0.025	0.8
Wind barrier	Hunton Windproof	12	0.049	0.25
Insulation (1st layer)	Nativo Wood Fiber Insulation Loose Fill	200	0.038	5.26
Insulation (2nd layer)	Nativo Wood Fiber Insulation Boards	50	0.038	1.32
Soundproofing layer	Fermacell gypsum fiber	12.5	0.316	0.039
Vapor barrier	Hunton Intello Plus	0.2	0.17	0.0012
Interior cladding	Gypsum board	15	0.17	0.09
Internal surface resistance	Surface in contact with air			0.13
Total		**324.7**		**8.06**

Roof

The selected materials, corresponding thicknesses, thermal conductivities and resistances for the roof construction, defined by Hunton, are displayed in Table 6.23. The total thermal resistance for the roof was calculated to be 9.34 (m^{2}K)/W, using Equation 3.1. The U-value for the roof was calculated to be 0.11 W/(m^{2}K), using Equation 3.3. The TEK17 minimum requirement for roofs, $U_{roof} \leq 0.13$ W/(m^{2}K), given in Table 3.2 was therefore satisfied.

Table 6.23: The selected Hunton construction of the roof.

Construction layer	**Selected material**	**Thickness [mm]**	**Thermal conductivity [W/(mK)]**	**Thermal resistance [m^{2}K/W]**
External surface resistance	Surface in contact with air			0.04
Roofing	Tiles	15	2	0.0075
Cavity	Air	20	0.025	0.8
Wind barrier	Hunton Windproof	18	0.049	0.37
Insulation (1st layer)	Nativo Wood Fiber Insulation Loose Fill	200	0.038	5.26
Insulation (2nd layer)	Nativo Wood Fiber Insulation Boards	100	0.038	2.63
Soundproofing layer	Fermacell gypsum fiber	12.5	0.316	0.039
Vapor barrier	Hunton Intello Plus	0.2	0.17	0.0012
Interior cladding	Gypsum board	15	0.17	0.09
Internal surface resistance	Surface in contact with air			0.10
Total		**380.7**		**9.34**

Ground floor

The selected materials, corresponding thicknesses, thermal conductivities and resistances for the ground floor construction, defined by Hunton, are displayed in Table 6.24. The total thermal resistance for this floor construction was calculated to be 10.62 (m^{2}K)/W, using Equation 3.1. The U-value was calculated to be 0.095 W/(m^{2}K), using Equation 3.3. The TEK17 minimum requirement for floors, $U_{floor} \leq 0.10$ W/(m^{2}K), given in Table 3.2 was therefore satisfied. The Hunton floors are constructed to have the possibility of implementing heating pipes to achieve a hydronic radiant floor system.

Table 6.24: The selected Hunton construction of the ground floor.

Construction layer	**Selected material**	**Thickness [mm]**	**Thermal conductivity [W/(mK)]**	**Thermal resistance [m^2K/W]**
Internal surface resistance	Surface in contact with air			0.10
Floor covering	Fermacell gypsum fiber	10	0.316	0.032
Impact sound insulation	Hunton Silencio	36	0.05	0.72
Subfloor	Forestia standard chipboard flooring	22	0.14	0.16
Insulation	Nativo Wood Fiber Insulation Loose Fill	350	0.038	9.21
Structural base	Crushed stone	200	0.5	0.40
Total		**618**		**10.62**

Intermediate floor

The selected materials, corresponding thicknesses, thermal conductivities and resistances for the intermediate floor construction, defined by Hunton, are displayed in Table 6.25. The total thermal resistance for this floor construction was calculated to be 6.95 (m^2K)/W, using Equation 3.1. The U-value was calculated to be 0.14 W/(m^2K), using Equation 3.3.

Table 6.25: The selected Hunton construction of the intermediate floor.

Construction layer	**Selected material**	**Thickness [mm]**	**Thermal conductivity [W/(mK)]**	**Thermal resistance [m^2K/W]**
Internal surface resistance	Surface in contact with air			0.10
Floor covering	Fermacell gypsum fiber	10	0.316	0.032
Impact sound insulation	Hunton Silencio	36	0.05	0.72
Subfloor	Forestia standard chipboard flooring	22	0.14	0.16
Insulation	Nativo Wood Fiber Insulation Loose Fill	200	0.038	5.26
Soundproofing layer	Gyproc AP 25	25	0.05	0.5
Ceiling (1st layer)	Fermacell gypsum fiber	12.5	0.316	0.039
Ceiling (2nd layer)	Fermacell gypsum fiber	12.5	0.316	0.039
Internal surface resistance	Surface in contact with air			0.10
Total		**318**		**6.95**

6.4 Chosen building structure for the passive house models

The passive house models for the three building types were based on the simulation background given in the sections "General input parameters" and "Chosen building structure for the TEK17 models". However, some adjustments were necessary to meet the passive house requirements. Firstly, the normalized thermal bridge value was reduced to 0.03 $W/(m^2K)$, in accordance with Table 3.3. Further, the insulation thicknesses in the construction of the opaque walls, roof and ground floors were increased, while the rest of the construction components remained the same as for the TEK17 models. The change in insulation thicknesses is further described in the following sections.

Opaque walls

The thermal insulation layer consisting of mineral wool was increased from 200 mm in the TEK17 model to 350 mm in the passive house model. This was to meet the passive house requirement with a U-value of maximum 0.1 $W/(m^2K)$. With a thermal insulation thickness of 350 mm, the total U-value of the opaque wall was calculated to be 0.091 $W/(m^2K)$. When the insulation layer is larger than 200 mm, a convection barrier is recommended.

Roof

The thermal insulation layer consisting of mineral wool was increased from 250 mm in the TEK17 model to 400 mm in the passive house model. This was to meet the passive house requirement with a U-value of maximum 0.08 - 0.09 $W/(m^2K)$. With a thermal insulation thickness of 400 mm, the total U-value of the roof was calculated to be 0.074 $W/(m^2K)$.

Ground floor

The thermal insulation layer consisting of mineral wool was increased from 300 mm in the TEK17 model to 450 mm in the passive house model. This was to meet the passive house requirement with a U-value of maximum 0.08 $W/(m^2K)$. With a thermal insulation thickness of 450 mm, the total U-value of the ground floor without heating pipes was calculated to be 0.076 $W/(m^2K)$ for the floor construction with parquet as floor covering and 0.077 $W/(m^2K)$ for the floor construction ceramic tiles as floor covering. The total U-value of the ground floor with heating pipes was calculated to be 0.072 $W/(m^2K)$ for both parquet and ceramic tiles as floor covering.

Increased insulation thicknesses

The increased insulation thicknesses are displayed in Table 6.26, comparing the insulation thicknesses in the TEK17 models with the passive house models.

Table 6.26: Summary of the insulation thicknesses.

Construction	Thickness of insulation TEK17 [mm]	Thickness of insulation Passive house [mm]	Increased thickness [mm]
Opaque wall	200	350	150
Roof	250	400	150
Ground floor	300	450	150

7 Results and discussion

The following section presents the simulation results for the models and the respective discussion regarding the results. An overview of the various IDA ICE models developed in this thesis, along with the applied technologies and heating units, is presented in Table 7.1. These models represent the various scenarios, namely S0, S1 and S2, corresponding to the use of ideal heaters, radiators and floor heating, respectively.

Table 7.1: Overview of the different models with respective scenarios.

	S0 TEK17	**S1 TEK17**	**S2 TEK17**	**S0 Hunton**	**S0 Passive**	**S1 Passive**	**S2 Passive**
Temperature setting 1	X						
Temperature setting 2	X	X	X	X	X	X	X
Ideal heaters	X			X	X		
Radiators		X				X	
Floor heating			X				X
Heat pump			X				X

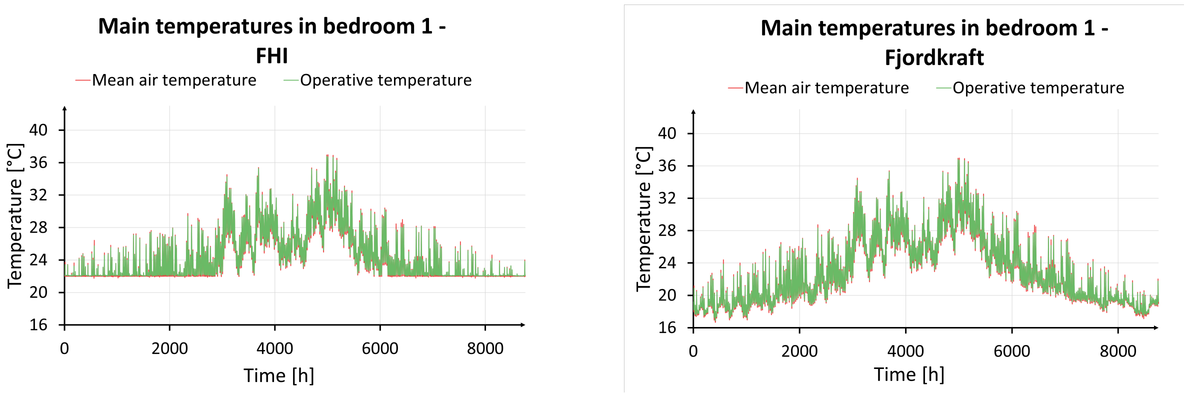
7.1 Single family house - TEK17

Scenario 0

Scenario 0 involved modeling ideal heaters as a reference scenario to establish a foundation for the sizing of radiators. Two different temperature settings were evaluated:

1. A standard temperature level between 22 - 24°C defined by FHI.
2. Specific setpoint temperatures for each zone given in Table 2.2 recommended by Fjordkraft.

The temperature distribution in bedroom 1 is displayed in Figure 7.1. Both of the two mentioned temperature settings above were individually implemented in the model. With setting 2, the suggested temperature level for a bedroom is between 16 - 18°C. These figures illustrate significant variations in the indoor temperatures throughout the year, which did not result in an acceptable indoor environment as the temperatures were too high. In this situation, it would be necessary with cooling in order to achieve an acceptable indoor temperature.

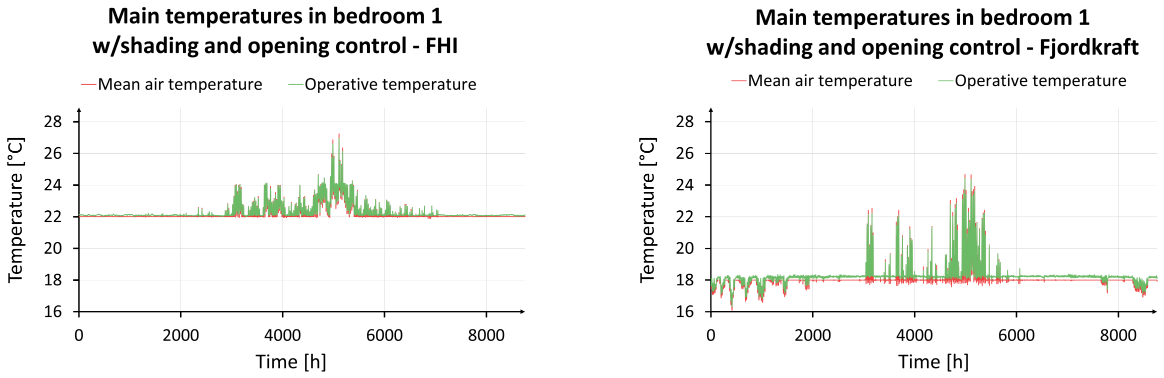


((a)) Main temperatures in bedroom 1 - FHI.

((b)) Main temperatures in bedroom 1 - Fjordkraft.

Figure 7.1: Single family house, Scenario 0 - TEK17: Temperature distribution in bedroom 1.

With the aim of avoiding such high indoor temperatures, external shading and opening control of the windows were considered. Generic markisolettes were implemented as external shading, in addition to PI temperature controlled opening of the windows. The temperature distribution for bedroom 1 after the implementation of these measures is displayed in Figure 7.2. The models with external shading and opening control resulted in comfortable indoor temperatures for the majority of the year. Based on these figures, this measure was evaluated to be necessary and was used in all the models to achieve an adequate thermal indoor environment.



((a)) Main temperatures in bedroom 1 w/shading and opening control - FHI.

((b)) Main temperatures in bedroom 1 w/shading and opening control - Fjordkraft.

Figure 7.2: Single family house, Scenario 0 - TEK17: Temperature distribution in bedroom 1 with external shading and opening control.

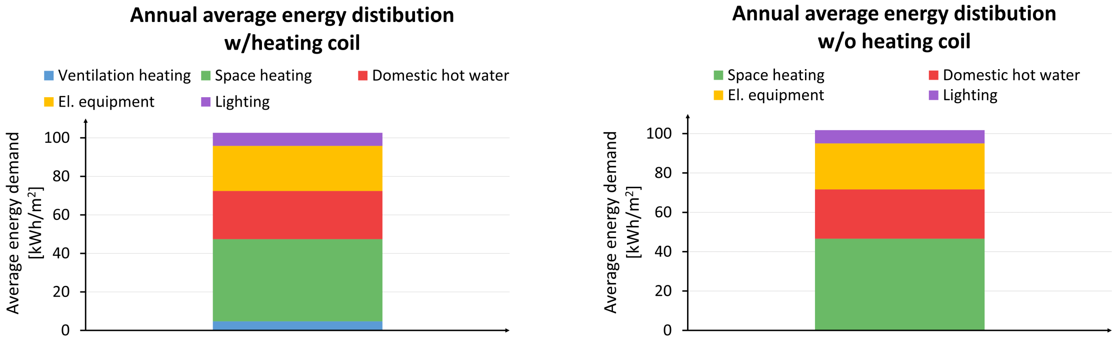
The temperature distribution for the model with setting 2 had an overall lower temperature than the model with setting 1. Specifically for bedroom 1, it can be observed that the temperature distribution in Figure 7.2(b) varied between 16 - 18 °C. However, during the summer months, the temperature varied between 18 - 25 °C. This was evaluated to be acceptable temperatures for a short period of time.

It is often preferred to have a colder temperature level in a bedroom, and therefore a setpoint temperature at 16 - 18°C is beneficial. In this case, it was not necessary with cooling of the room, since the temperature was at an adequate level for the majority of the time. This applied to all of the rooms in the single family house, as it would not be profitable to implement cooling when the cooling demand is low and only occurred during a short period of time.

Based on the comparison between the two temperature settings evaluated, setting 2 was the most optimal temperature solution for the single family house. This solution gave an overall lower and acceptable temperature distribution throughout the year and eliminated the demand for cooling. To conclude, this temperature solution was therefore applied to all of the models for the single family house.

Further, the total energy demand was analyzed. The total energy demand for a single family house must not exceed the maximum allowed energy demand given in TEK17. By using Equation 3.4 with a heated floor area of 174.6 m^2, the maximum allowed energy demand for the single family house was calculated to be 109.2 kWh/(m^2year). With temperature setting 2, the total annual energy demand was simulated to be 17 911 kWh/year, and the annual average energy demand was 103 kWh/(m^2year), for the model with heating coil. This annual average energy distribution is displayed in Figure 7.3(a). This was an acceptable energy level that satisfied the TEK17 maximum allowed energy demand.

Figure 7.3(a) displays that the air handling unit accounted for approximately 5% of the total energy demand as ventilation heating. The air handling unit preheats the outdoor air with an electric heating coil. However, this is an expensive heating alternative, and is not an energy efficient solution for space heating[76]. Further, the heating coil was turned off and this situation is displayed in Figure 7.3(b), where the energy demand for space heating was entirely covered by ideal heaters. The total annual energy demand was simulated to be 17 809 kWh/year, and the annual average energy demand was 102 kWh/(m^2year) for this model without heating coil. This was an acceptable energy level that satisfied the TEK17 maximum allowed energy demand.

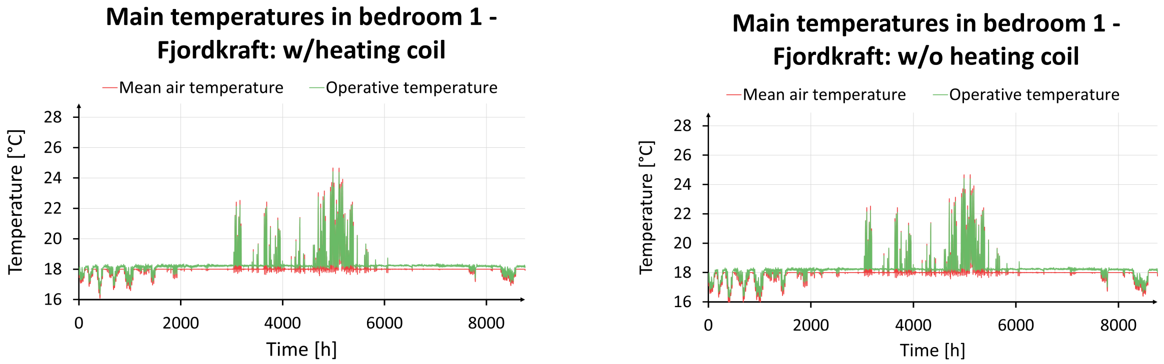


((a)) Annual average energy distribution for the building with a heating coil.

((b)) Annual average energy distribution for the building without a heating coil.

Figure 7.3: Single family house, Scenario 0 - TEK17: Comparison of the annual average energy distribution with and without a heating coil.

By comparing the two graphs, it can be seen that the ventilation heating had an insignificant impact on both the total energy demand and temperature distribution. This is illustrated in Figure 7.4 for bedroom 1, where the temperature distribution in the zones stayed approximately the same.



((a)) Main temperatures in bedroom 1 with a heating coil.

((b)) Main temperatures in bedroom 1 without a heating coil.

Figure 7.4: Single family house, Scenario 0 - TEK17: Temperature distribution in bedroom 1 with and without a heating coil.

The simulated peak power demands for space heating of the single family house are displayed in Table 7.2. The simulated peak power demands associated with the two temperature settings were evaluated, both with and without a heating coil in the air handling unit. When the heating coil was turned off, a slight increase in peak power demands occurred for both cases. This is because the ideal heater had to compensate for the heating demand initially covered by the air handling unit.

Compared to the FHI temperatures, the peak power demands in the bedrooms and the corridor were lower with the Fjordkraft temperatures. However, the peak power demands for the bathrooms and the kitchen and living room were higher with the Fjordkraft temperatures than with the FHI temperatures. This is because of the low temperatures in the adjacent zones next to the bathrooms and the kitchen and living room in the Fjordkraft models.

Table 7.2: Single family house, Scenario 0 - TEK17: Simulated peak power demands for space heating.

Room	**Simulated peak power demand [W]**			
	FHI		**FK**	
Heating coil	**w**	**w/o**	**w**	**w/o**
Bedroom 1	309	360	0	94
Bedroom 2	192	244	0	52
Bedroom 3	370	478	0	120
Corridor	370	425	10	114
Bathroom 1	252	366	392	576
Bathroom 2	237	316	366	493
Kitchen/Living room	1497	1705	1748	2142

Scenario 1

The TEK17 model for the single family house was modified by implementing radiators as heating units instead of having ideal heaters. The radiators were sized based on an evaluation of the simulated peak power demands for space heating presented in Table 7.2. The chosen peak powers for space heating is displayed in Table 7.3. These were determined with temperature setting 2, to achieve a more comfortable thermal environment. In addition, the heating coil was turned off.

Table 7.3: Single family house, Scenario 1 - TEK17: Chosen peak powers for space heating.

Room	**Chosen peak power [W]**
Heating coil	**w/o**
Bedroom 1	150
Bedroom 2	100
Bedroom 3	150
Corridor	150
Bathroom 1	550
Bathroom 2	450
Kitchen/ Living room	1750

The model was simulated with the chosen parameters for radiators in the section "Heating units" under "Simulation input". The water based space heating profile is displayed in Figure 7.5.

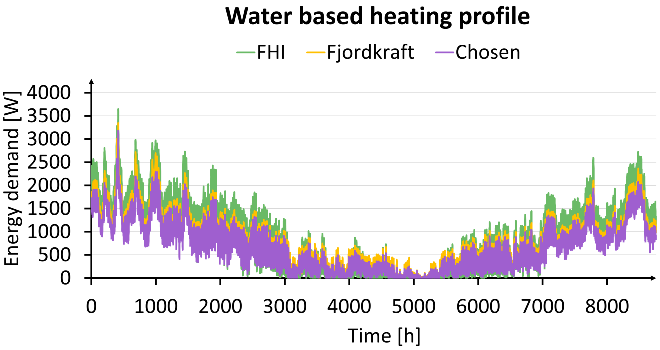
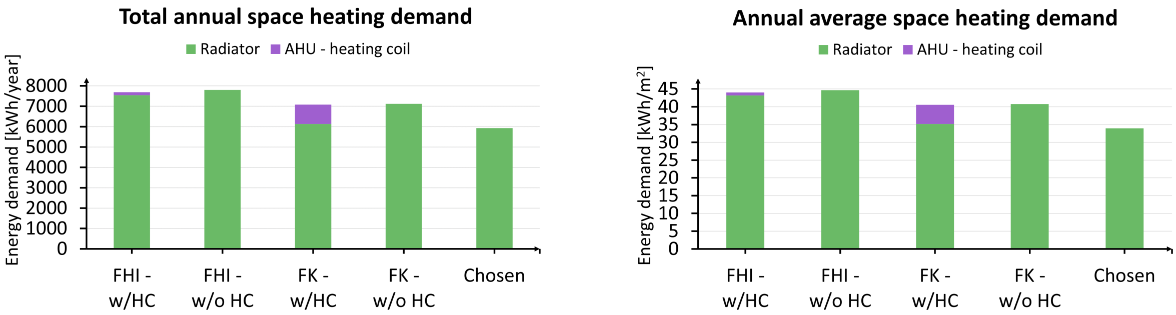


Figure 7.5: Singe family house, Scenario 1 - TEK17: The water based space heating profile.

Figure 7.5 illustrates the yearly water based space heating profile for FHI, FK and the chosen peak powers. With the latter case, the yearly heating profile was overall lower compared to FHI and FK. In addition, it can be seen that the water based heating profiles followed a similar trend for the three cases. As expected, the water based heating demand decreased during the summer months due to the higher outdoor temperatures in this period.

The total annual and the annual average space heating demands are displayed in Figure 7.6(a) and Figure 7.6(b), respectively.



((a)) Total annual space heating demand. ((b)) Annual average space heating demand.

Figure 7.6: Single family house, Scenario 1 - TEK17: Total annual and annual average space heating demand.

It can be seen that the air handling unit covered a small share of the total space heating demand. The figures show that when the heating coil was turned off, the radiators had to compensate to cover the total heating demand. With the chosen peak powers from Table 7.3, the energy demand for space heating was significantly reduced compared to the other four categories simulated. The heating coil in the air handling unit was therefore determined to be turned off in all of the models presented in the following sections.

The temperature distribution in bedroom 1 is displayed in Figure 7.7 with the chosen peak powers from Table 7.3. By simulating the model with temperature setting 2, it can be seen that the indoor temperatures were relatively stable around the recommended temperature level between 16 - 18 °C throughout the year. There were some expected temperature variations during the summer months, with a peak of approximately 24.5 °C. Overall, this represented an adequate indoor temperature.

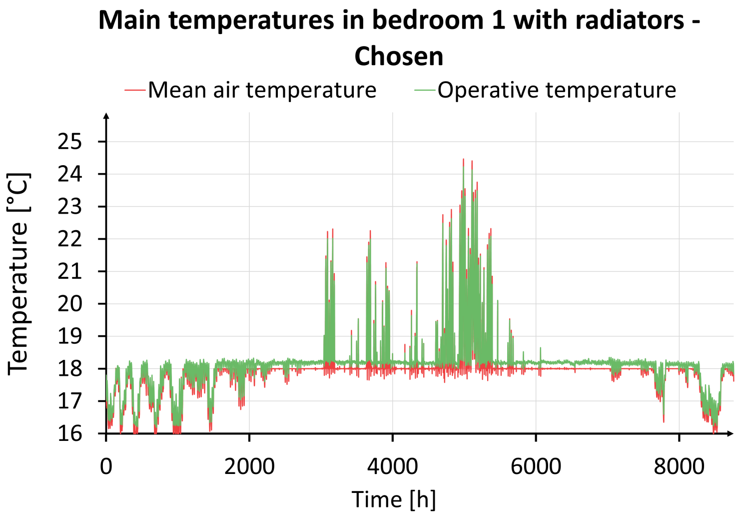


Figure 7.7: Single family house, Scenario 1 - TEK17: Main temperatures in bedroom 1 - Chosen.

The monthly energy distribution for the single family house with radiators is displayed in Figure 7.8. As seen in this figure, the share of energy demand for space heating varied throughout the year with a higher share in the winter months. The energy demand for the other three internal loads was approximately constant throughout the year. The single family house had the highest energy demand in January, with a demand of approximately 2000 kWh. The lowest energy demand occurred during the summer, with a demand just above 800 kWh in June, July and August. The reason for this was the minimal space heating demand during these months, due to higher outdoor temperatures.

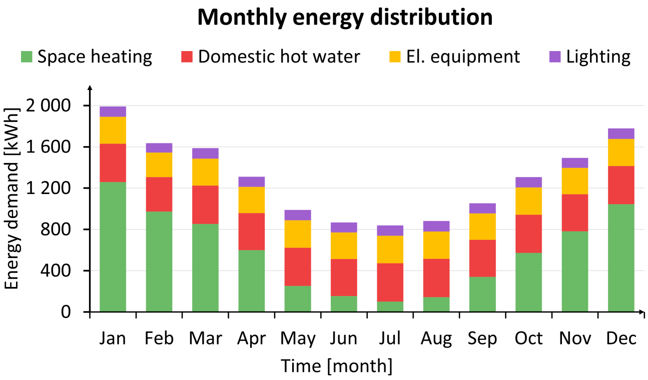
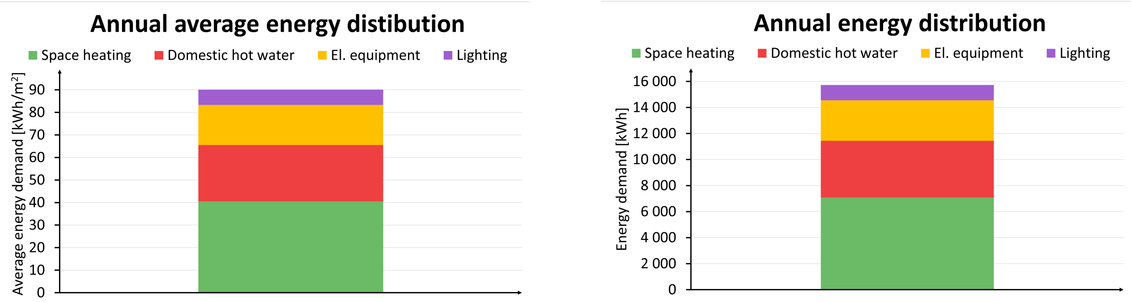


Figure 7.8: Single family house, Scenario 1 - TEK17: Monthly energy distribution.

The annual average and the annual energy distribution for the TEK17 model with radiators are displayed in Figure 7.9. The average energy demand was 90 kWh/(m^{2}year), which means that the building satisfied the TEK17 maximum allowed energy demand. This was a reduction of approximately 12% compared to the situation with ideal heaters as heating units. The total annual energy distribution for the building was 15 714 kWh/year.

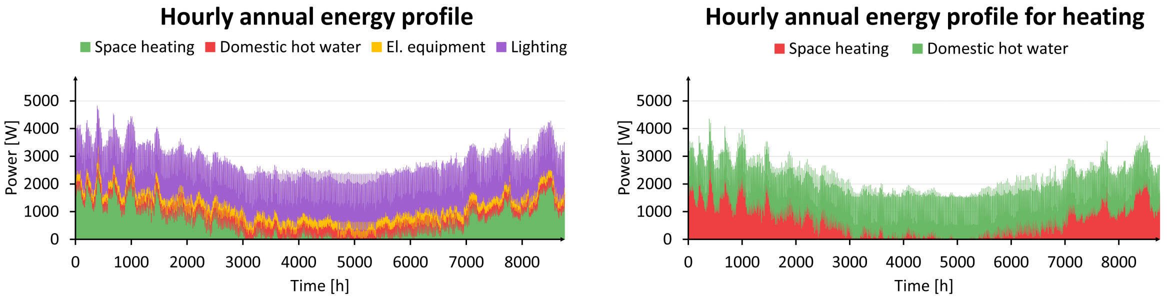


((a)) Annual average energy distribution.

((b)) Annual energy distribution.

Figure 7.9: Single family house, Scenario 1 - TEK17: Energy distribution.

The hourly annual energy profile and the hourly annual energy profile for heating are displayed in Figure 7.10. As seen in these figures, the share of energy demand for space heating varied throughout the year with a higher share in the winter months. This result was as expected since the outdoor temperatures are lower during this period. In the summer months, the share of energy demand for space heating was approximately nonexistent. The energy demand for the other three internal loads was relatively constant throughout the year.



((a)) Hourly annual energy profile. ((b)) Hourly annual energy profile for heating.

Figure 7.10: Single family house, Scenario 1 - TEK17: Annual energy profiles.

The total energy duration curve is displayed in Figure 7.11. The energy duration curve displays the power from space heating, domestic hot water, electrical equipment and lighting. The duration curve had a total peak power of approximately 5 800 W, with space heating representing the largest share.

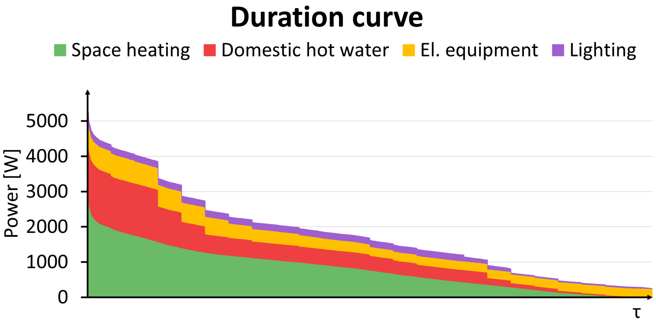
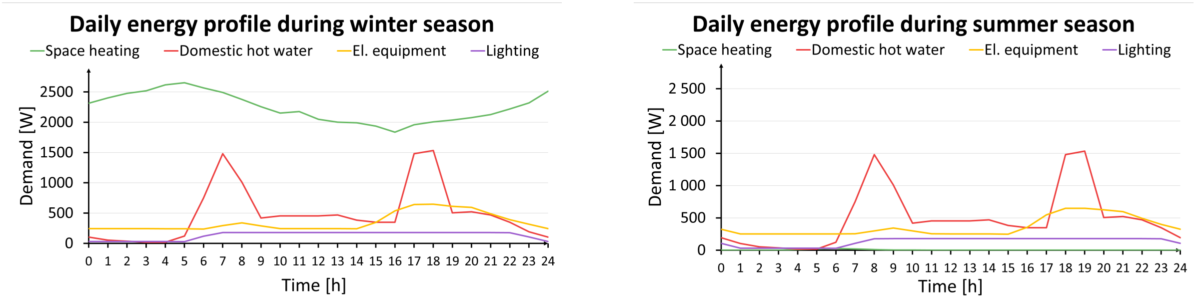


Figure 7.11: Single family house, Scenario 1 - TEK17: Duration curve.

The daily energy profile for the single family TEK17 house with radiators for a winter and summer season is displayed in Figure 7.12.



((a)) Daily energy profile during winter season.

((b)) Daily energy profile during summer season.

Figure 7.12: Single family house, Scenario 1 - TEK17: Daily energy profiles.

The winter curves represent the 11th of February and the summer curves represent the 2nd of August. Due to cold outdoor temperatures during the winter, space heating in the building was necessary. As a result of high outdoor temperatures during the summer season, there was no space heating demand in the summer months. The curve for domestic hot water, electrical equipment, and lighting had the same schedule for the winter and summer seasons and was equal.

Scenario 2

The TEK17 model for the single family house was modified by implementing hydronic radiant floors in specific zones of the building. The floor heating was implemented in the bathrooms and in the kitchen and living room with different heat rates as described in the section "Heating units" under "Simulation input". The floor was sized to emit 10 W/m^2 for each degree difference between the floor surface temperature and the air temperature. The heat rate was therefore set to emit 40 W/m^2 for the bathrooms and 20 W/m^2 for the kitchen and living room. An air-to-water heat pump was implemented to the single family house in combination with the hydronic radiant floor. This heat pump was designed to cover the base load for space and domestic hot water heating, whereas district heating was set to cover the peak load.

The temperature distribution for bedroom 1 is displayed in Figure 7.13. The temperature was 18°C during the majority of the year, with some peak temperatures during the summer months. This was an adequate temperature distribution for the zone and illustrated a comfortable indoor environment. This also applied to the other zones in the building.

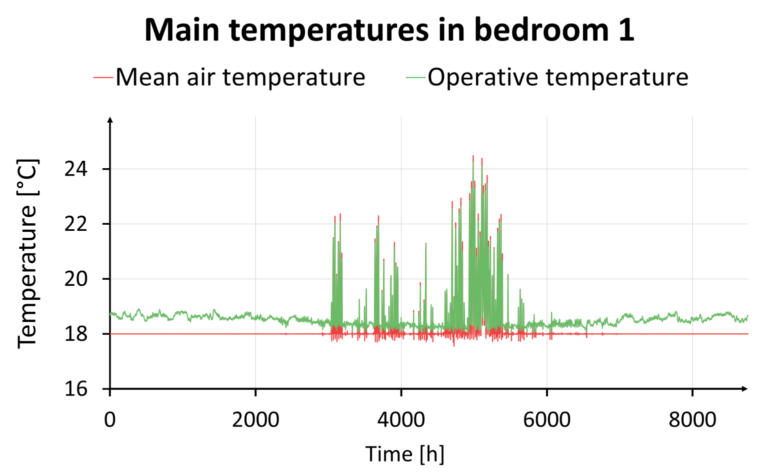
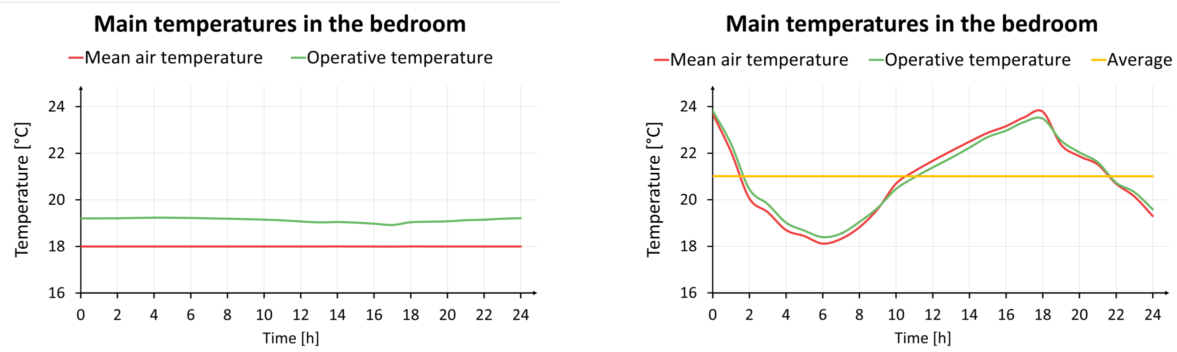


Figure 7.13: Single family house, Scenario 2 - TEK17: Main temperatures in bedroom 1.

The daily temperature profiles for bedroom 1, considering a day during the coldest and warmest season of the year are displayed in Figure 7.14.



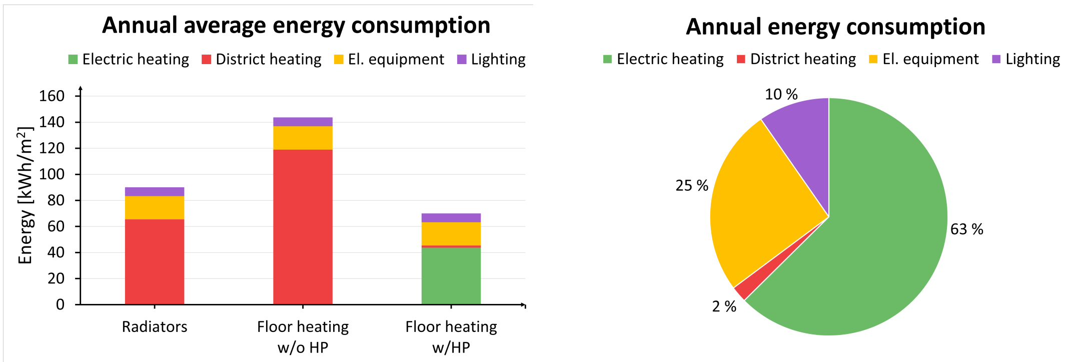
((a)) Daily temperature profile during winter season.

((b)) Daily temperature profile during summer season.

Figure 7.14: Single family house, Scenario 2 - TEK17: Daily temperature profiles.

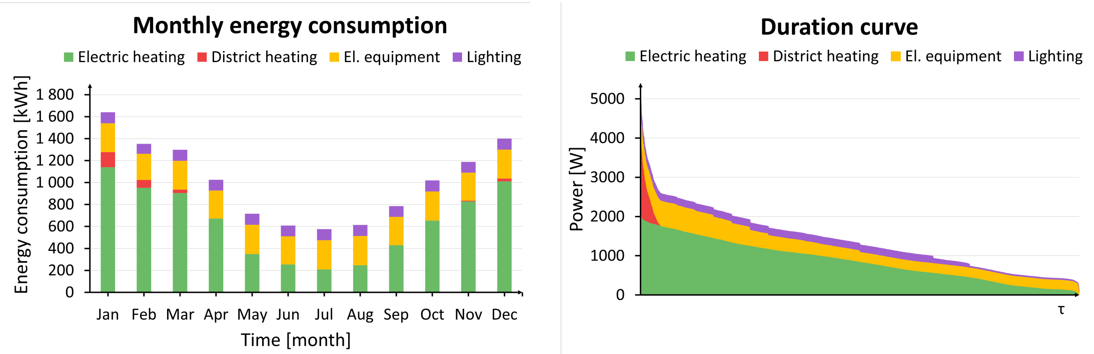
The winter curves in Figure 7.14(a) represent the 11th of February, and the summer curves in Figure 7.14(b) represent the 2nd of August. The temperature in bedroom 1 during the winter season remained relatively constant with an average temperature of 18.5°C throughout the day, while the temperature during the summer varied drastically. The peak temperature for the summer situation was approximately 24°C, whereas the lowest temperature was 18°C. The average temperature was consequently 21°C.

Figure 7.15 displays four different figures that represent the distribution of the energy consumption for the TEK17 single family house.



((a)) Comparison of the energy consumption between three different single family house models.

((b)) Floor heating w/HP: Annual distribution of the energy consumption.



((c)) Floor heating w/HP: Monthly distribution of the energy consumption.

((d)) Floor heating w/HP: Total energy duration curve.

Figure 7.15: Single family house, Scenario 2 - TEK17: Distribution of energy consumption and energy duration curve.

A comparison of the annual average energy consumption between different scenarios for the single family house is displayed in Figure 7.15(a). For the scenario with radiators, the energy consumption was drastically lower compared to the scenario with floor heating without a heat pump. The annual average energy consumption for the building with radiators was 90 kWh/(m^{2}year), whereas for the building with floor heating and without a heat pump, the consumption was 144 kWh/(m^{2}year). In both cases, district heating was the only source that covered the total heating demand. This significant increase in energy demand is further investigated in the section "Comparison of heat losses".

In the scenario with floor heating and a heat pump, the heat pump was selected to cover the base load, while district heating was selected to cover the peak load. Consequently, the heat pump consumed energy to satisfy nearly the entire heating demand, since the energy consumption associated with district heating was close to zero. As the chosen heat pump had a COP of 3.62, and the district heating system had an efficiency of 1, the total amount of purchased energy to cover the same heating demand was significantly reduced to 70 kWh/(m^2year). The total annual energy demand was simulated to be 12 222 kWh/year. An evaluation of the heating systems is further discussed in the section "Evaluation of the heating systems".

The annual distribution of the energy consumption for the single family house is displayed in Figure 7.15(b). This pie chart represents the energy consumption for the building when the single family house had floor heating and a heat pump installed. The electric heating accounted for the biggest share, with 63% of the total energy consumption. Further, the share of energy consumed for electrical equipment and lighting accounted for a smaller part of the total consumption, with 25% and 10% respectively. Lastly, the district heating accounted for an insignificant part of the total consumption with 2%. This chart emphasizes that the heat pump covered most of the heating demand for the building, both for space and domestic hot water heating, while district heating covered the peaks.

The monthly energy consumption for the single family house is displayed in Figure 7.15(c). This figure illustrates the monthly energy distribution from the four loads during one year. The electric heating was used during the whole year with the highest consumption in the coldest months. This means that the heat pump was in use the entire year, and covered the whole heating demand from April to November. The district heating was only in use during January, February, March and December. Hence, it supplied the building with a small share of additional heat during the most critical months to cover the peak demands. Both the energy consumption for electrical equipment and for lighting were constant throughout the year.

The duration curve for the single family house is displayed in Figure 7.15(d). This curve emphasizes the fact that the heat pump covered the base load and was used the entire year. The district heating system covered the peak load and was only used for a short period of time during the year.

7.2 Single family house - Hunton construction

Scenario 0

The single family house was modified by implementing constructions defined by Hunton. The construction of the opaque walls, the roof, the ground and intermediate floors are given in Table 6.22, Table 6.23, Table 6.24 and Table 6.25, respectively. The model with the Hunton construction was solely simulated with ideal heaters as the chosen heating unit, to exclusively evaluate this reference scenario.

Generic markisolettes were implemented as external shading, in addition to PI temperature controlled opening of the windows. Temperature setting 2, with specific setpoint temperatures recommended by Fjordkraft, was applied to the model in accordance with the TEK17 models for the single family house. With temperature setting 2, the suggested temperature level for a bedroom is 16 - 18°C. The temperature distribution for bedroom 1 is displayed in Figure 7.16.

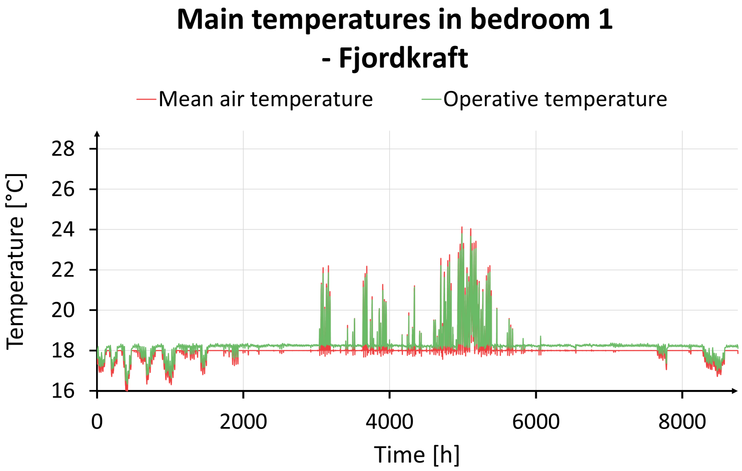
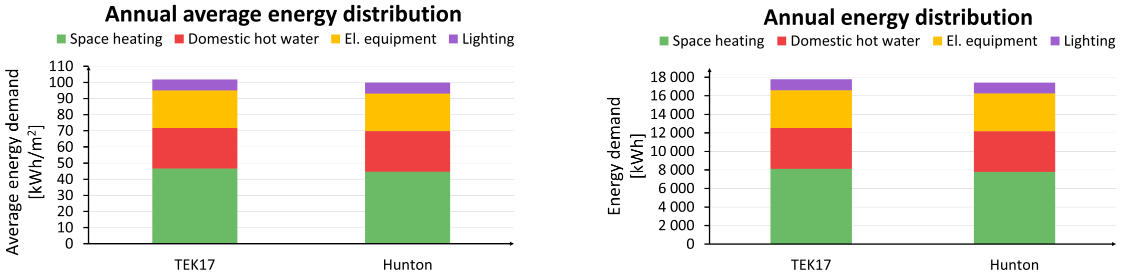


Figure 7.16: Single family house, Scenario 0 - Hunton: Main temperatures in bedroom 1.

It can be observed in Figure 7.16 that the temperature distribution for bedroom 1 varied between 16 - 18°C. However, during the summer months, the temperature varied between 18 - 24°C. This was evaluated to be adequate temperatures for a short period of time. It can also be seen that it was not necessary with cooling of the room since the temperature was at an acceptable level for the majority of the year. This applied to all of the rooms in the single family house, as it would not be profitable to implement cooling when the cooling demand was minimal and only occurred during a short period of time.

Further, the total energy demand was analyzed. The total energy demand for a single family house should not exceed the maximum allowed energy demand given in TEK17. By using Equation 3.4 with a heated floor area of 174.6 m^2, the maximum allowed energy demand for the single family house was calculated to be 109.2 kWh/(m^{2}year). Figure 7.17(a) displays a comparison between the annual average energy demand of a TEK17 and a Hunton construction. For the single family house with Hunton construction, the annual average energy demand was simulated to be 100 kWh/(m^{2}year). This was slightly lower compared to the TEK17 construction with an annual average energy demand of 102 kWh/(m^{2}year).



((a)) Comparison of the annual average energy distributions.

((b)) Comparison of the annual energy distributions.

Figure 7.17: Single family house, Scenario 0: Comparison of the annual average and total energy distributions between the TEK17 and the Hunton models.

As seen in Figure 7.17(b), the total annual energy demand for the Hunton model was 17 425 kWh/year. This was relatively similar to the annual energy demand for the TEK17 model of 17 809 kWh/year. The models satisfying the TEK17 requirements were therefore evaluated to give a realistic result, illustrating how the energy demand in the buildings with Hunton construction can be like.

7.3 Single family house - Passive house

The TEK17 single family house was upgraded with passive house measures defined in the section "Chosen building structure for the passive house models". As determined for the TEK17 models, temperature setting 2 gave the most optimal indoor environment, with external shading and PI temperature control of the windows. In addition, the heating coil in the air handling unit was determined to be turned off in the following scenarios.

Scenario 0

After implementing the passive house measures to the single family house, the indoor temperatures were still acceptable. The temperature distribution for bedroom 1 is displayed in Figure 7.18.

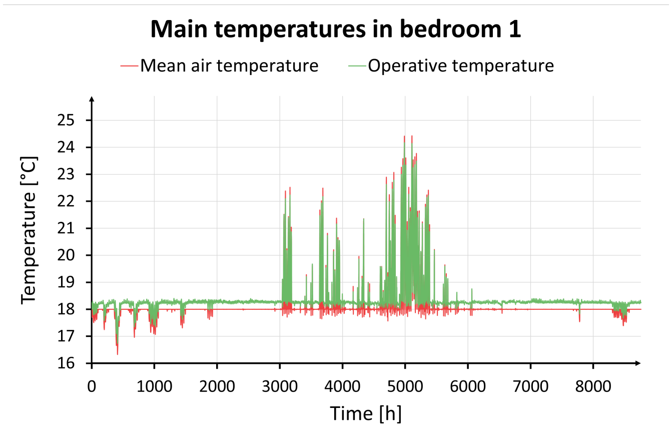
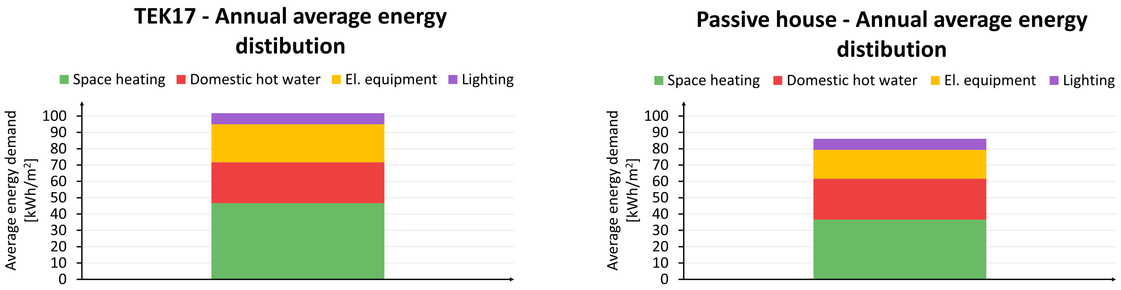


Figure 7.18: Single family house, Scenario 0 - Passive: Main temperatures in bedroom 1.

A comparison between the annual average energy distribution for the TEK17 model and the passive house model is displayed in Figure 7.19. As seen in Figure 7.19(a), the annual average energy demand for the TEK17 model was 102 kWh/(m^{2}year). For the passive house model the energy demand was significantly reduced to 86 kWh/(m^{2}year), as displayed in Figure 7.19(b). The total annual energy demand was 15 016 kWh/year. The reduction was caused by a lower space heating demand, in addition to a lower electrical equipment demand in the passive house model.



((a)) TEK17: Annual average energy distribution.

((b)) Passive: Annual average energy distribution.

Figure 7.19: Single family house, Scenario 0: Comparison of the annual average energy distribution between the TEK17 and the passive house models.

Figure 7.19(b) also displays that the passive house had a space heating demand of 37 kWh/(m^2year). This means that the passive house with ideal heaters was not within the calculated net energy demand for space heating for a passive residential building of 15 kWh/(m^2year) as described in the section "Requirements for energy efficiency" in the literature review. Whereas the three other loads covering lighting, electrical equipment and domestic hot water heating accounted for a total of approximately 50 kWh/(m^2year). According to the literature review, this building satisfied the maximum limit of 58.7 kWh/(m^2year) for these internal loads.

A comparison of the simulated peak power demands associated with the two temperature settings is displayed in Table 7.4. As previously stated, the recommendations by Fjordkraft are the most optimal to achieve a comfortable indoor thermal environment. This was also the most energy efficient solution, as the simulated peak power demands were significantly reduced compared to setting 1 based on FHI's recommendations, as illustrated in Table 7.4. This temperature setting eliminated the heating demands in the bedrooms and the corridor. To compensate for this, the demands were slightly higher in the remaining zones compared to FHI.

Table 7.4: Single family house, Scenario 0 - Passive: Simulated peak power demands for space heating.

Room	**Simulated peak power demand [W]**	
	FHI	**FK**
Bedroom 1	281	0
Bedroom 2	203	0
Bedroom 3	383	0
Corridor	320	0
Bathroom 1	303	501
Bathroom 2	258	421
Kitchen/ Living room	1293	1660

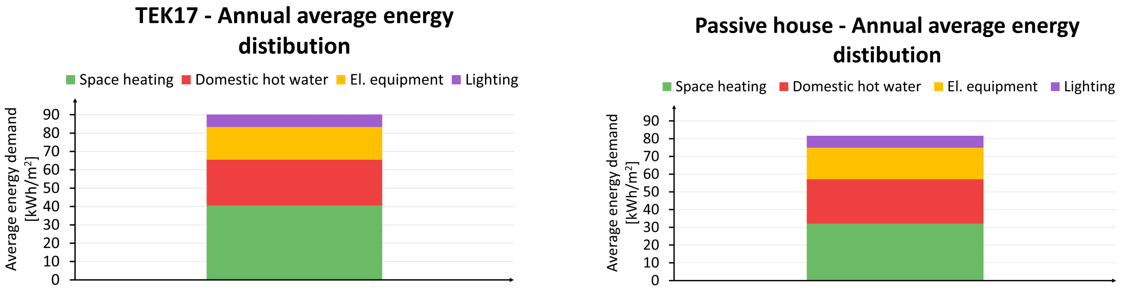
Scenario 1

The passive single family house model was modified by implementing radiators as heating units, instead of ideal heaters. The radiators were sized based on an evaluation of the simulated peak power demands for space heating presented in Table 7.4, using the recommendations by Fjordkraft. The chosen peak powers for radiators in both the TEK17 and the passive single family house are displayed in Table 7.5.

Table 7.5: Single family house, Scenario 1: Comparison of the chosen peak powers for space heating between the TEK17 and the passive house model.

Room	**Chosen peak power [W]**	
	TEK17	**PH**
Bedroom 1	150	0
Bedroom 2	100	0
Bedroom 3	150	0
Corridor	150	0
Bathroom 1	550	500
Bathroom 2	450	400
Kitchen/ Living room	1750	1350

A comparison of the annual average energy distribution between the TEK17 and the passive house model is displayed in Figure 7.20. As seen in Figure 7.20(a), the annual average energy demand for the TEK17 model was 90 kWh/(m^{2}year). For the passive house model, the energy demand was considerably reduced to 81 kWh/(m^{2}year), as seen in Figure 7.20(b). The total annual energy demand was 14 143 kWh/year. This reduction was due to a lower space heating demand in the passive house model.



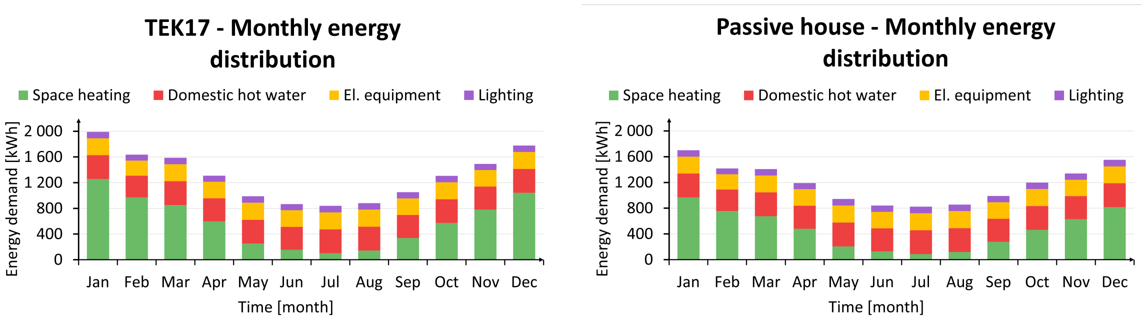
((a)) TEK17: Annual average energy distribution.

((b)) Passive: Annual average energy distribution.

Figure 7.20: Single family house, Scenario 1: Comparison of the annual average energy distribution between the TEK17 and the passive house models.

The space heating demand was reduced from 40.5 kWh/(m^{2}year) in the TEK17 model to 32 kWh/(m^{2}year) in the passive house model. This means that the passive house with radiators, just like scenario 0, was not within the calculated net energy demand for space heating for a passive residential building of 15 kWh/(m^{2}year), as described in the section "Requirements for energy efficiency" in the literature review. The three other loads covering lighting, electrical equipment and domestic hot water heating accounted for a total of approximately 50 kWh/(m^{2}year). According to the literature review, this building satisfied the maximum limit of 58.7 kWh/(m^{2}year) for these internal loads.

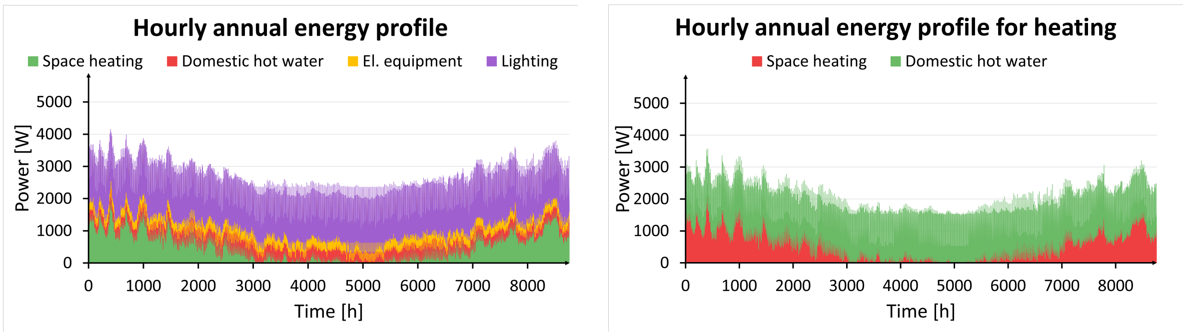
For scenario 1, the monthly energy distributions for the single family house, both with TEK17 and passive house measures, are displayed in Figure 7.21. As illustrated, the two figures had the same energy distribution trend. However, the passive house had an overall lower energy demand compared to the TEK17 model. This especially applied to the coldest months of the year, whereas for the summer months, the energy demand remained approximately the same for the two models. This reduction was caused by the decreased space heating demand in the passive house due to the passive house measures.



((a)) TEK17: Monthly energy distribution. ((b)) Passive: Monthly energy distribution.

Figure 7.21: Single family house, Scenario 1: Comparison of the monthly energy distribution between the TEK17 and the passive house models.

The hourly annual energy profile and the hourly annual energy profile for heating are displayed in Figure 7.22.



((a)) Hourly annual energy profile. ((b)) Hourly annual energy profile for heating.

Figure 7.22: Single family house, Scenario 1 - Passive: Energy profiles.

As seen in these figures, the share of energy demand for space heating varied throughout the year with a higher share in the winter months. This result was as expected since the outdoor temperatures are lower during this period. In the summer months, the share of energy demand for space heating was approximately nonexistent. The energy demand for the other three internal loads was relatively constant throughout the year.

The total energy duration curve is displayed in Figure 7.23. The energy duration curve displays the power from space heating, domestic hot water, electrical equipment and lighting. The duration curve had a total peak power of approximately 4 800 W, with space heating representing the largest share.

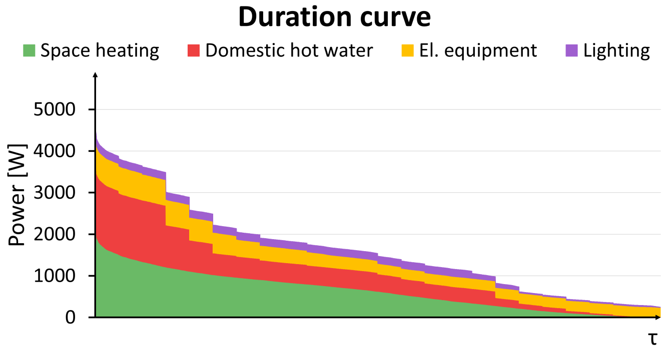
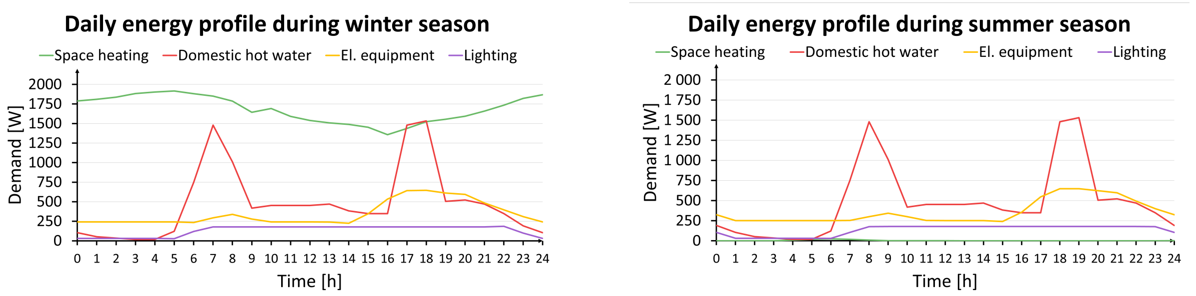


Figure 7.23: Single family house, Scenario 1 - Passive: Duration curve.

The daily energy profile for the single family passive house with radiators for a winter and summer season is displayed in Figure 7.24.



((a)) Daily energy profile during winter season. **((b))** Daily energy profile during summer season.

Figure 7.24: Single family house, Scenario 1 - Passive: Daily energy profiles.

The winter curves represent the 11th of February and the summer curves represent the 2nd of August. The daily energy profile for the single family passive house with radiators for winter is displayed in Figure 7.24(a). The space heating was reduced by approximately 500 W each hour compared to the building satisfying the TEK17 requirements in Figure 7.12(a). The other parameters, such as domestic hot water, electrical equipment and lighting, remained the same. The same graph for the summer season is displayed in Figure 7.24(b), and was similar to Figure 7.12(b) for the TEK17 model with radiators.

Scenario 2

The passive house model for the single family house was modified by removing the radiators, and implementing hydronic radiant floors in specific zones of the building. The floor heating was implemented in the bathrooms and in the kitchen and living room with different heat rates as described in the section "Heating units" under "Simulation input". The floor was sized to emit 10 W/m^2 for each degree temperature difference between the floor surface temperature and the air temperature. The heat rate was therefore set to emit 40 W/m^2 for the bathrooms and 20 W/m^2 for the kitchen and living room. An air-to-water heat pump was implemented to the single family house in combination with the hydronic radiant floor. This heat pump was designed to cover the base load for space and domestic hot water heating. District heating was set to cover the peak load.

The temperature distribution for bedroom 1 is displayed in Figure 7.25. The temperature was approximately 18°C during the majority of the year, with some peak temperatures during the summer months. This was an adequate temperature distribution for the zone and illustrated a comfortable indoor environment. This applied to the other zones in the building as well.

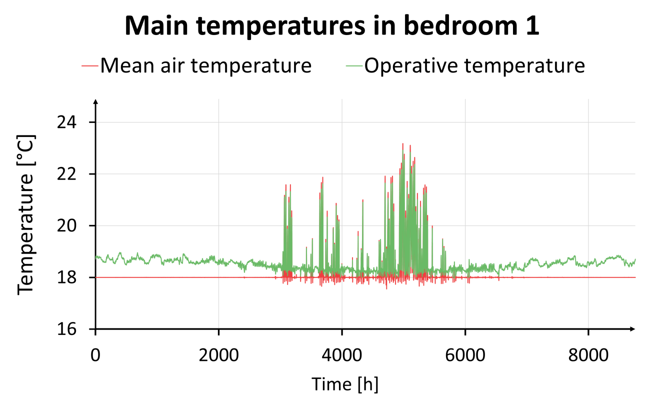
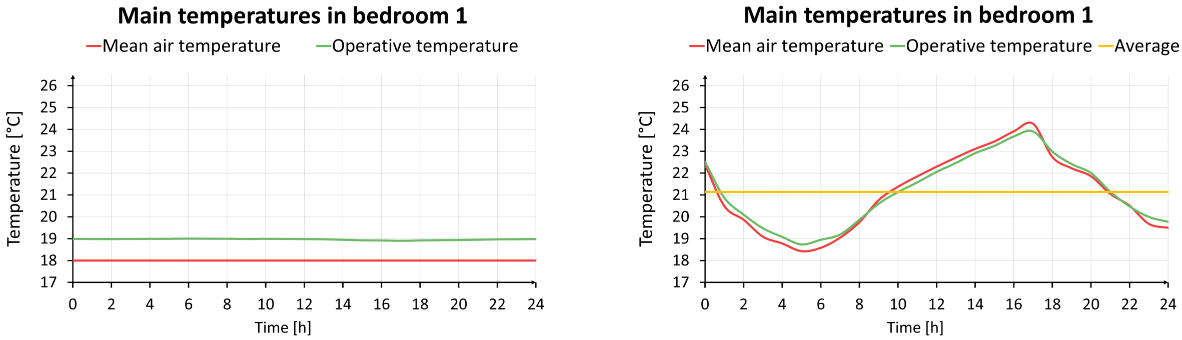


Figure 7.25: Single family house, Scenario 2 - Passive: Main temperatures in bedroom 1.

The daily temperature profiles for bedroom 1, considering a day during the coldest and warmest season of the year are displayed in Figure 7.26.



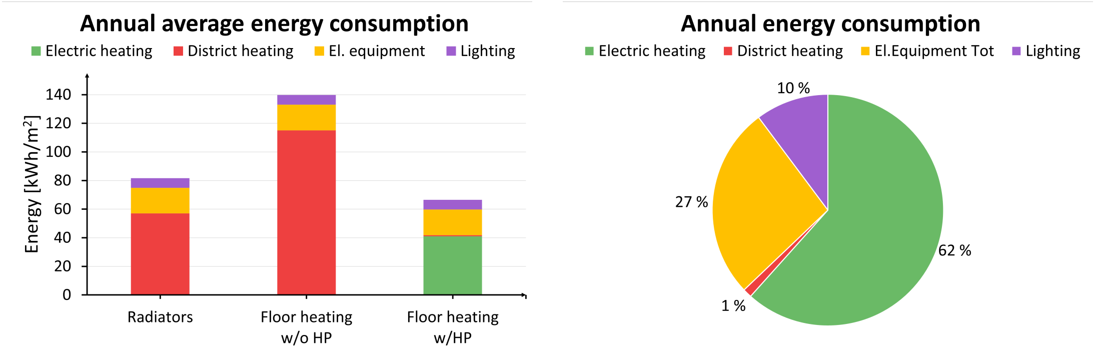
((a)) Daily temperature profile during winter season.

((b)) Daily temperature profile during summer season.

Figure 7.26: Single family house, Scenario 2 - Passive: Daily temperature profiles.

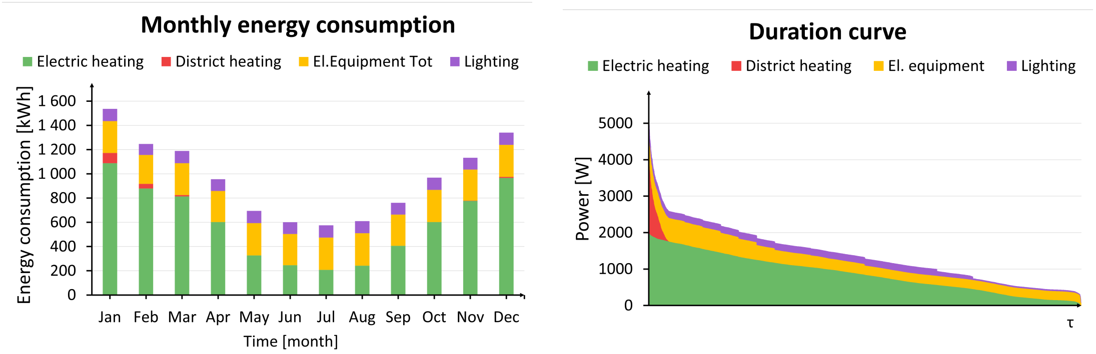
The winter curves in Figure 7.26(a) represent the 11th of February, and the summer curves in Figure 7.26(b) represent the 2nd of August. The temperature in bedroom 1 during the winter season remained relatively constant with an average temperature of 18.5°C throughout the day, while the temperature during the summer varied drastically. The peak temperature for the summer situation was slightly above 24°C, whereas the lowest temperature was 18.5°C. The average temperature was consequently 21.1°C.

Figure 7.27 displays four different figures that represent the distribution of the energy consumption for the single family passive house.



((a)) Comparison of the energy consumption between three different single family house models.

((b)) Floor heating w/HP: Annual distribution of the energy consumption.



((c)) Floor heating w/HP: Monthly distribution of the energy consumption.

((d)) Floor heating w/HP: Total energy duration curve.

Figure 7.27: Single family house, Scenario 2 - Passive: Distribution of energy consumption and energy duration curve.

A comparison of the annual average energy consumption between different scenarios for the single family house is displayed in Figure 7.27(a). For the scenario with radiators, the energy consumption was drastically lower compared to the scenario with floor heating without a heat pump. The annual average energy consumption for the building with radiators was 81 kWh/(m^2year), whereas for the building with floor heating and without a heat pump, the consumption was 140 kWh/(m^2year). In both cases, district heating was the only source that covered the total heating demand. This significant increase in energy demand is further investigated in the section ”Comparison of heat losses”.

In the scenario with floor heating and a heat pump, the heat pump was selected to cover the base load, while district heating was selected to cover the peak load. Consequently, the heat pump consumed energy to satisfy nearly the entire heating demand, since the energy consumption associated with district heating was close to zero. As the chosen heat pump had a COP of 3.62, and the district heating system had an efficiency of 1, the total amount of purchased energy to cover the same heating demand was significantly reduced to 67 kWh/(m^{2}year). The total annual energy demand was simulated to be 11 698 kWh/year. An evaluation of the heating systems is further discussed in the section "Evaluation of the heating systems".

The electric heating is the total amount of heat supplied by the heat pump and covers two areas of heating; space and domestic hot water heating. Based on the simulation results from IDA ICE, these demands amounted to 78.5% and 21.5%, respectively. The district heating covered 1% of the energy demand, and was therefore neglected. For scenario 2 in Figure 7.27(a), the electric heating consumption was 41 kWh/(m^{2}year). Hence, 32.2 kWh/(m^{2}year) was consumed for space heating, and 8.8 kWh/(m^{2}year) for domestic hot water heating. Similar to scenario 0 and 1, the space heating demand was not within the calculated net energy demand for space heating for a passive residential building of 15 kWh/(m^{2}year) as described in the section "Requirements for energy efficiency" in the literature review. In fact, the single family passive house with scenario 2 had twice as high a demand as the requirement. This was unexpected since the passive house was constructed to meet all the energy requirements given in NS3700. However, the energy demands for lighting, electrical equipment and domestic hot water were in total 33.5 kWh/(m^{2}year), which satisfied the requirement of maximum 58.7 kWh/(m^{2}year).

The annual distribution of the energy consumption for the single family house is displayed in Figure 7.27(b). This pie chart represents the energy consumption for the building when the single family house had floor heating and a heat pump installed. The electric heating accounted for the biggest share, with 62% of the total energy consumption. Further, the share of energy consumed for electrical equipment and lighting accounted for a smaller part of the total consumption, with 27% and 10% respectively. Lastly, the district heating accounted for an insignificant part of the total consumption with 1%. This chart emphasizes that the heat pump covered most of the heating demand for the building, while district heating covered the peaks.

The monthly energy consumption for the single family house is displayed in Figure 7.27(c). This figure illustrates the monthly energy distribution from the four loads during one year. The electric heating was used during the whole year with the highest consumption in the coldest months. This means that the heat pump was in use the entire year, and covered the whole heating demand from April to November. The district heating was only in use during January, February, March and December. Hence, it supplied the building with a small share of additional heat during the most critical months to cover the peak demands. Both the energy consumption for electrical equipment and for lighting were constant throughout the year.

The duration curve for the single family house is displayed in Figure 7.27(d). This curve emphasizes the fact that the heat pump covered the base load and was used the entire year. The district heating system covered the peak load, and was solely used for a short period of time during the year.

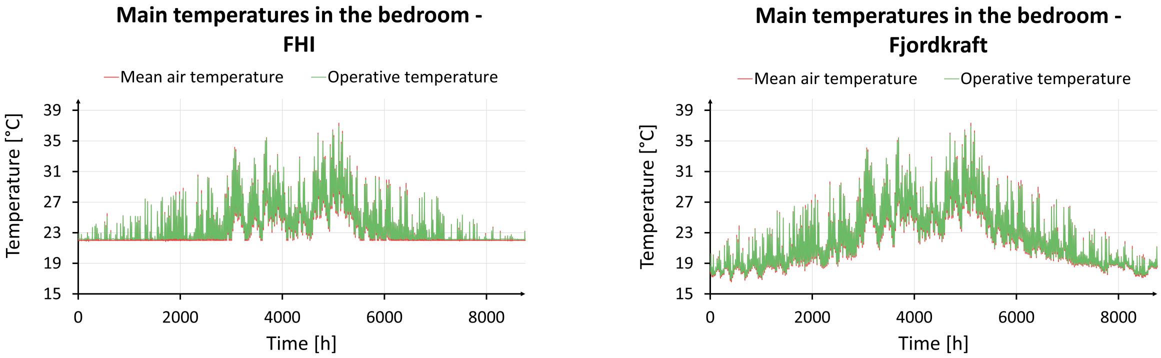
7.4 Row house - TEK17

Scenario 0

Similar to the models for the single family house, the row house was also initially simulated with ideal heaters as a reference scenario to establish a foundation for the sizing of radiators. As stated in the section "Single family house - TEK17", using a heating coil in the air handling unit is not an energy efficient heating solution. Therefore, the heating coil was turned off in all of the models for the row house. The same two different temperature settings were also evaluated for the row house:

1. A standard temperature level between 22 - 24°C defined by FHI.
2. Specific setpoint temperatures for each zone given in Table 2.2 recommended by Fjordkraft.

The temperature distribution in the bedroom is displayed in Figure 7.28. Both of the two mentioned temperature settings above were individually implemented in the model. With setting 2, the suggested temperature level for a bedroom is 16 - 18°C. These figures illustrate significant variations in the indoor temperatures throughout the year, which did not result in an acceptable indoor environment as the temperatures were too high. In this situation, it would be necessary with cooling in order to achieve an acceptable indoor temperature.

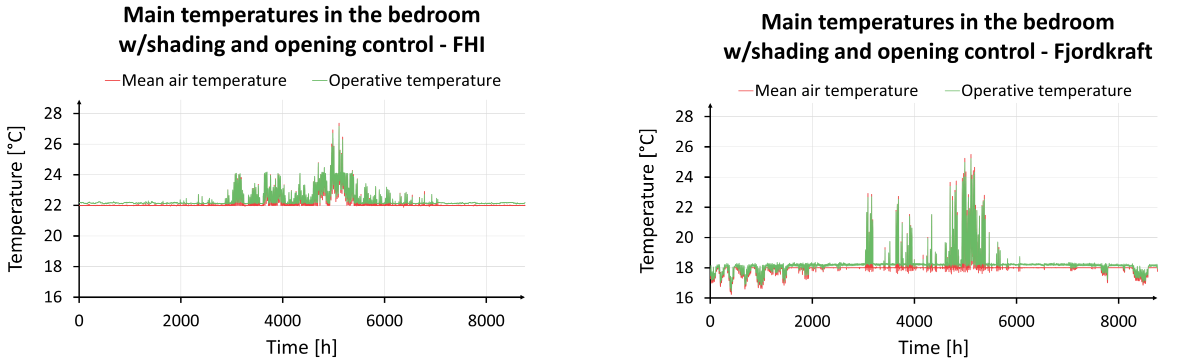


((a)) Main temperatures in the bedroom - FHI.

((b)) Main temperatures in the bedroom - Fjordkraft.

Figure 7.28: Row house, Scenario 0 - TEK17: Temperature distribution in the bedroom.

With the aim of avoiding such high indoor temperatures, external shading and opening control of the windows were considered. Generic markisolettes were implemented as external shading, in addition to PI temperature controlled opening of the windows. The temperature distributions for bedroom 1 after the implementation of these measures are displayed in Figure 7.29. The models with external shading and opening control resulted in comfortable indoor temperatures for the majority of the year. Based on these figures, this measure was evaluated to be necessary and was used in all the models to achieve an adequate thermal indoor environment.



((**a**)) Main temperatures in the bedroom w/shading and opening control - FHI.

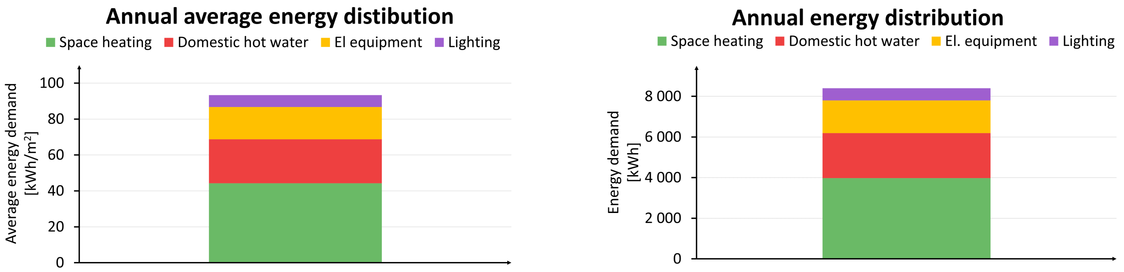
((**b**)) Main temperatures in the bedroom w/shading and opening control - Fjordkraft.

Figure 7.29: Row house, Scenario 0 - TEK17: Temperature distribution in the bedroom with external shading and opening control.

Analogous to the model for the single family house with an ideal heater, the temperature distribution for the row house with setting 2 had an overall lower temperature than the model with setting 1. Since it is often preferred to have a colder temperature level in a bedroom, setting 2 with a setpoint temperature between 16 - 18°C is beneficial. In this case, it was not necessary with cooling of the room since the temperature was at an acceptable level for the majority of the year. This applied to all of the rooms in the single family house, as it would not be profitable to implement cooling when the cooling demand was low and only occurred during a short period of time.

Based on the comparison between the two temperature settings evaluated, setting 2 was the most optimal temperature solution for the row house. This solution gave an overall lower and acceptable temperature distribution throughout the year and eliminated the demand for cooling. To conclude, this temperature solution was therefore applied to all of the models for the row house.

Further, the energy demand was analyzed. The annual average and the total energy distribution for the row house are displayed in Figure 7.30.



((**a**)) Annual average energy distribution.

((**b**)) Annual energy distribution.

Figure 7.30: Row house, Scenario 0 - TEK17: Energy distribution.

The total energy demand for a row house must not exceed the maximum allowed energy demand given in TEK17. By using Equation 3.4 with a heated floor area of 88.39 m^2, the row house had a maximum total energy demand of 118.1 kWh/(m^{2}year). The annual average energy distribution for the TEK17 model is displayed in Figure 7.30(a). The average energy demand was 94 kWh/(m^{2}year), which means that the building satisfied the TEK17 maximum allowed energy demand of 118.1 kWh/(m^2 year). The total annual energy distribution for the building is displayed in Figure 7.30(b). The total annual energy demand for space heating, domestic hot water, electrical equipment and lighting was 8 460 kWh/year.

The simulated peak power demands for space heating of the TEK17 row house with the two temperature settings are displayed in Table 7.6.

Table 7.6: Row house, Scenario 0 - TEK17: Simulated peak power demands for space heating.

Room	**Simulated peak power demand [W]**	
	FHI	**FK**
Bedroom	512	154
Bathroom	438	633
Corridor	100	0
Kitchen/ Living room	993	1074

Scenario 1

The TEK17 model for the row house was modified by implementing radiators as heating units, instead of having ideal heaters. The radiators were sized based on an evaluation of the simulated peak power demands for space heating, presented in Table 7.6. The chosen peak power demands for heating are displayed in Table 7.7. These peak power demands were determined with temperature setting 2, to achieve a more comfortable thermal environment.

Table 7.7: Row house, Scenario 1 - TEK17: Chosen peak powers for space heating.

Room	Chosen peak power [W]
Bedroom	200
Bathroom	600
Corridor	0
Kitchen/ Living room	950

The model was simulated with the chosen parameters for radiators in the section "Heating units" under "Simulation input". The water based space heating profile is displayed in Figure 7.31.

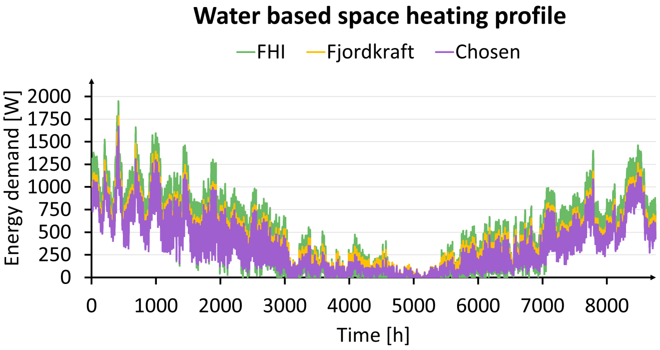
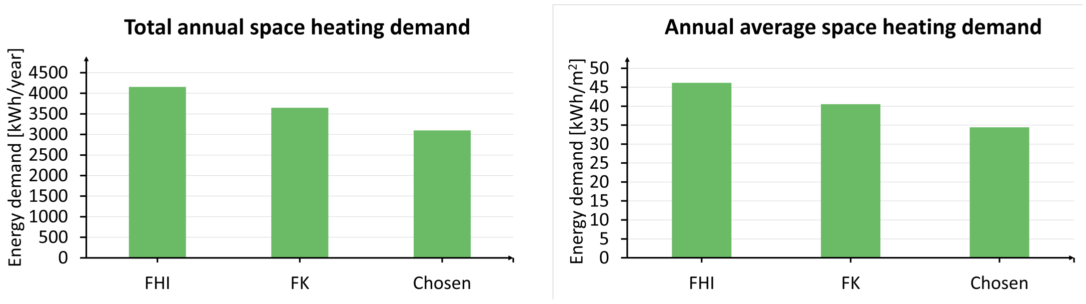


Figure 7.31: Row house, Scenario 1 - TEK17: The water based space heating profile.

Figure 7.31 illustrates the yearly water based space heating profile for FHI, FK and the chosen peak powers. With the latter case, the yearly heating profile was overall lower compared to FHI and FK. In addition, it can be seen that the water based heating profiles followed a similar trend for the three cases. As expected, the water based heating demand decreased during the summer months due to the higher outdoor temperatures in this period.

The total annual and the annual average space heating demand are displayed in Figure 7.32(a) and Figure 7.32(b), respectively. It can be seen from these figures that the space heating demand was clearly reduced with the chosen peak powers compared to the two other categories.



((a)) Total annual space heating demand. ((b)) Annual average space heating demand.

Figure 7.32: Row house, Scenario 1 - TEK17: Comparison of the total annual and the annual average space heating demand.

The temperature distribution in the bedroom is displayed in Figure 7.33. The temperature distribution was stable between 16 - 18°C during the majority of the year. However, during the summer months, the temperature had a peak of 25°C. Overall, this also represented an acceptable indoor temperature.

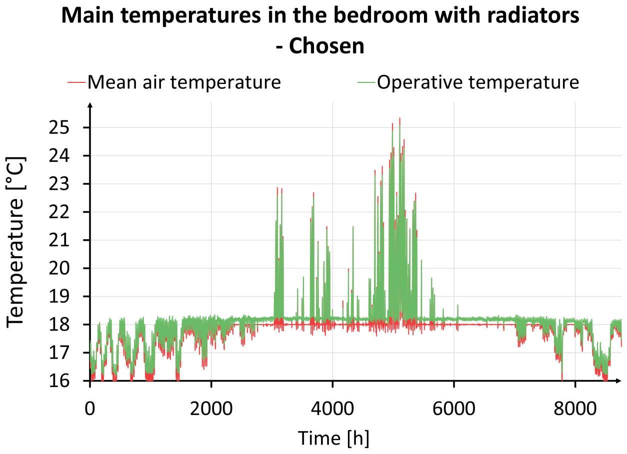


Figure 7.33: Row house, Scenario 1 - TEK17: Main temperatures in the bedroom - Chosen.

The monthly energy distribution for the row house with radiators is displayed in Figure 7.34.

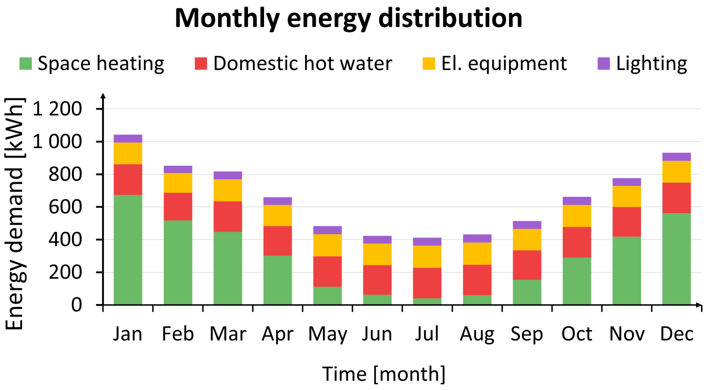
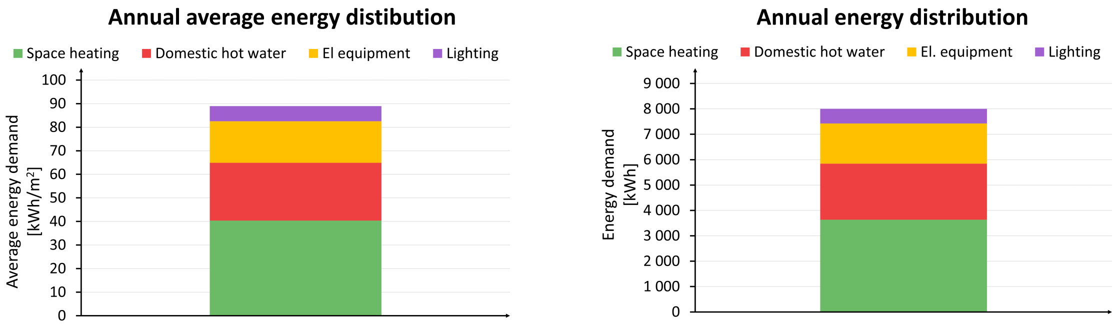


Figure 7.34: Row house, Scenario 1 - TEK17: Monthly energy distribution.

As seen in this figure, the share of energy demand for space heating varied throughout the year, with a higher share in the winter months. The energy demand for the other three internal loads was approximately constant throughout the year. The row house had the highest energy demand in January, with approximately 1 000 kWh. The lowest energy demand occurred during the summer, with a demand just above 400 kWh in June, July and August. The reason for this was the minimal space heating demand during these months, due to higher outdoor temperatures.

The annual and the annual average energy distribution for the TEK17 model with radiators are displayed in Figure 7.35. The average energy demand was 89 kWh/(m^2year), which means that the building satisfied the TEK17 maximum allowed energy demand of 118.1 kWh/(m^2year). This was a reduction of approximately 6% compared to the situation with ideal heaters as heating units. The total annual energy demand for the building was 8 010 kWh/year.

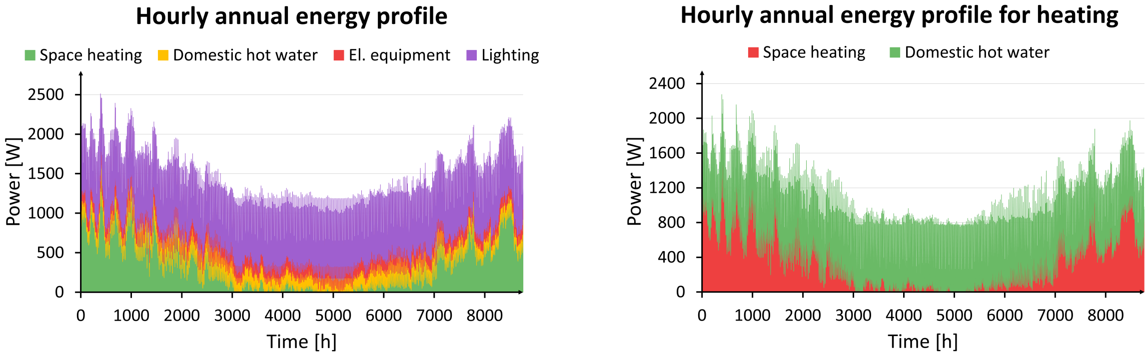


((a)) Annual average energy distribution.

((b)) Annual energy distribution.

Figure 7.35: Row house, Scenario 1 - TEK17: Annual average and total annual energy distribution.

The hourly annual energy profile and the hourly annual energy profile for heating are displayed in Figure 7.36.



((a)) Hourly annual energy profile.

((b)) Hourly annual energy profile for heating.

Figure 7.36: Row house, Scenario 1 - TEK17: Annual energy profiles.

As seen in these figures, the share of energy demand for space heating varied throughout the year with a higher share in the winter months. This result was as expected since the outdoor temperatures are lower during this period. In the summer months, the share of energy demand for space heating was approximately nonexistent. The energy demand for the other three internal loads was relatively constant throughout the year.

The total energy duration curve is displayed in Figure 7.37. The energy duration curve displays the power from space heating, domestic hot water, electrical equipment and lighting. The duration curve had a total peak power of 2 980 W, with space heating representing the largest share.

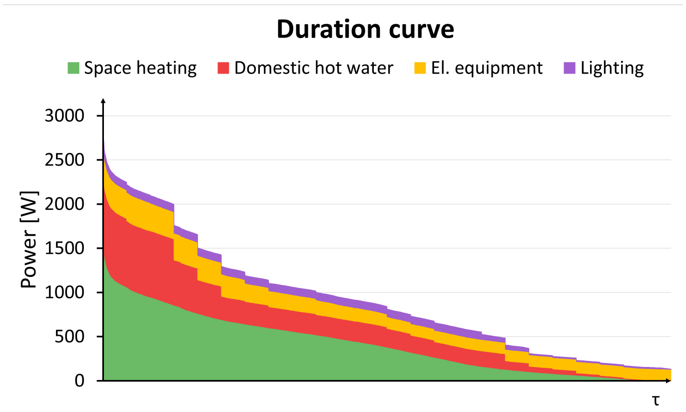
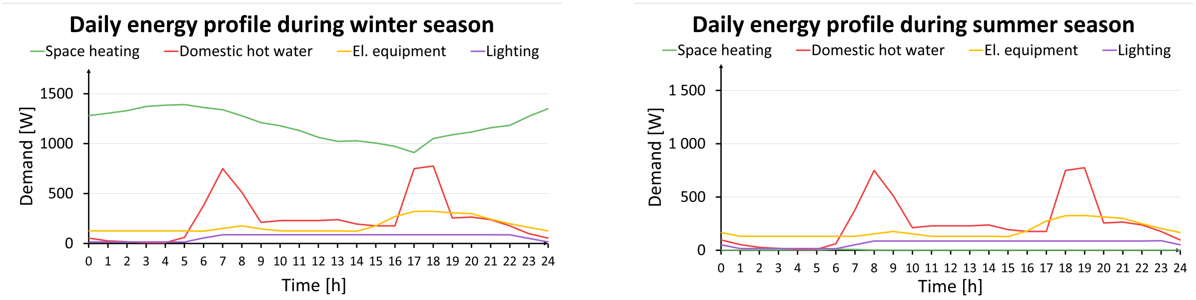


Figure 7.37: Row house, Scenario 1 - TEK17: Duration curve.

The daily energy profile for the TEK17 row house with radiators for a winter and summer season is displayed in Figure 7.38.



((a)) Daily energy profile during winter season. ((b)) Daily energy profile during summer season.

Figure 7.38: Row house, Scenario 1 - TEK17: Daily energy profiles.

The winter curves represent the 11th of February and the summer curves represent the 2nd of August. Due to cold outdoor temperatures during the winter, space heating in the building was necessary. As a result of high outdoor temperatures during the summer season, there were no space heating demands in the summer months. The curve for domestic hot water, electrical equipment, and lighting had the same schedule for the winter and summer seasons and was equal.

Scenario 2

The TEK17 model for the row house was modified by implementing hydronic radiant floors in specific zones of the building. The floor heating was implemented in the bathrooms and in the kitchen and living room with different heat rates as described in the section ”Heating units” under ”Simulation input”. The floor was sized to emit 10 W/m^2 for each degree difference between the floor surface temperature and the air temperature. Therefore, the heat rate was set to emit 40 W/m^2 for the bathrooms and 20 W/m^2 for the kitchen and living room. An air-to-water heat pump was implemented to the row house in combination with the hydronic radiant floor. This heat pump was designed to cover the base load for space and domestic hot water heating. District heating was set to cover the peak load.

The temperature distribution for the bedroom is displayed in Figure 7.39. The temperature was 18°C during the majority of the year, with some peak temperatures during the summer months. This was an adequate temperature distribution for the zone and illustrated a comfortable indoor environment. This also applied to the other zones in the building.

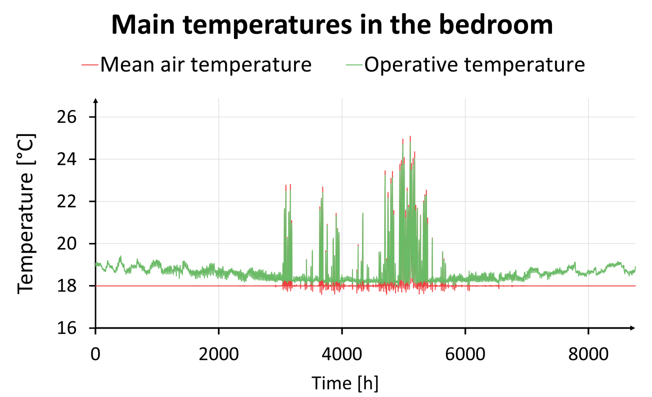
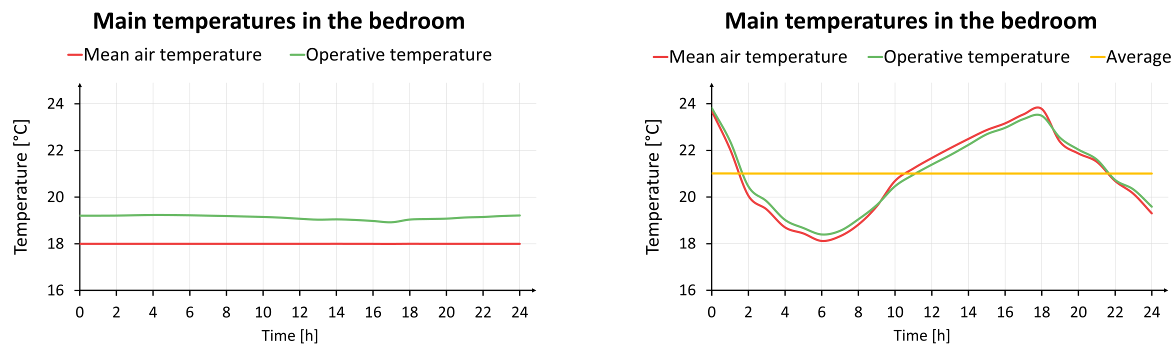


Figure 7.39: Row house, Scenario 2 - TEK17: Main temperatures in the bedroom.

The daily temperature profiles for bedroom 1, considering a day during the coldest and warmest season of the year are displayed in Figure 7.40.



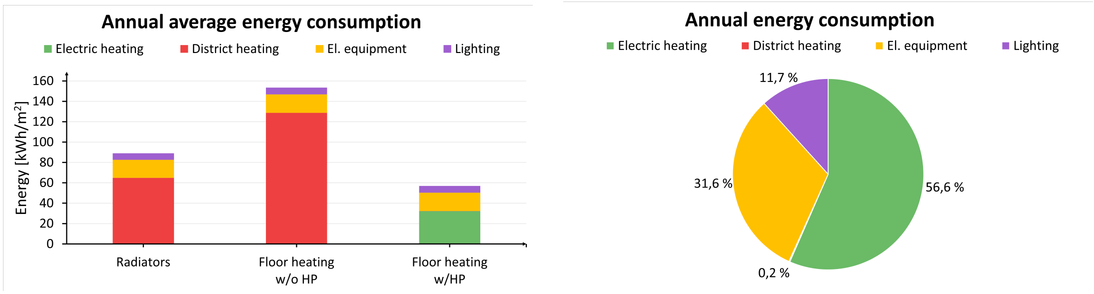
((a)) Daily temperature profile during winter season.

((b)) Daily temperature profile during summer season.

Figure 7.40: Row house, Scenario 2 - TEK17: Daily temperature profiles.

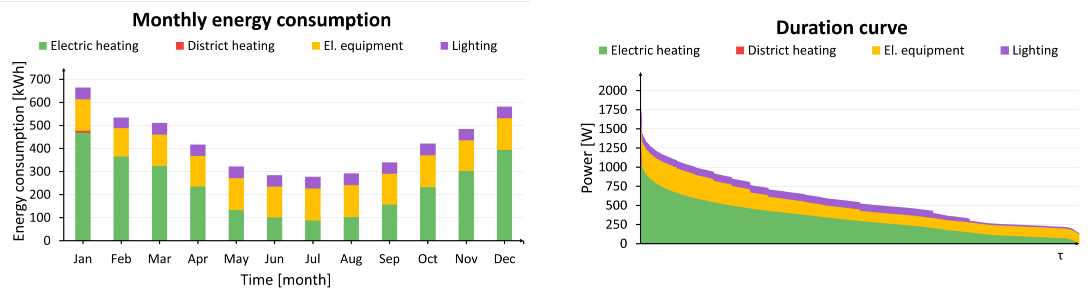
The winter curves in Figure 7.40(a) represent the 11th of February and the summer curves in Figure 7.40(b) represent the 2nd of August. The temperature during the winter season stayed relatively constant with an average temperature of 18.5°C throughout the day, while the temperature during the summer varied drastically. The peak temperature for the summer day was at 24°C, and the lowest was at approximately 18°C. The average temperature was consequently 21°C.

Figure 7.41 displays four different figures that represent the distribution of the energy consumption for the row house.



((a)) Comparison of the energy consumption between three different row house models.

((b)) Floor heating w/HP: Annual distribution of the energy consumption.



((c)) Floor heating w/HP: Monthly distribution of the energy consumption.

((d)) Floor heating w/HP: Total energy duration curve.

Figure 7.41: Row house, Scenario 2 - TEK17: Distribution of energy consumption and energy duration curve.

A comparison of the annual average energy consumption between different scenarios for the row house is displayed in Figure 7.41(a). For the scenario with radiators, the energy consumption was drastically lower compared to the scenario with floor heating without a heat pump. The annual average energy consumption for the building with radiators was 89 kWh/(m^{2}year), whereas for the building with floor heating and without a heat pump, the consumption was 153 kWh/(m^{2}year). In both cases, district heating was the only source that covered the total heating demand. This significant increase in energy demand is further investigated in the section "Comparison of heat losses".

In the scenario with floor heating and a heat pump, the heat pump was selected to cover the base load, while district heating was selected to cover the peak load. Consequently, the heat pump consumed energy to satisfy nearly the entire heating demand, since the energy consumption associated with district heating was close to zero. As the chosen heat pump had a COP of 3.62, and the district heating system had an efficiency of 1, the total amount of purchased energy to cover the same heating demand was significantly reduced to 58 kWh/(m^2year). The total annual energy demand was simulated to be 5 220 kWh/year. An evaluation of the heating systems is further discussed in the section "Evaluation of the heating systems".

The annual distribution of the energy consumption for the row house is displayed in Figure 7.41(b). This pie chart represents the energy consumption for the building when the row house had floor heating and a heat pump installed. The electric heating accounted for the biggest share, with 62.3% of the total energy consumption. Further, the share of energy consumed for electrical equipment and lighting accounted for a smaller part of the total consumption, with 27.1% and 10.3%, respectively. Lastly, the district heating accounted for an insignificant part of the total consumption with about 0.3%. This chart emphasizes that the heat pump covered most of the heating demand for the building, both for space and domestic hot water heating, while district heating covered the peaks.

The monthly energy consumption for the row house is displayed in Figure 7.41(c). This figure illustrates the monthly energy distribution from the four loads during one year. The electric heating was used during the whole year with the highest consumption in the coldest months. This means that the heat pump was in use the entire year and covered the whole heating demand from February to December. The district heating was only in use during January, which means it supplied the building with additional heat during the most critical month to cover the peak demand. Both the energy consumption for electrical equipment and for lighting was constant throughout the year.

The duration curve for the row house is displayed in Figure 7.41(d). This curve emphasizes the fact that the heat pump covered the base load and was used the entire year. The district heating system covered the peak load and was only used for a short period of time during the year.

7.5 Row house - Passive house

The TEK17 row house model was upgraded with passive house measures defined in the section "Chosen building structure for the passive house models". As determined for the TEK17 models, temperature setting 2 gave the most optimal indoor environment, with external shading and PI temperature control of the windows. In addition, the heating coil in the air handling unit was determined to be turned off in the following scenarios.

Scenario 0

After implementing the passive house measures to the row house model, the indoor temperatures were still acceptable. The temperature distribution for the bedroom is displayed in Figure 7.42.

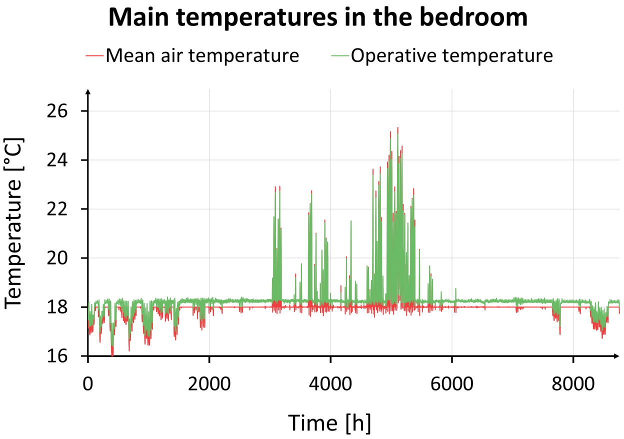
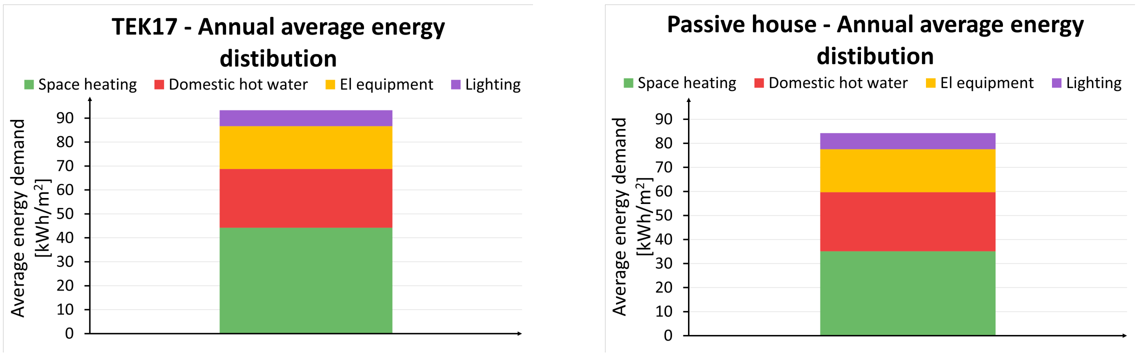


Figure 7.42: Row house, Scenario 0 - Passive: Main temperatures in the bedroom.

A comparison of the annual average energy distribution between the TEK17 model and the passive house model is displayed in Figure 7.43.



((a)) TEK17: Annual average energy distribution.

((b)) Passive: Annual average energy distribution.

Figure 7.43: Row house, Scenario 0: Comparison of the annual average energy distribution between the TEK17 and the passive house models.

As seen in Figure 7.43(a), the annual average energy demand for the TEK17 model was 94 kWh/(m^2year). For the passive house model, the energy demand was reduced to 84 kWh/(m^2year), as displayed in Figure 7.43(b). This reduction was caused by the lower space heating demand in the passive house model due to the implemented passive house measures. The total annual energy demand for the passive row house with ideal heaters was 7 560 kWh/year.

Figure 7.43(b) also displays that the passive house had a space heating demand of 35 kWh/(m^2year). This means that the passive row house with ideal heaters, such as the passive single family house with scenario 0, was not within the calculated maximum net energy demand for space heating of 15 kWh/(m^2year), as described in the section ”Requirements for energy efficiency” in the literature review. Whereas the three other loads covering lighting, electrical equipment and domestic hot water heating accounted for a total of 49 kWh/(m^2year), which according to the literature review, satisfied the maximum limit of 58.7 kWh/(m^2year).

Table 7.8 compares the simulated peak power demands corresponding with the two temperature settings. As previously mentioned, Fjordkraft's suggestion for an adequate indoor thermal environment was the most optimal temperature setting. This was also the most energy efficient solution, as the simulated peak power demands were significantly reduced compared to setting 1 based on FHI's recommendations, as illustrated in Table 7.5. The heating demand was eliminated in the corridor, and drastically reduced in the bedroom because of this temperature setting. Compared to FHI, the demand was slightly higher in the bedroom, kitchen and living room to compensate for this reduction.

Table 7.8: Row house, Scenario 0 - Passive: Simulated peak power demands for space heating.

Room	**Simulated peak power demand [W]**	
	FHI	**FK**
Bedroom	448	80
Bathroom	397	570
Corridor	113	0
Kitchen/ Living room	854	877

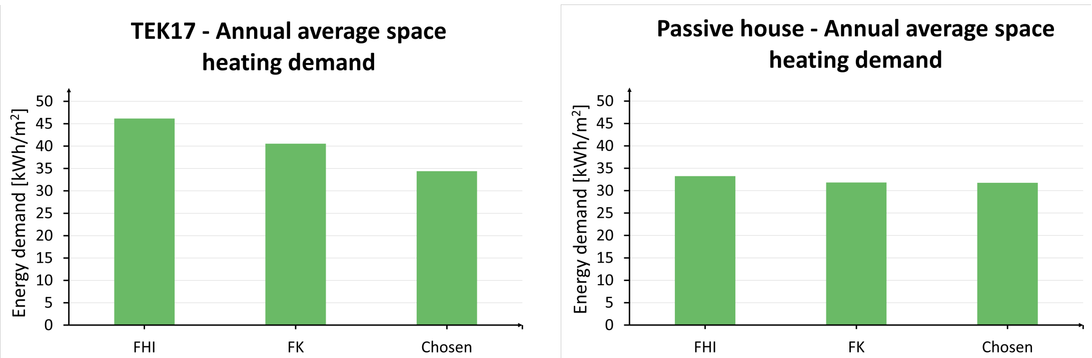
Scenario 1

The passive row house model was modified by implementing radiators as heating units, instead of ideal heaters. The radiators were sized based on an evaluation of the simulated peak power demands for space heating, presented in Table 7.8. The chosen peak powers for the passive row house are displayed in Table 7.9 and compared to the chosen peak powers for the TEK17 row house. It can be seen from this table that the passive house had overall lower peak powers as a result of the lower space heating demand in the zones.

Table 7.9: Row house, Scenario 1 - Passive: Comparison of the chosen peak power demands for space heating between the TEK17 and the passive house model.

Room	**Chosen peak power demand [W]**	
	TEK17	**PH**
Bedroom	200	100
Bathroom	600	550
Corridor	0	0
Kitchen/ Living room	950	750

A comparison of the annual average space heating demand between the TEK17 and passive row house is displayed in Figure 7.44. As the figures illustrate, a passive row house had a much lower space heating demand compared to a TEK17 row house. For the TEK17 model, there was a visible reduction in the space heating demand when the temperatures were lowered. In contrast, the space heating demand remained approximately the same when the temperatures were lowered in the passive house.

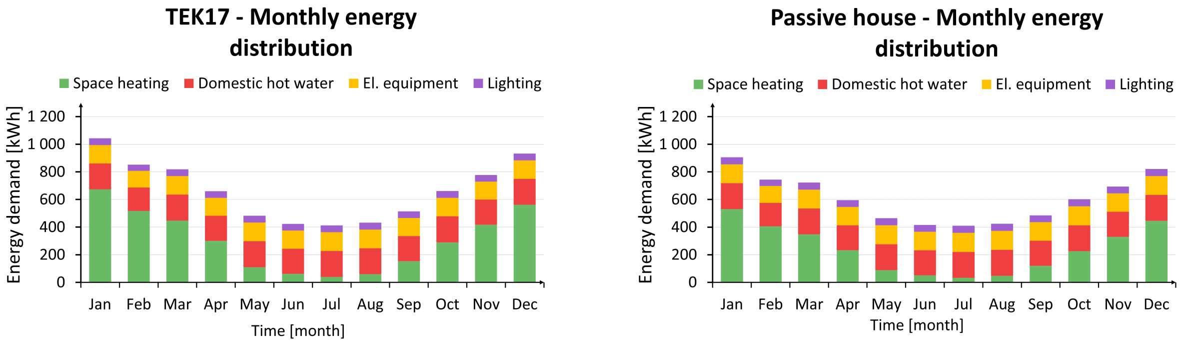


((a)) TEK17: Annual average space heating demand.

((b)) Passive: Annual average space heating demand.

Figure 7.44: Row house, Scenario 1: Comparison of the annual average space heating demand between the TEK17 and the passive house models.

For scenario 1, the monthly energy distributions for the row houses, both with TEK17 and passive house measures, are displayed in Figure 7.45. As illustrated in these two figures, the passive row house had an overall lower energy demand per month, with a peak in January of approximately 900 kWh, whereas the TEK17 model had a peak of approximately 1 050 kWh. The cause of this reduction was the decreased space heating demand for the passive house due to the implemented passive house measures. However, during the months between May and September, the energy distribution was relatively similar in both cases. The energy demand for electrical equipment, lighting, and domestic hot water was constant throughout the year for both of the models.

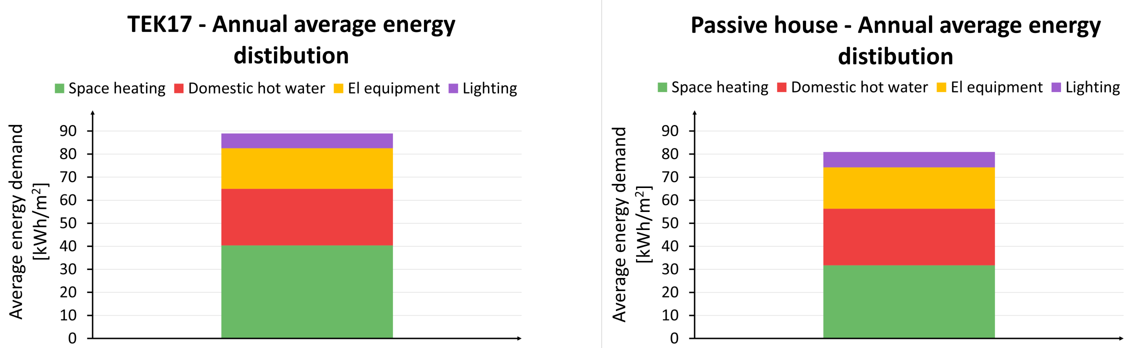


((a)) TEK17: Monthly energy distribution.

((b)) Passive: Monthly energy distribution.

Figure 7.45: Row house, Scenario 1: Comparison of the monthly energy distribution between the TEK17 and the passive house models.

Figure 7.46 illustrates a comparison of the annual average energy distribution between the TEK17 and the passive house models.



((a)) TEK17: Annual average energy distribution.

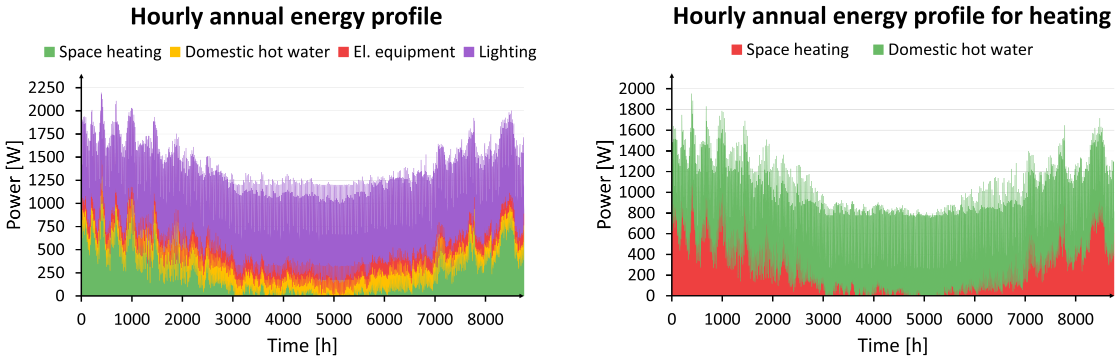
((b)) Passive: Annual average energy distribution.

Figure 7.46: Row house, Scenario 1: Comparison of the annual average energy distribution between the TEK17 and the passive house models.

As seen in Figure 7.46(a), the annual average energy demand for the TEK17 model was 89 kWh/(m^{2}year). For the passive house model, the energy demand was reduced to 81 kWh/(m^{2}year), as shown in Figure 7.46(b). This reduction was caused by the passive house model's decreased space heating demand due to the implemented passive house measures. The total annual energy demand for the passive row house with radiators was 7 290 kWh/year.

In the passive house model, the space heating demand was reduced from 40.5 kWh/(m^{2}year) in the TEK17 model to 32 kWh/(m^{2}year). This means that the passive house with radiators, just like scenario 0, was not within the calculated maximum net energy demand for space heating for a passive residential building of 15 kWh/(m^{2}year), as described in the section "Requirements for energy efficiency" in the literature review. The three other loads covering lighting, electrical equipment and domestic hot water heating accounted for a total of 49 kWh/(m^{2}year), which according to the literature review, satisfied the maximum limit of 58.7 kWh/(m^{2}year).

The hourly annual energy profile and the hourly annual energy profile for heating are displayed in Figure 7.47. As seen in these figures, the share of energy demand for space heating varied throughout the year with a higher share in the winter months. This result was as expected since the outdoor temperatures are lower during this period. In the summer months, however, the share of energy demand for space heating was approximately zero. The energy demand for the other three internal loads was relatively constant throughout the year.



((**a**)) Hourly annual energy profile.

((**b**)) Hourly annual energy profile for heating.

Figure 7.47: Row house, Scenario 1 - Passive: Annual energy profiles.

The total energy duration curve for the passive row house with radiators is displayed in Figure 7.48.

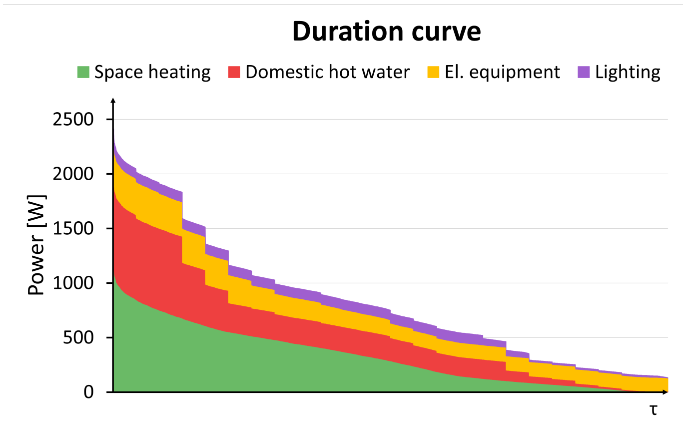
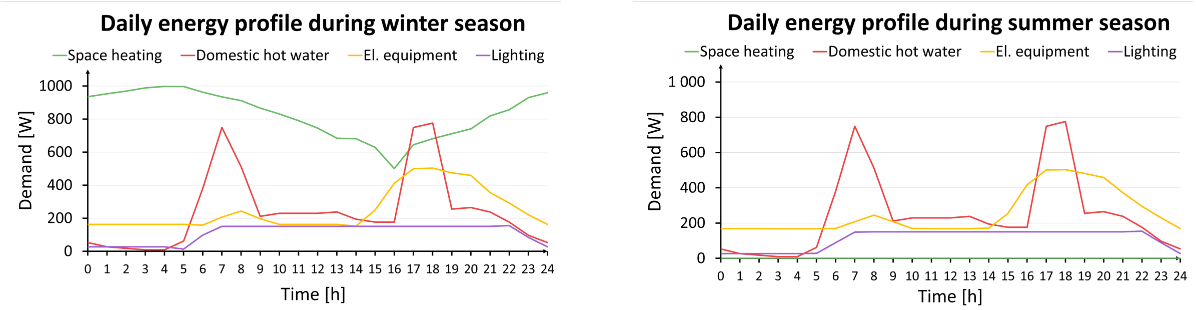


Figure 7.48: Row house, Scenario 1 - Passive: Duration curve.

The energy duration curve displays the power from space heating, domestic hot water, electrical equipment and lighting. The duration curve had a total peak power of approximately 2 675 W, where space heating represented the largest share.

The daily energy profiles for the passive row house with radiators for a winter and summer season are displayed in Figure 7.49.



((a)) Daily energy profile during winter season. ((b)) Daily energy profile during summer season.

Figure 7.49: Row house, Scenario 1 - Passive: Daily energy profiles.

The winter profile represents the 11th of February and the summer profile represents the 2nd of August. The daily energy profile for the passive row house with radiators for winter is displayed in Figure 7.49(a). The space heating was reduced by approximately 500 W each hour compared to the TEK17 row house in Figure 7.38(a). The other parameters, such as domestic hot water, electrical equipment and lighting, remained the same. The daily profile for the summer season is displayed in Figure 7.49(b), and was similar to Figure 7.38(b) for the TEK17 row house with radiators.

Scenario 2

The passive house model for the row house was modified by removing the radiators, and implementing hydronic radiant floors in specific zones of the building. The floor heating was implemented in the bathroom, kitchen and living room with different heat rates as described in the section "Heating units" under "Simulation input". The floor was sized to emit 10 W/m^2 for each degree temperature difference between the floor surface temperature and the air temperature. Therefore, the heat rate was set to emit 40 W/m^2 for the bathroom and 20 W/m^2 for the kitchen and living room. An air-to-water heat pump was implemented to the row house in combination with the hydronic radiant floor. The heat pump was designed to cover the base load for space and domestic hot water heating. District heating was set to cover the peak load.

The temperature distribution for the bedroom with scenario 2 is displayed in Figure 7.50. The temperature was 18°C during the majority of the year, with some peak temperatures during the summer months. This was an adequate temperature distribution for the zone and illustrated a comfortable indoor environment. This applied to the other zones in the building as well.

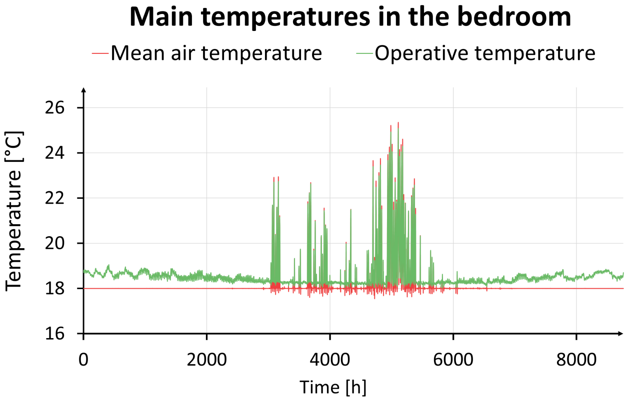
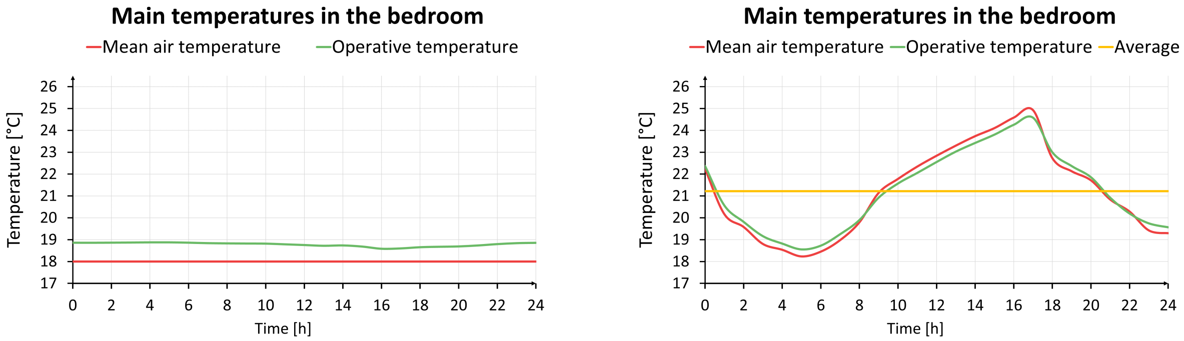


Figure 7.50: Row house, Scenario 2 - Passive: Main temperatures in the bedroom.

The daily temperature profiles for the bedroom, considering a day during the coldest and warmest season are displayed in Figure 7.51.



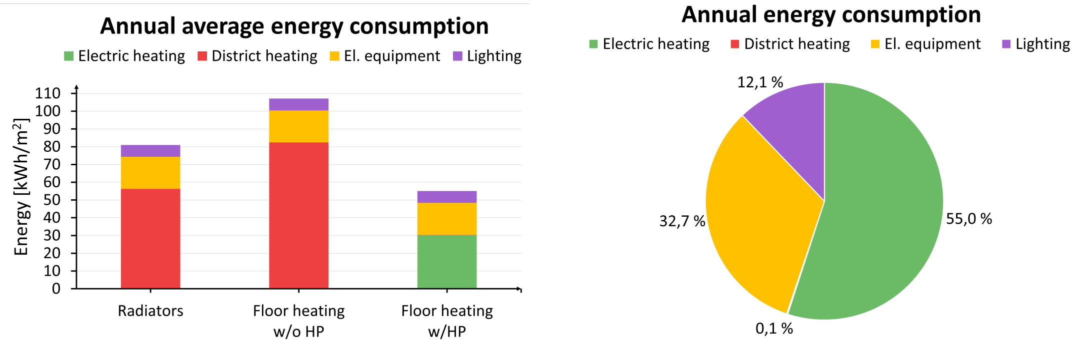
((a)) Daily temperature profile during winter season.

((b)) Daily temperature profile during summer season.

Figure 7.51: Row house, Scenario 2 - Passive: Daily temperature profiles.

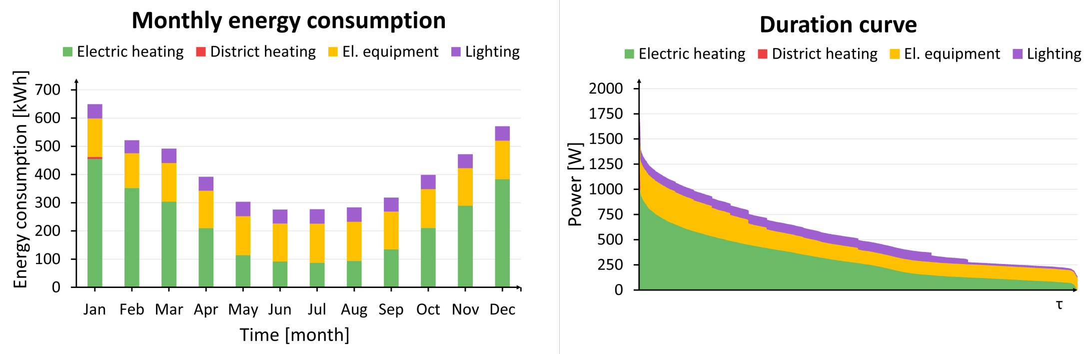
The winter profile in Figure 7.51(a) represents the 11th of February, and the summer profile in Figure 7.51(b) represents the 2nd of August. The daily temperature during the winter season remained relatively constant with an average temperature of 18.5°C throughout the day, while the daily temperature during the summer season varied drastically. The peak temperature for the summer day was 25°C, whereas the lowest temperature was 18°C. The average temperature was consequently 21.2°C.

Figure 7.52 displays four different figures representing the distribution of the energy consumption for the passive row house.



((a)) Comparison of the energy consumption between three different row house models.

((b)) Floor heating w/HP: Annual distribution of the energy consumption.



((c)) Floor heating w/HP: Monthly distribution of the energy consumption.

((d)) Floor heating w/HP: Total energy duration curve.

Figure 7.52: Row house, Scenario 2 - Passive: Distribution of energy consumption and energy duration curve.

A comparison of the annual average energy consumption between different scenarios for the passive row house is displayed in Figure 7.52(a). For the scenario with radiators, the energy consumption was drastically lower compared to the scenario with floor heating without a heat pump. The annual average energy consumption for the building with radiators was 81 kWh/(m^{2}year), whereas for the building with floor heating and without a heat pump, the consumption was 107 kWh/(m^{2}year). In both cases, district heating was the only source that covered the total heating demand. This significant increase in energy demand is further investigated in the section ”Comparison of heat losses”.

In the scenario with floor heating and a heat pump, the heat pump was selected to cover the base load, while district heating was selected to cover the peak load. Consequently, the heat pump consumed energy to satisfy nearly the entire heating demand, since the energy consumption associated with district heating was close to zero. As the chosen heat pump had a COP of 3.62, and the district heating system had an efficiency of 1, the total amount of purchased energy to cover the same heating demand was significantly reduced to 55 kWh/(m^{2}year). The total annual energy demand was simulated to be 4 950 kWh/year. An evaluation of the heating systems is further discussed in the section "Evaluation of the heating systems".

Similar to the single family house, the electric heating is the total amount of heat supplied by the heat pump and covers two areas of heating; space and domestic hot water heating. Based on the simulation results from IDA ICE, these demands amounted to 70.2% and 29.8%, respectively. The district heating covered 0.1% of the energy demand, and was therefore neglected. For scenario 2 in Figure 7.52(a), the electric heating consumption was 30 kWh/(m^{2}year). Hence, 21.3 kWh/(m^{2}year) was consumed for space heating and 9.0 kWh/(m^{2}year) for domestic hot water heating. Similar to scenario 0 and 1, the space heating demand did not satisfy the passive house requirement of maximum 15 kWh/(m^{2}year). In fact, the passive row house with scenario 2 was approximately 6 kWh/(m^{2}year) higher than the requirement. This was unexpected since the passive house was constructed to meet all the energy requirements given in NS3700. However, the energy demand for lighting, electrical equipment and domestic hot water was in total 33.7 kWh/(m^{2}year), which satisfied the requirement of maximum 58.7 kWh/(m^{2}year).

The annual distribution of the energy consumption for the row house is displayed in Figure 7.52(b). This pie chart represents the energy consumption for the building when the row house had floor heating and a heat pump installed. The electric heating accounted for the biggest share, with 55% of the total energy consumption. Further, the share of energy consumed for electrical equipment and lighting accounted for a smaller part of the total consumption, with 32.7% and 12.1% respectively. Lastly, the district heating accounted for an insignificant part of the total consumption with about 0.1%. This chart emphasizes that the heat pump covered most of the heating demand for the building, both for space and domestic hot water heating, while district heating covered the peaks.

The monthly energy consumption for the row house is displayed in Figure 7.52(c). This figure illustrates the monthly energy distribution from the four loads during one year. The electric heating was used during the whole year, with the highest consumption in the coldest months. This means that the heat pump was in use the entire year and covered the whole heating demand from February to December. The district heating was only in use during January, which means it supplied the building with additional heat during the most critical month to cover the peak demand. Both the energy consumption for electrical equipment and for lighting was constant throughout the year.

The duration curve for the row house is displayed in Figure 7.52(d). This curve emphasizes the fact that the district heating covers the peak load and was only used for a short period of time during the year. The heat pump covers the base load and was used the entire year.

7.6 Apartment building - TEK17

Scenario 0

Similar to the models for the single family house and the row house, the apartment building was initially simulated with ideal heaters as a reference scenario to establish a foundation for the sizing of radiators. As stated in the section ”Single family house - TEK17”, using a heating coil in the air handling unit is not an energy efficient heating solution. Therefore, the heating coil was turned off in all of the models for the apartment building. The same two different temperature settings were also evaluated for the apartment building:

1. A standard temperature level between 22 - 24°C defined by FHI.
2. Specific setpoint temperatures for each zone given in Table 2.2 recommended by Fjordkraft.

The temperature distribution for bedroom 1 in the different apartment units is displayed in Figure 7.53. Both temperature settings above were individually implemented in the model. Generic markisolettes were also implemented as external shading in the model, in addition to PI temperature controlled opening of the windows.

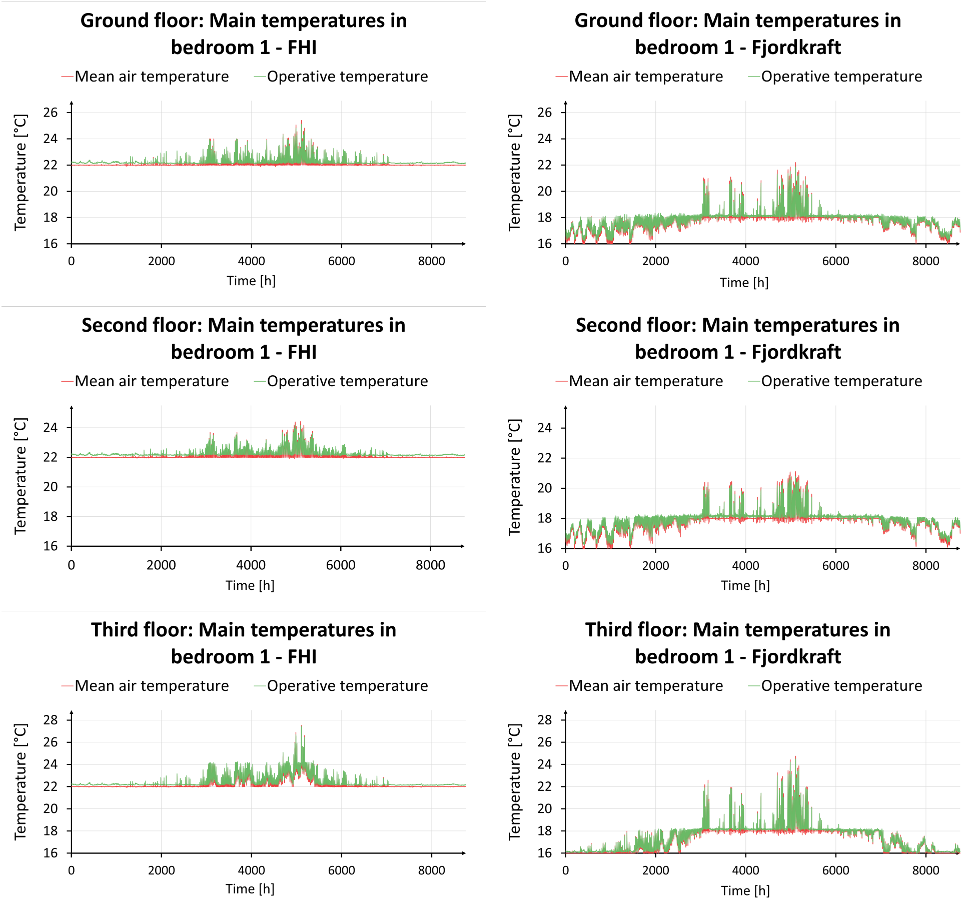
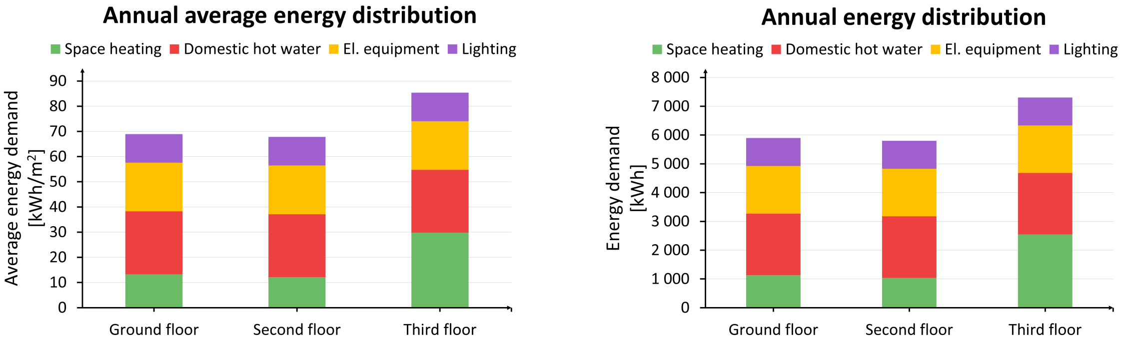


Figure 7.53: Apartment building, Scenario 0 - TEK17: Temperature distributions in bedroom 1 at the three floors.

Analogous to the models with ideal heaters for the single family house and the row house, the temperature distribution for the apartment building with temperature setting 2 had an overall lower temperature level compared to the model with setting 1. Since it often is preferred to have a colder temperature level in a bedroom, setting 2 with a setpoint temperature between 16 - 18°C was evaluated to be beneficial. In this case, it was not necessary with cooling of the bedrooms since the temperatures were at an adequate level for the majority of the time. This applied to all of the rooms in the apartment building, as it would not be profitable to implement cooling when the cooling demand was low and only occured during a short period of time.

Based on the comparison between the two temperature settings evaluated, setting 2 was the most optimal temperature solution for the apartment building as well. This solution gave an overall lower and acceptable temperature distribution throughout the year and eliminated the demand for cooling. Therefore, this temperature solution was applied to all of the models for the apartment building, which is presented in the following sections.

Further, the energy demand of the building was analyzed. In relation to the section "Requirements for energy efficiency" under "Method", the total energy demand for a building must not exceed the maximum allowed energy demand of 95 kWh/(m^{2}year). The annual average and the total annual energy distributions for the three apartment units in the TEK17 model are displayed in Figure 7.54.



((a)) Annual average energy distribution. ((b)) Annual energy distribution.

Figure 7.54: Apartment building, Scenario 0 - TEK17: Energy distributions.

The annual average energy demands for the three simulated apartment units are displayed in Figure 7.54(a). It can be observed that the apartment units on the ground and second floor had an average energy demand of approximately 70 kWh/(m^{2}year). The first floor was therefore assumed to have the same average energy demand. The average energy demand for the apartment unit on the third floor was 85 kWh/(m^{2}year). By taking this into account, 75% of the building had an energy demand of 70 kWh/(m^{2}year), while 25% of the building had an energy demand of 85 kWh/(m^{2}year). The calculated annual average energy demand for the whole apartment building was therefore 74 kWh/(m^{2}year). Hence, the apartment building satisfied the TEK17 maximum allowed energy demand of 95 kWh/(m^{2}year).

The total annual energy distributions for the three simulated apartment units are displayed in Figure 7.54(b). It can be observed that the apartment unit on the third floor had the highest annual energy demand of approximately 7 250 kWh/year. The apartment units on the ground and second floor both had an energy demand of roughly 6 000 kWh/year each. The reason for the higher annual energy demand for the apartment unit on the third floor was that it was located in the top of the building, resulting in a larger surface area exposed to the outdoor environment. Consequently, the unit had a higher amount of heat losses, and thereby a higher energy demand for space heating. The energy demand for domestic hot water, electrical equipment and lighting was approximately the same for the three apartment units. Based on the annual average energy demand for the whole apartment building of 74 kWh/(m^{2}year), the total annual energy demand was calculated to be 5 163 kWh/year for each unit with a gross floor area of 70.5 m^2..

Table 7.10 displays the simulated peak power demands corresponding to the two temperature settings for the three floors. As seen in these tables, temperature setting 2 based on the Fjordkraft recommendations gave an overall lower peak power demand. The heating demand was eliminated in the corridor and in bedroom 2 for the ground and second floor. In addition, the demand was drastically reduced in bedroom 1 at all floors, whereas the demand in the bathrooms slightly increased. For the kitchen and living rooms, the peak power demand remained approximately the same for the third floor, while for the other two floors, this demand drastically decreased.

Table 7.10: Apartment building, Scenario 0 - TEK17: Simulated peak power demands for space heating.

Room - Ground floor	**Simulated peak power demand [W]**	
	FHI	**FK**
Bedroom 1	450	166
Bedroom 2	187	0
Kitchen/ Living room	737	398
Bathroom	277	401
Corridor	109	0

Room - Second floor	**Simulated peak power demand [W]**	
	FHI	**FK**
Bedroom 1	426	141
Bedroom 2	168	0
Kitchen/ Living room	593	245
Bathroom	258	387
Corridor	117	0

Room - Third floor	**Simulated peak power demand [W]**	
	FHI	**FK**
Bedroom 1	495	365
Bedroom 2	214	103
Kitchen/ Living room	800	804
Bathroom	302	443
Corridor	212	0

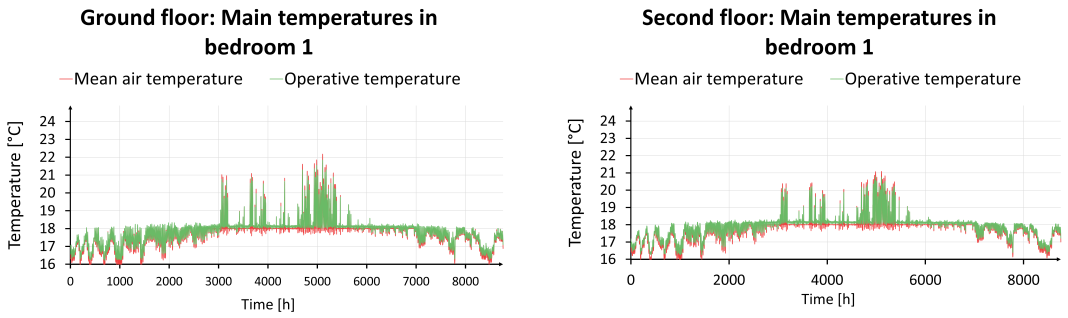
Scenario 1

The TEK17 model for the apartment building was modified by implementing radiators as heating units, instead of ideal heaters. The radiators were sized based on an evaluation of the simulated peak power demands for space heating presented in Table 7.10. The chosen peak powers for heating of the three given floors are displayed in Table 7.11. These peak powers were determined with temperature setting 2 to have a more comfortable thermal environment in each zone. In addition, the heating coil was turned off.

Table 7.11: Apartment building, Scenario 1 - TEK17: Chosen peak powers for space heating.

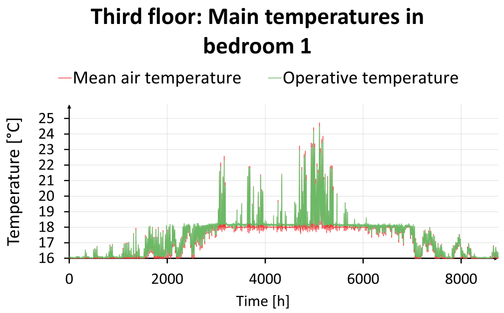
Room	**Chosen peak powers [W]**		
	Ground floor	**Second floor**	**Third floor**
Bedroom 1	200	150	350
Bedroom 2	0	0	150
Kitchen/Living room	350	200	750
Bathroom	400	350	450
Corridor	0	0	0

The temperature distribution in the apartment building remained acceptable after implementing radiators. This is displayed in Figure 7.55. During the majority of the year, the temperature in the bedrooms varied between 16 - 18°C, while it reached some higher levels during the summer.



((a)) Ground floor.

((b)) Second floor.



((c)) Third floor.

Figure 7.55: Apartment building, Scenario 1 - TEK17: Temperature distributions.

The monthly energy distribution for the apartment building with radiators is displayed in Figure 7.56. As seen in this figure, the share of energy demand for space heating varied throughout the year, with a higher share in the winter months. The other three categories were relatively constant throughout the year. The apartment units in the building had the highest energy demand in January, with a demand of approximately 590 kWh for the units on the ground and second floor, and 925 kWh for the unit on the third floor. The energy demand for space heating was at its lowest during the summer months, around June, July and August.

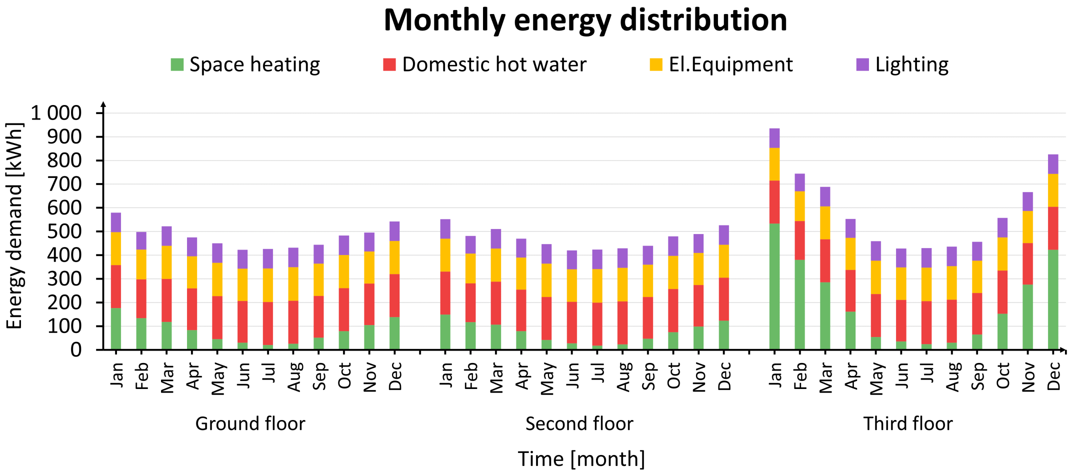
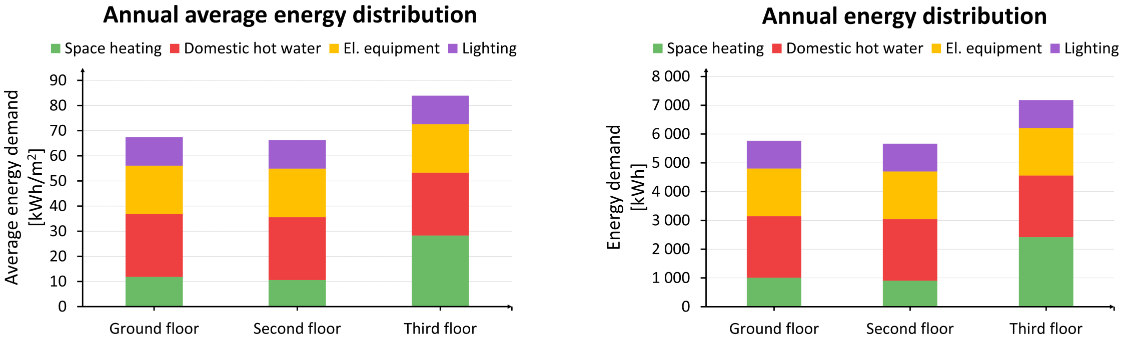


Figure 7.56: Apartment building, Scenario 1 - TEK17: Monthly energy distribution.

The annual average and the total annual energy distributions for the apartment building are displayed in Figure 7.57.



((a)) Annual average energy distribution.

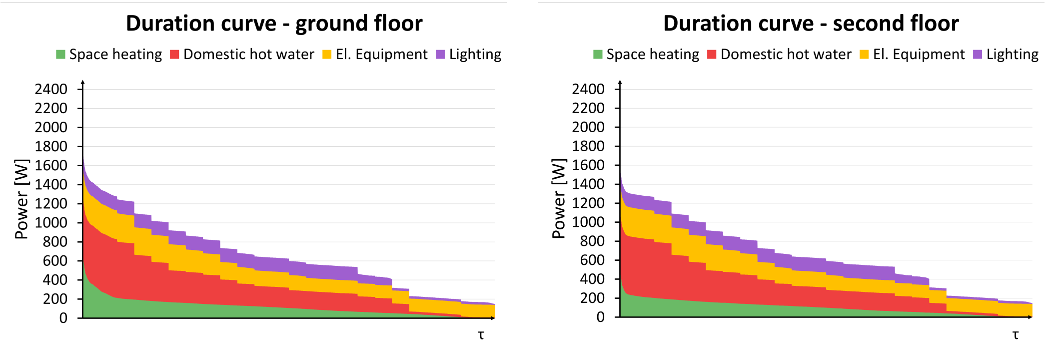
((b)) Annual energy distribution.

Figure 7.57: Apartment building, Scenario 1 - TEK17: Energy distributions.

The annual average energy distribution for the TEK17 apartment building with radiators is displayed in Figure 7.57(a). The average energy demand was approximately 68 kWh/(m^{2}year) for the apartment units on the ground and second floor. The average energy demand for the first floor was then assumed to be the same. The average energy demand for the third floor unit was 83 kWh/(m^{2}year). By taking this into account, 75% of the building had an energy demand of 68 kWh/(m^{2}year), while 25% of the building had an energy demand of 83 kWh/(m^{2}year). The calculated annual average energy demand for the whole apartment building was therefore 72 kWh/(m^{2}year). This means that the building satisfied the TEK17 maximum allowed energy demand of 95 kWh/(m^{2}year). This was a small reduction in energy demand compared to the situation with ideal heaters.

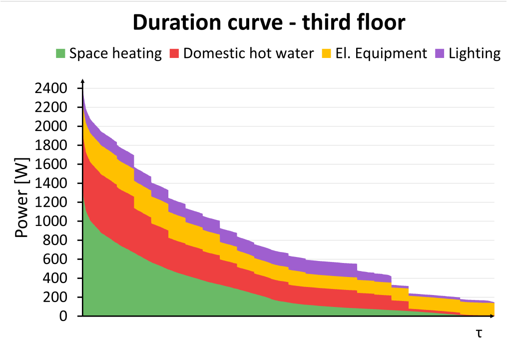
The total annual energy demands for the apartment units are displayed in Figure 7.57(b). The annual energy demand was slightly above 5 500 kWh for the units on the ground and second floor, while it was slightly above 7 000 kWh for the third floor unit. Based on the annual average energy demand for the whole apartment building of 72 kWh/(m^{2}year), the total annual energy demand was calculated to be 5 023 kWh/year for each unit with a gross floor area of 70.5 m^2.

The total energy duration curve for the simulated units in the apartment building is displayed in Figure 7.58. These curves display the power from space heating, domestic hot water, electrical equipment and lighting. The apartment unit on the third floor had the highest peak power of approximately 2 400 W, while the two other floors had a peak power of approximately 1 600 W. The largest shares of the energy demand came from space heating and domestic hot water.



((a)) Total energy duration curve for the ground floor.

((b)) Total energy duration curve for the second floor.



((c)) Total energy duration curve for the third floor.

Figure 7.58: Apartment building, Scenario 1 - TEK17: Duration curves.

7.7 Apartment building - Passive house

The TEK17 apartment building was upgraded with passive house measures defined in the section "Chosen building structure for the passive house models". As previously determined, temperature setting 2 resulted in the most optimal indoor environment with external shading and PI temperature control for opening of the windows. Therefore, this temperature setting was applied in the following scenarios. Further, the heating coil was turned off.

Scenario 0

After implementing the passive house measures to the apartment building, the indoor temperatures were still acceptable. This is illustrated in Figure 7.59 for bedroom 1 in the ground floor apartment unit, where the temperature distribution was within an acceptable range during the whole year. This applied to all the other zones in the building as well.

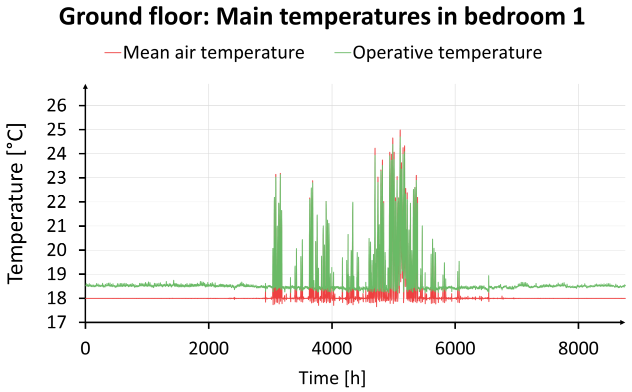
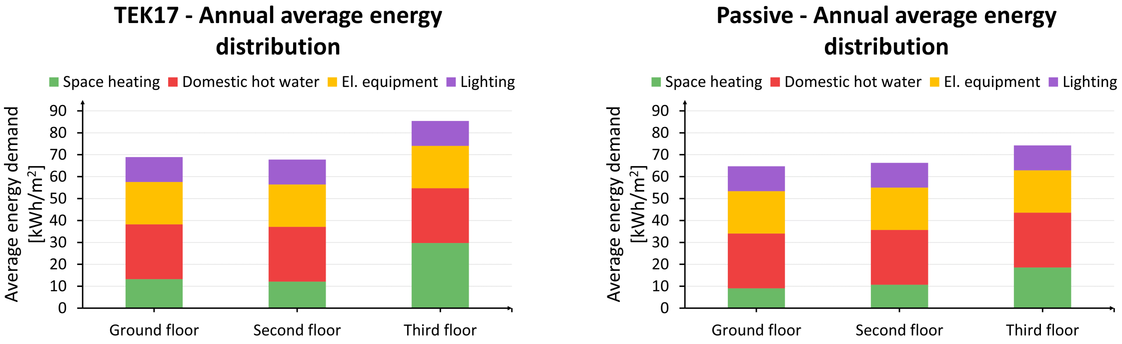


Figure 7.59: Apartment building, Scenario 0 - Passive: Main temperatures in bedroom 1 on the ground floor.

In Figure 7.60, the annual average energy distribution is displayed for the three apartment units. This figure compares the energy distribution in the TEK17 model with the distribution in the passive house model.



((a)) TEK17: Annual average energy distribution.

((b)) Passive: Annual average energy distribution.

Figure 7.60: Apartment building, Scenario 0: Comparison of the annual average energy distribution between the TEK17 and the passive house models.

As these figures illustrate, the change in the annual average energy distribution was relatively small when applying passive house measures to the apartment building. This change was smaller than expected, since the reduction for both the single family house and the row house were more significant when the passive house measures were applied. The change can be seen by studying the space heating demands, where the biggest reduction was for the apartment unit on the third floor. The three remaining loads, domestic hot water, electrical equipment and lighting, stayed constant and were not affected by the passive house measures.

The average energy demand was approximately 65 kWh/(m^2year) for the apartment units on the ground and second floor. The first floor was therefore assumed to have the same average energy demand. The average energy demand for the apartment unit on the third floor was 75 kWh/(m^2year). By taking this into account, 75% of the building had an energy demand of 65 kWh/(m^2year), while 25% of the building had an energy demand of 75 kWh/(m^2year). The calculated annual average energy demand for the whole apartment building was therefore 67.5 kWh/(m^2year). The total annual energy demand was 4 759 kWh/year for each unit with a gross floor area of 70.5 m^2.

The average energy demand for space heating was calculated to be 13 kWh/(m^2year). This value was calculated based on the average energy distribution for space heating for the ground, second and third floors, as displayed in Figure 7.60(b). This satisfied the requirement of a net energy demand lower than 15 kWh/(m^2year) for a passive house, as described in the section "Requirements for energy efficiency" under "Method". The average energy demand for domestic hot water, electrical equipment and lighting was 56 kWh/(m^2year), which satisfied the maximum requirement of 58.7 kWh/(m^2year) for a passive house.

Table 7.12 displays the simulated peak power demands for the three floors, and compares the demands corresponding to the two temperature settings. The table illustrates that scenario 2, based on the Fjordkraft recommendations, gave an overall lower simulated peak power demand. In addition, this setting resulted in a more comfortable thermal environment, and was therefore selected as the most suitable choice. Consequently, the heating demand was eliminated in the corridors, and drastically reduced in bedroom 1, due to the lower temperature setpoints. For the ground and second floors, the peak power demands were eliminated in bedroom 2, while for the third floor this demand was significantly reduced. However, in contrast with temperature setting 1 based on the FHI recommendations, the demand was slightly higher in the bathrooms to compensate for the lower demand in the other zones. In addition, the peak power demand in the kitchen and living room remained approximately the same for the third floor, whereas for the two other floors the demand was reduced.

Table 7.12: Apartment building, Scenario 0 - Passive: Simulated peak power demands for space heating.

Room - Ground floor	**Simulated peak power demand [W]**	
	FHI	**FK**
Bedroom 1	369	74
Bedroom 2	158	0
Kitchen/ Living room	575	216
Bathroom	248	362
Corridor	56	0

Room - Second floor	**Simulated peak power demand [W]**	
	FHI	**FK**
Bedroom 1	363	73
Bedroom 2	153	0
Kitchen/ Living room	491	119
Bathroom	243	362
Corridor	91	0

Room - Third floor	**Simulated peak power demand [W]**	
	FHI	**FK**
Bedroom 1	392	265
Bedroom 2	175	48
Kitchen/ Living room	587	585
Bathroom	262	396
Corridor	147	0

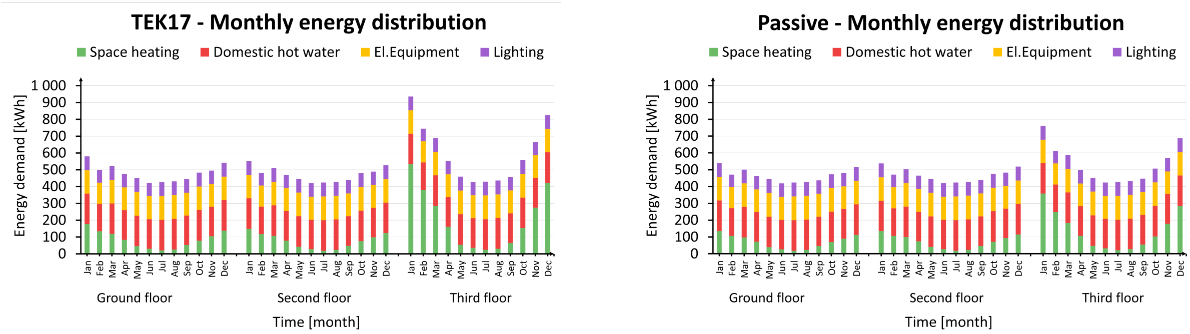
Scenario 1

The passive house model for the apartment building was modified by implementing radiators as heating units, instead of ideal heaters. The radiators were sized based on an evaluation of the simulated peak power demands for space heating, presented in Table 7.12. A comparison of the chosen peak powers for the TEK17 and the passive house models are displayed in Table 7.13. This table emphasizes how the passive house model, compared to the TEK17 model, had overall lower peak powers due to the lower space heating demands.

Table 7.13: Apartment building, Scenario 1: Comparison of the chosen peak powers for space heating between the TEK17 and the passive house model.

Room	**Chosen peak power [W]**					
	Ground floor		**Second floor**		**Third floor**	
	TEK17	**PH**	**TEK17**	**PH**	**TEK17**	**PH**
Bedroom 1	200	100	150	100	350	300
Bedroom 2	0	0	0	0	150	0
Kitchen/ Living room	350	250	200	150	750	550
Bathroom	400	350	350	350	450	400
Corridor	0	0	0	0	0	0

A comparison of the monthly energy distribution between the TEK17 and the passive apartment building with radiators are displayed in Figure 7.61. As seen in this figure, the share of energy demand for space heating varied throughout the year, with a higher share in the winter months. The other three categories were constant throughout the year.



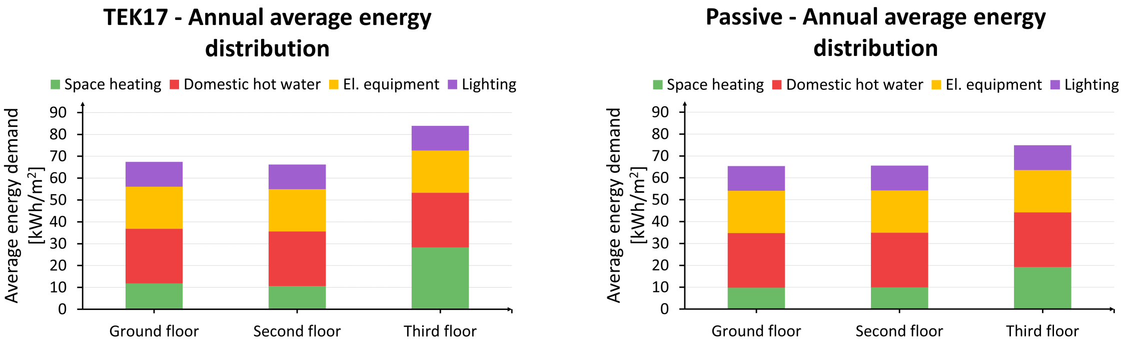
((a)) TEK17: Monthly energy distribution.

((b)) Passive: Monthly energy distribution.

Figure 7.61: Apartment building, Scenario 1: Comparison of the monthly energy distribution between the TEK17 and the passive house models.

For the passive house model in Figure 7.61(b), the apartment units in the building had the highest energy demand in January, with a demand of approximately 550 kWh for the units on the ground and the second floor, and 750 kWh for the unit on the third floor. The energy demand for space heating was at its lowest during the summer months, around June, July and August. By comparing the two distribution profiles, it can be observed that the passive house model had a slightly lower energy demand due to the reduced space heating demand in the zones. However, this reduction was very small for the ground and second floor, and more significant for the third floor.

The annual average energy distribution for the passive apartment building with radiators is displayed in Figure 7.62, and compared to the situation with TEK17 requirements. For the passive house situation, the average energy demand was 65 kWh/(m^{2}year) for the apartment units on the ground and second floor. The first floor was therefore assumed to have the same energy demand. The third floor had an energy demand of approximately 75 kWh/(m^{2}year). This situation was similar to scenario 0 where 75% of the building had an energy demand of 65 kWh/(m^{2}year), while 25% of the building had an energy demand of 75 kWh/(m^{2}year). The calculated annual average energy demand for the whole building was thereby 67.5 kWh/m^2. Similar to scenario 0, the total annual energy demand for the passive house building was 4 759 kWh/year for each unit with a gross floor area of 70.5 m^2.



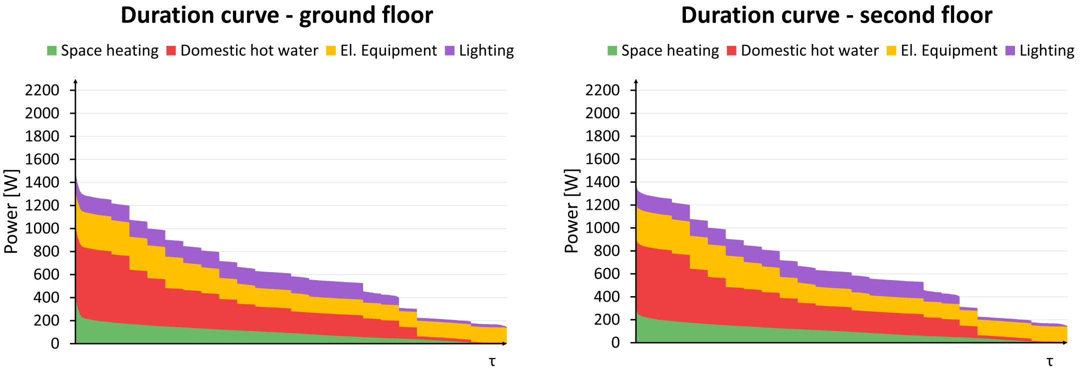
((a)) TEK17: Annual average energy distribution.

((b)) Passive: Annual average energy distribution.

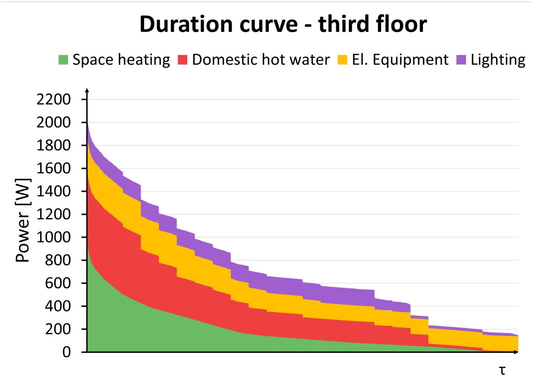
Figure 7.62: Apartment building, Scenario 1: Comparison of the annual average energy distribution between the TEK17 and the passive house models.

The annual average energy demand for space heating was calculated to be 13 kWh/(m^{2}year), based on Figure 7.62(b). This satisfied the requirement of a net energy demand lower than 15 kWh/(m^{2}year) for a passive house, as described in the section "Requirements for energy efficiency" under "Method". The average energy demand for domestic hot water, electrical equipment and lighting was 56 kWh/(m^{2}year), which satisfied the maximum requirement of 58.7 kWh/(m^{2}year) for a passive house. By comparing the two distribution graphs, the passive house measures had quite a small impact on the annual average energy distribution for the apartment building.

The total energy duration curves for the simulated units in the apartment building are displayed in Figure 7.63. These curves display the power from space heating, domestic hot water, electrical equipment and lighting. The apartment unit on the third floor had the highest peak power of approximately 2 000 W, while the other two floors had a peak power of approximately 1 400 W. The largest shares of the energy demand came from space and domestic hot water heating. Compared to the situation with the TEK17 apartment building, these duration curves had a lower peak power.



((a)) Ground floor. **((b))** Second floor.



((c)) Third floor.

Figure 7.63: Apartment building, Scenario 1 - Passive: Duration curves.

7.8 Comparison of the presented results

The presented results were compared with regard to energy demand for a TEK17 and a passive house. The annual energy demand and the annual average energy distribution were analyzed, in addition to the percentage reduction. Based on this analysis, recommendations were made.

Annual energy demand

The annual energy demands for the single family house, the row house and the apartment building are summarized in Table 7.14. The aggregated annual energy demand displays the total energy demand for the total units per building type. These values were calculated by multiplying the total annual energy demand per unit with the number of units for the specific building type, given in Table 2.1. These results established that the energy demands for the buildings were reduced when implementing passive house measures.

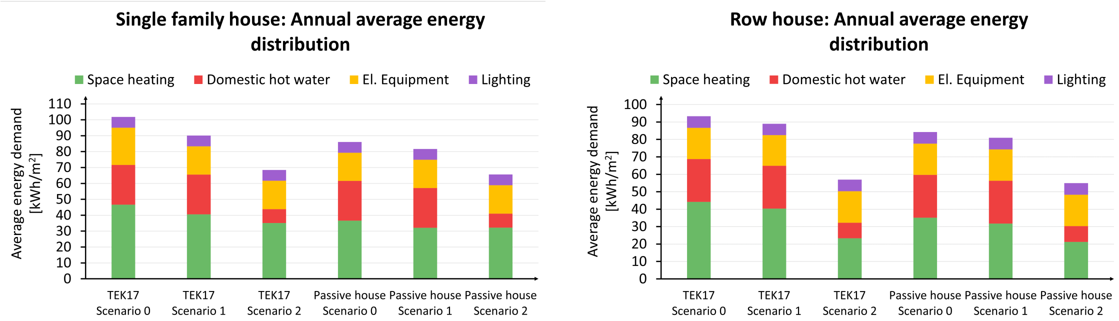
Table 7.14: Summary of the annual energy demands for the single family house, the row house and the apartment building models.

	Annual average energy demand [kWh/(m^{2}year)]			**Total annual energy demand per unit [kWh/(unit year)]**			**Annual aggregated energy demand [kWh/year]**		
Building type	**SFH**	**RH**	**AB**	**SFH**	**RH**	**AB**	**SFH**	**RH**	**AB**
TEK17 Scenario 0	102	94	74	17 806	8 460	5 163	302 756	245 340	1 295 788
TEK17 Scenario 1	90	89	72	15 714	8 010	5 023	267 138	232 290	1 260 648
TEK17 Scenario 2	70	58	-	12 222	5 220	-	207 774	151 380	-
Hunton Scenario 0	100	-	-	17 425	-	-	296 226	-	-
Passive Scenario 0	86	84	67.5	15 016	7 560	4 759	255 265	219 240	1 177 190
Passive Scenario 1	81	81	67.5	14 143	7 290	4 759	240 424	211 410	1 185 975
Passive Scenario 2	67	55	-	11 698	4950	-	198 869	143 550	-

From Table 7.14, it can be observed that a small reduction in energy demands occurred by replacing the ideal heaters with radiators. This is because the radiators represent a realistic scenario, and are not able to meet the heating demand at all times, unlike the ideal heaters which represent an ideal situation with 100% efficiency. The ideal heaters can therefore deliver the required heating demand, and maintain the desired setpoint temperatures, at all times. This scenario is consequently not realistic. It can also be observed that the energy demand was reduced in scenario 2 by implementing a hydronic radiant floor system to the models. This reduction was due to the heat pump installed with a COP = 3.62.

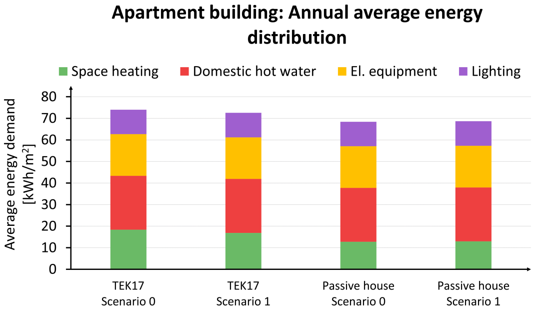
Annual average energy distribution

The annual average energy distribution per unit for the single family house, the row house and the apartment building is displayed in Figure 7.64. The average energy demand is displayed for both TEK17 and passive house models for each of the three scenarios. In these figures, loads such as space heating, domestic hot water, electrical equipment and lighting are illustrated.



((a)) Single family house.

((b)) Row house.



((c)) Apartment building.

Figure 7.64: Annual average energy distribution for the single family house, the row house and the apartment building models.

The energy demands for the different models were compared, and the graphs in Figure 7.64 clearly emphasize that a passive house model had a lower energy demand than a TEK17 model. The various TEK17 buildings satisfy all of the energy requirements given by Byggforskserien. Further, all of the passive house models had a total demand for domestic hot water, electrical equipment and lighting below the maximum demand limit of 58.7 kWh/(m^2year) given by NS3700. However, the single family passive houses and the passive row houses did not satisfy the maximum calculated space heating demand of 15 kWh/(m^2year) for passive residential buildings, whereas the passive apartment building was within this limit. To ensure that all buildings satisfy this required passive house limit, the implementation of further measures will be necessary, thereby providing a foundation for further work.

Percentage reduction of energy demand

Figure 7.65 displays the reduction of energy demands from a TEK17 to a passive house for the three building types, with the specific scenarios implemented. The reduction trends, given in percent, are illustrated with a green, purple and red bar for the single family house, the row house and the apartment building, respectively.

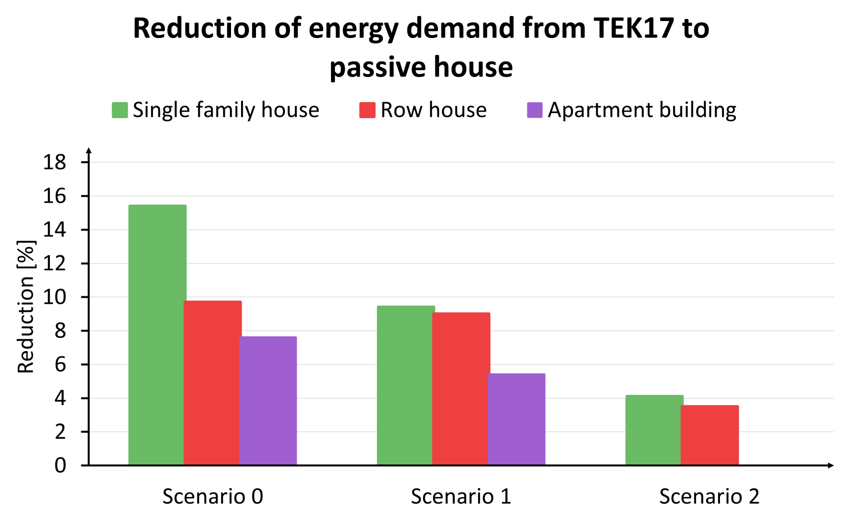


Figure 7.65: Reduction in energy demands from TEK17 to passive house models with the different scenarios.

As Figure 7.65 displays, scenario 0 had the highest reduction when passive house measures were applied. However, this represents an ideal situation and is therefore not realistic. For the single family house, the energy demand was reduced by 9.4% for scenario 1, and by 4.1% for scenario 2. This trend is also illustrated for the row house, where the energy demand was reduced by 9% for scenario 1, and by 3.5% for scenario 2. For the apartment building, the energy demand was reduced by 5.4% for scenario 1.

Based on these results, the single family house had the most significant energy demand reduction for all the scenarios. The reason behind this greater energy demand reduction for the single family house was found to be the larger area of opaque walls. The opaque walls of the single family house was thereby further affected by the increased insulation thicknesses in the passive house model. The bars representing the row house and the apartment building showed a smaller energy demand reduction. These two building types had a smaller area of opaque walls since some walls faced heated areas, meaning less area was affected by the increased insulation thicknesses.

Recommendations

As a zero emission neighborhood was the basis for this master's thesis, it provided an interest in investigating the impact of passive house measures. Consequently, both TEK17 and passive house models were created to analyze this impact. Two distinct scenarios were established based on the simulation of either radiators or a floor heating system in the models. These represented scenario 1 and 2, respectively. To determine a recommendation regarding the investment of passive house measures, the energy savings and investment costs are analyzed and discussed in the following paragraphs.

It was expected to achieve a significant reduction in energy demand when passive house measures were applied. After analyzing the energy demands between the TEK17 and passive house models, the percentage reduction was studied. However, after this evaluation, it became clear that the initial expectations were not fulfilled since the percentage reduction in energy demands were relatively low.

In scenario 1, the single family house, the row house and the apartment building had a percentage reduction of respectively 9.4%, 9% and 5.4% when passive house measures were implemented. In scenario 2, the single family house and the row house had a percentage reduction of 4.1% and 3.5%, respectively. In other words, all of the building types had a reduction in energy demand below 10%, which was much lower than the initial expectations.

The minimal energy savings may prevent the solution from being viable, and it is therefore crucial to consider the investment costs of passive house measures in comparison to the total energy savings. With regard to the section ”Passive houses” in the literature review, passive house measures can present a challenge in terms of investment costs. A low percentage reduction in the energy demand might therefore make the investment unprofitable.

Table 7.15 displays the saved energy and the respective saved costs per unit per year after passive house measures were applied. As seen in this table, the reduction in energy consumption was relatively small. With an electricity price of 1.888 NOK/kWh, this also resulted in low cost savings. This applies to both scenario 1 with radiators, and scenario 2 with floor heating.

Table 7.15: Saved energy per unit per year between TEK17 and passive house models.

	Saved energy [kWh/(unit year)]			**Saved costs [NOK/(unit year)]**		
Building type	**SFH**	**RH**	**AP**	**SFH**	**RH**	**AP**
Scenario 1	1 571	720	298	2 966	1 360	563
Scenario 2	524	270	-	990	510	-

The payback period can determine how economically favorable an energy system is. In relation with the section ”Payback period” under ”Method”, a simple method given in Equation 3.12 was used to calculate the payback period. According to the section ”Passive houses” in the literature review, the investment cost for building a passive house is approximately 300 000 - 367 000 NOK higher than for building a TEK17 house. The value of 367 000 NOK was therefore used together with the annual savings given in Table 7.15. The respective calculated payback periods are displayed in Table 7.16. As a result, it is not possible to recoup the passive house investment cost within the building’s expected lifetime of approximately 60 years.

Table 7.16: The calculated payback periods.

	PBP [years]		
Building type	**SFH**	**RH**	**AP**
Scenario 1	124	270	652
Scenario 2	371	720	-

It is possible that future advancements will make passive houses more economically viable. However, based on the current situation with high investment costs, in addition to the analysis performed in this thesis, investing in passive house measures is not recommended for the project at Tanberghøgda.

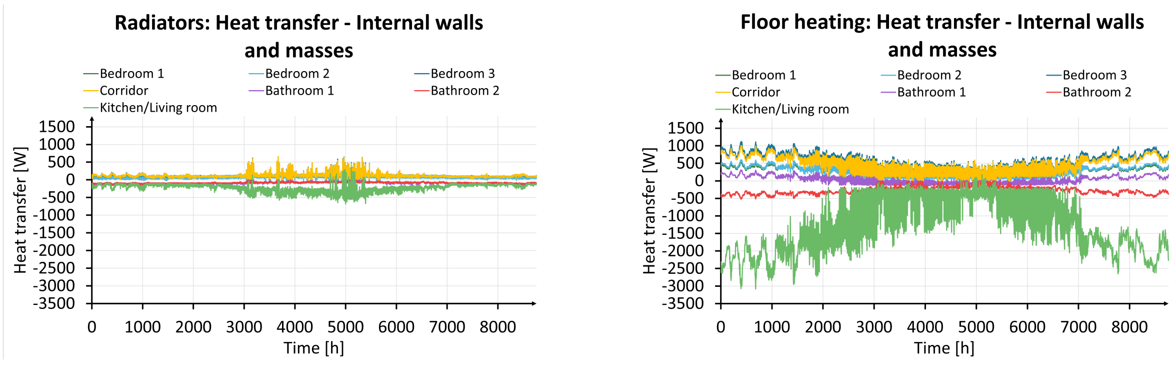
7.9 Comparison of heat losses

It was discovered in the section "Single family house - TEK17" for scenario 2, that the building with floor heating had a drastically higher space heating demand compared to scenario 1. The comparison of the annual average energy demand between scenario 1 and 2 is illustrated in Figure 7.15(a). It was expected that scenario 2 would have a slightly higher heat loss compared to scenario 1, but the increase in the space heating demand of about 82% was unexpected. This being the case, the basis for further investigation was provided, with the aim to discover the reason behind the increased heat losses. As a consequence, the TEK17 single family house was thoroughly studied, with the main focus on three specific, and potential, sources behind the drastic increase; heat loss due to internal walls and masses, the envelope, and infiltration and openings.

Internal walls and masses

When floor heating is used, the whole building body is heated, in contrast to the scenario with radiators, where only the room air is heated. Based on Equation 3.8 and Equation 3.9 in the section "Method", floor heating systems have a potentially larger internal heat transfer compared to radiators. This is a consequence of the additional term related to internal walls and masses. Heat transfer between internal walls and masses was therefore expected to be significant in scenario 2, and approximately zero in scenario 1.

As illustrated in Figure 7.66, the expectations were met. Upon observation, a significant disparity was noted in the level of heat exchanged between the rooms in scenario 2 compared to scenario 1. In the scenario with floor heating, the kitchen and living room emitted a large amount of heat. Consequently, heat was delivered from the first to the ground floor. In the scenario with radiators, there was minimal heat transfer between the rooms. This is because radiators mainly heat up the room air, resulting in an insignificant amount of heat in the internal walls and masses, resulting in minimal internal heat losses.

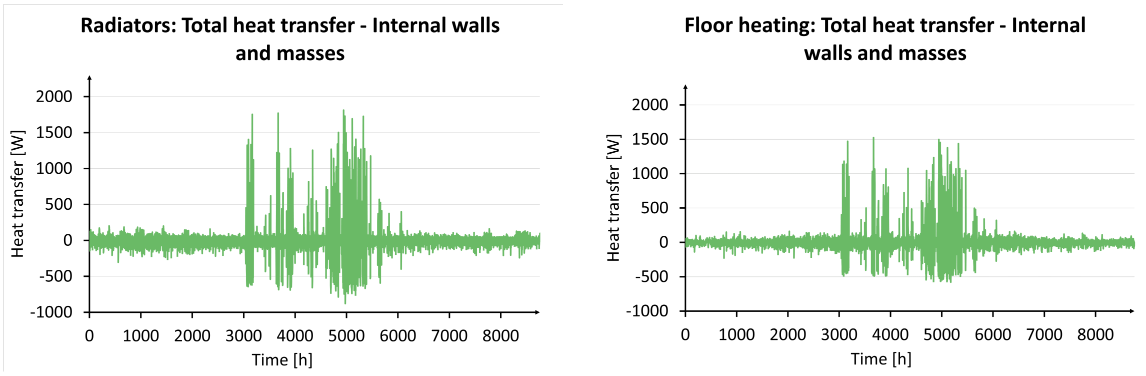


((a)) Scenario 1: Heat transfer for each zone through the internal walls and masses.

((b)) Scenario 2: Heat transfer for each zone through the internal walls and masses.

Figure 7.66: Single family house, TEK17: Comparison of the heat transfer through the internal walls and masses between scenario 1 and 2.

However, when considering the total heat transfer illustrated in Figure 7.67, it was found that the total internal heat loss was approximately equal for both scenarios. This was despite the fact that there seemed to be a notable difference in the level of heat exchanged between the rooms in scenario 2 compared to scenario 1. Hence, it was be established that the increase in heat losses for the models with floor heating was not due to heat transfer through the internal walls and masses.



((a)) Scenario 1: Total heat transfer through the internal walls and masses.

((b)) Scenario 2: Total heat transfer through the internal walls and masses.

Figure 7.67: Single family house, TEK17: Comparison of the total heat transfer through the internal walls and masses between scenario 1 and 2.

A comparison of the average heat transfer through internal walls and masses between scenario 1 and 2 is illustrated in Figure 7.68. This figure displays that the average heat transfer was equal for scenario 1 and 2, and approximately zero. This trend corresponds well with the figures illustrating the total heat transfer, which was equal in the two scenarios, as illustrated in Figure 7.67

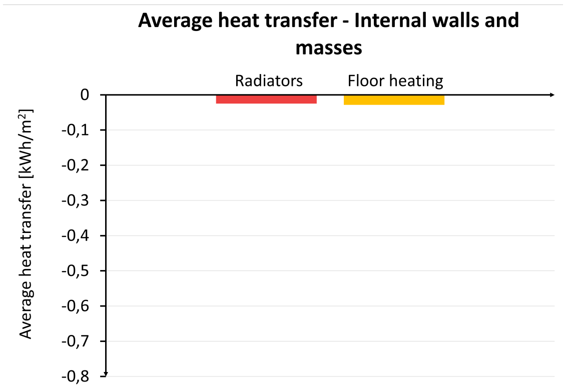
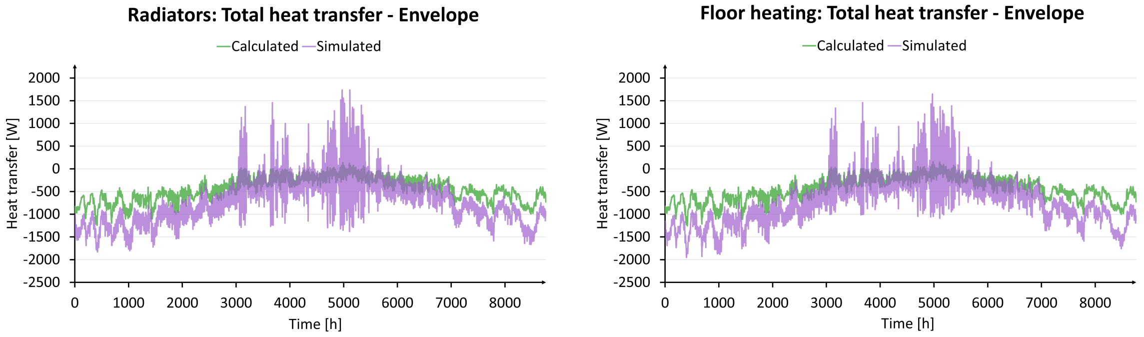


Figure 7.68: Single family house, TEK17: Comparison of the average heat transfer through internal walls and masses between scenario 1 and 2.

Envelope

As previously stated, the floor heating heats up the whole building body, and not just the indoor air. Therefore, there was a suspicion that the large heat loss in the models with floor heating was caused by an increased transmission heat loss through the building envelope. However, based on Equation 3.11 in the section "Method", it would be expected that the heat loss through the envelope would be approximately equal for both cases. This is because all of the parameters in the calculation method were the same, except for the indoor temperatures, which were very similar. To evaluate this, the total transmission heat loss was calculated. As a result, Figure 7.69 emphasizes the fact that the calculated transmission heat loss was approximately identical for scenarios 1 and 2. The same applied to the simulated transmission heat loss. Hence, the theoretical expectations were met and it was concluded that the envelope did not cause the increased heat loss observed between the two scenarios.



((a)) Scenario 1: Total heat transfer through the envelope.

((b)) Scenario 2: Total heat transfer through the envelope.

Figure 7.69: Single family house, TEK17: Comparison of the total heat transfer through the envelope between scenario 1 and 2.

A comparison of the average heat transfer through the envelope between scenario 1 and 2 is illustrated in Figure 7.70. As displayed in this figure, the two scenarios had an equal average heat transfer of approximately 35 kWh/m^2 emitted. This figure shows the same trend as Figure 7.68. This trend corresponds well with the figures illustrating the total heat transfer which was equal in the two scenarios, as seen in Figure 7.69.

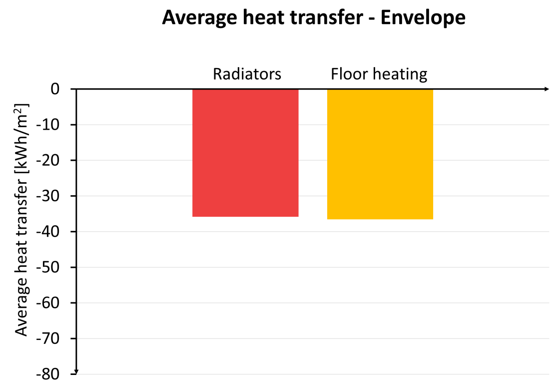
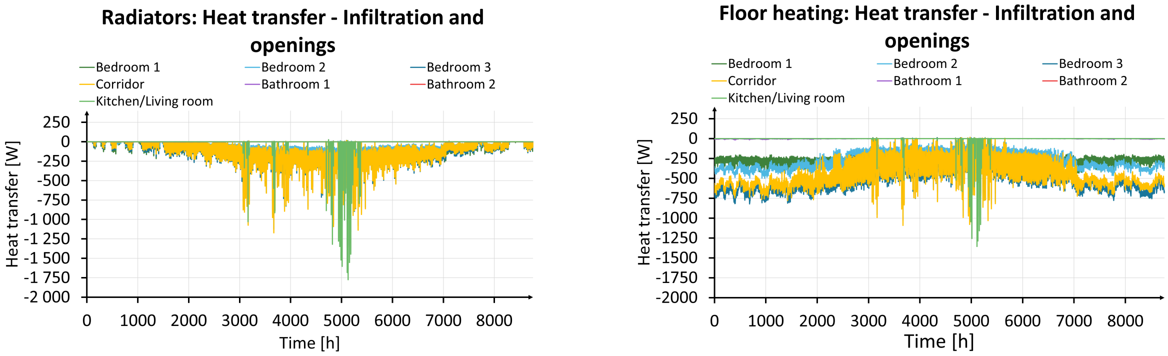


Figure 7.70: Single family house, TEK17: Comparison of the average heat transfer through the envelope between scenario 1 and 2.

Infiltration and openings

Lastly, the heat loss due to infiltration and openings was analyzed. Figure 7.71 illustrates the heat transfer in the different zones for both scenario 1 and 2. For both scenarios, the unheated zones had the highest heat transfer caused by infiltration and openings. A reason for this was suspected to be a more frequent opening of windows to achieve the desired low temperature setpoints in these zones. Scenario 2 had a much higher overall heat transfer in all of the zones compared to scenario 1, especially in the coldest months of the year. However, in scenario 1 there was a maximum heat loss of 1 750 W for the kitchen and living room, which was higher than the peak in scenario 2 of approximately 1 350 W.

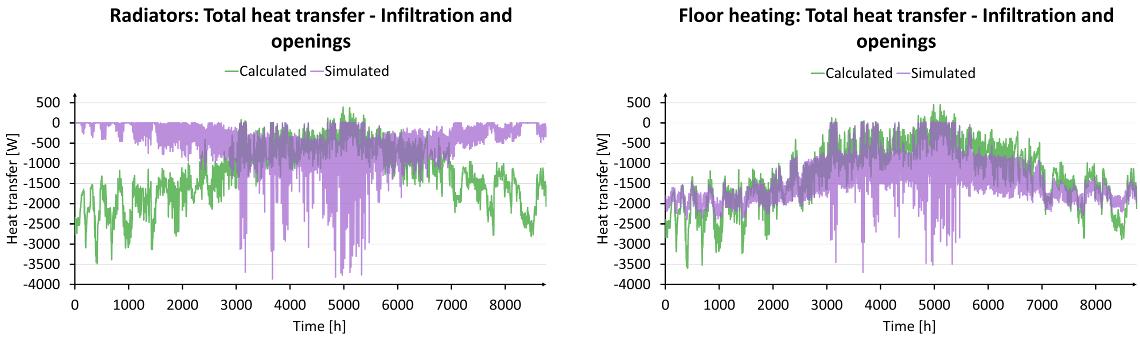


((a)) Scenario 1: Heat transfer for each zone due to infiltration and openings.

((b)) Scenario 2: Heat transfer for each zone due to infiltration and openings.

Figure 7.71: Single family house, TEK17: Comparison of the heat transfer for each zone due to infiltration and openings between scenario 1 and 2.

The simulated and calculated results are displayed in Figure 7.72, where the calculated results were based on Equation 3.10 in the section "Method". In accordance with the calculation method, it would be expected that the total infiltration heat losses would be approximately equal for both cases. This is because all of the parameters in the calculation method were the same, except for the indoor temperatures, which were very similar.



((a)) Scenario 1: Total heat transfer due to infiltration and openings.

((b)) Scenario 2: Total heat transfer due to infiltration and openings.

Figure 7.72: Single family house, TEK17: Comparison of the total heat transfer due to infiltration and openings between scenario 1 and 2.

The calculated infiltration heat losses were approximately identical in the two scenarios, which emphasized the theoretical expectation. In addition, the simulated infiltration heat loss for scenario 2 corresponded well with the calculated result, as illustrated in Figure 7.72(b). However, as Figure 7.72(a) illustrates, the simulated infiltration heat loss for scenario 1 strongly deviated from the calculated result. In other words, the simulated result for the model with radiators did not correlate with the theoretical background. Hence, it was likely to be a deviation in the TEK17 single family house model with radiators, which indicated a weakness in the IDA ICE model.

A comparison of the simulated average heat transfer due to infiltration and openings between scenario 1 and 2 is illustrated in Figure 7.73. The average heat transfer was significantly higher for scenario 2 compared to scenario 1, with a difference of approximately 55 kWh/m^2. This figure emphasizes the previous statement of how the result does not correlate with the theoretical background, as the average heat losses for the two scenarios are distinctly dissimilar.

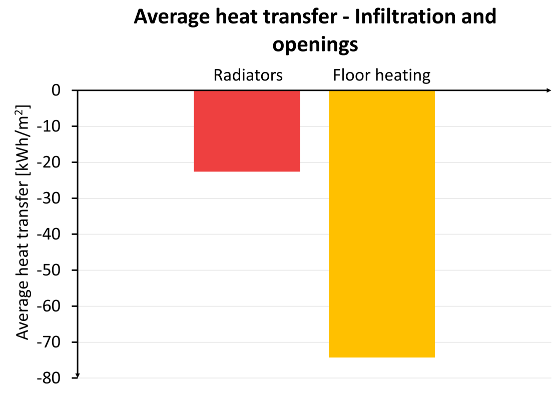
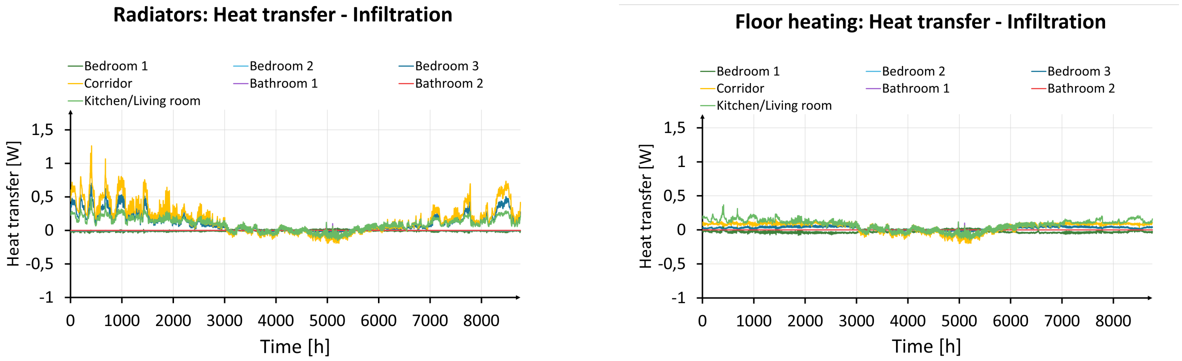


Figure 7.73: Single family house, TEK17: Comparison of the average heat transfer due to infiltration and openings between scenario 1 and 2.

The deviation that was discovered in the floor heating model was further investigated. It was suspected that the increased infiltration heat loss was caused by the frequent opening of windows, due to the applied PI temperature control in IDA ICE. The opening control of the windows was therefore set to ”never open” in order to investigate this influence.

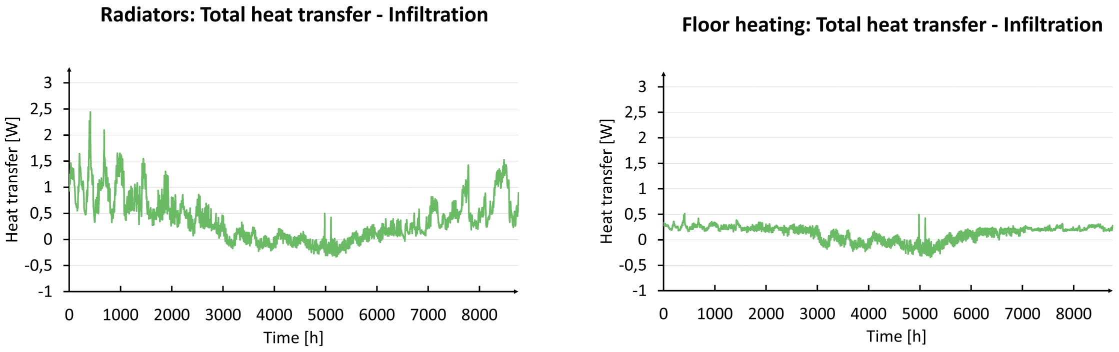
The resulting heat transfer for each zone is displayed in Figure 7.74 for both scenarios. The total heat transfer for both scenarios is displayed in Figure 7.75. The heat transfer was now drastically reduced to approximately zero in all of the zones. Hence, the total simulated heat loss found in Figure 7.72 was greatly affected by the opening of windows, which is not an unintentional heat loss. As it seemed like the simulated infiltration heat losses in IDA ICE includes opening of windows, the results given by the simulation tool contradicts the theoretical definition of infiltration given in section Infiltration in the literature review; ”Infiltration is defined as the unintentional introduction of outside air into a building, caused by pressure differences between the internal and external environments of a building”.



((**a**)) Scenario 1: Heat transfer for each zone due to infiltration and openings.

((**b**)) Scenario 2: Heat transfer for each zone due to infiltration and openings.

Figure 7.74: Single family house, TEK17: Comparison of the heat transfer for each zone due to infiltration and openings between scenario 1 and 2.



((**a**)) Scenario 1: Total heat transfer due to infiltration and openings.

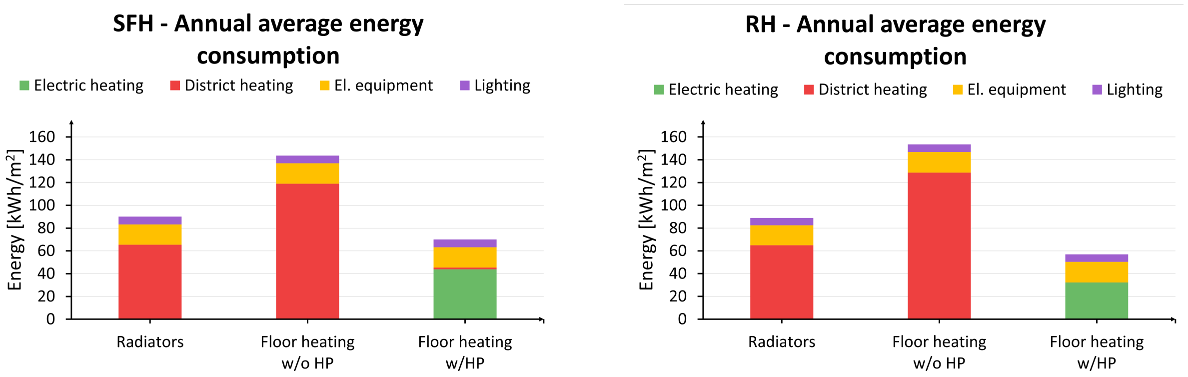
((**b**)) Scenario 2: Total heat transfer due to infiltration and openings.

Figure 7.75: Single family house, TEK17: Comparison of the total heat transfer due to infiltration and openings between scenario 1 and 2.

As illustrated in Figure 7.71, and as stated above, the scenario with floor heating heats up the entire building body, which resulted in a high level of heat transfer through the walls and masses, and thereby, between the different zones. The heated zones, which had higher setpoint temperatures, delivered heat to the unheated zones. This, together with the high internal heat transfer, caused the unheated zones to reach temperatures higher than the desired setpoint temperatures. The windows were therefore opened, due to the PI temperature control setting, which resulted in a significant heat loss for the building. The phenomenon which occurred here must be the reason behind the drastic increase in energy demand for space heating when floor heating was used. This did not happen to the same extent in the scenario with radiators, as they heat up the room air, and not the whole building body, resulting in a low internal heat transfer from the warmer to the colder zones.

7.10 Evaluation of the heating systems

In this master's thesis, two potential heating systems were simulated and analyzed; radiators and floor heating. After careful evaluation of the heating systems, it became clear that the radiators resulted in the lowest heating demand. This is illustrated in Figure 7.76, for the single family house and the row house. Based on the section "Heat pumps" in the literature review, radiators are not the optimal source to combine with a heat pump. In comparison to floor heating systems, they have a smaller heat emitter area, which results in the necessity of higher water flow temperatures, which further decreases the efficiency of the heat pump. With regard to this, only district heating was consumed to cover the heating demand when using radiators.



((a)) Single family house - Comparison of the energy consumption.

((b)) Row house - Comparison of the energy consumption.

Figure 7.76: TEK17 models with different heating systems: Comparison of the annual average energy consumption.

Floor heating, on the other hand, works great with a heat pump. Even though floor heating resulted in a higher heating demand, using a heat pump with a COP of 3.62 reduced the total energy consumption to such an extent that this combination outperformed the solution with radiators. By replacing the radiators with floor heating, the heating demand increased with 60% and 72% for the single family house and the row house, respectively. Further, when a heat pump was implemented to the models with floor heating, a reduction of 51% and 63% was obtained, when compared to the floor heating models without a heat pump. This applied to the single family house and the row house, respectively. Finally, as seen in Figure 7.76, the scenario with floor heating and a heat pump resulted in a reduction of 22% for the single family house and 36% for the row house, compared to the scenario with radiators. Based on these results, the scenario with floor heating and a heat pump was determined to be the most favorable.

Based on the evident energy consumption pattern of the two residential building types, it can be assumed that the apartment building will follow a similar trend. Thus, utilizing the combination of floor heating and a heat pump could also be beneficial for the apartment building. Nonetheless, this assumption requires additional research and analysis, and can be the basis for further work.

With regard to the section "Hydronic heating systems" in the literature review, floor heating gives a better thermal comfort, as the ideal heat distribution for humans is to have warmer feet and a cooler head. This optimal heat distribution can only be achieved with floor heating. Another advantage of floor heating is the possibility to turn down the setpoint temperatures due to the well distributed heat throughout the room. In addition, this type of heating system is invisible and more convenient with regard to spacing.

A weakness with the floor heating solution was how the heated zones at the first floor drastically heated the unheated zones on the ground floor. It is preferable to have quite low temperatures in bedrooms for good thermal comfort, and it was therefore a need to open the windows a large share of the time to achieve the desired thermal comfort. This frequent need for aeration in the bedrooms resulted in a significant increase of heat losses and caused the heating demand to increase drastically. A potential solution to this problem could be to place the unheated zones in the first floor, and thereby reduce the large internal heat transfer through the intermediate floor.

After conducting a thorough analysis, a floor heating system paired with a heat pump was evaluated to be an excellent choice for achieving high energy efficiency and adequate thermal comfort. However, the cost-effectiveness of this option remains uncertain, and further evaluation may be necessary to determine if it is an economically viable choice. Alternatively, the use of radiators is also a suitable and cost-effective solution. Ultimately, the recommended option depends on the priorities of the developer. All things considered, from an energy efficiency and thermal comfort point of view, the floor heating system in combination with a heat pump is the recommended solution for the project at Tanberghøgda.

8 Conclusion

This master's thesis focused on a zero emission residential area at Tanberghøgda in Hønefoss, which is currently being developed under the management of Fossen Utvikling AS. The basis for analyzing the effects of passive house measures were consequently established. Hence, two main types of constructions were developed; one complying with the TEK17 regulations and another following the passive house standard. In addition, a third construction was created to comply with the building solutions manufactured by Hunton, which are intended for use in the project. These constructions were implemented in three different types of buildings; a single family house, a row house and an apartment building. In addition, two specific scenarios were created, each simulating either radiators or a floor heating system. These scenarios were referred to as scenario 1 and scenario 2, respectively. In order to determine the feasibility of investing in passive house measures, the energy savings and investment costs were analyzed and discussed.

The aim of this thesis was to define appropriate types of building constructions and respective heating solutions for three different building types, to achieve minimal energy consumption of the zero emission residential area. To accomplish this, the simulation application IDA ICE was utilized. A literature review was performed to obtain relevant theory and calculation methods based on research, creating the basis for the execution of the thesis. Derived from this literature review, a simulation background for the models was established.

Different scenarios for heating were applied to the models. Initially, scenario 0 involved modeling ideal heaters as a reference scenario to establish a foundation for the sizing of radiators. Further, by utilizing heat rates obtained from scenario 0, radiators were sized and implemented into the models, representing scenario 1. Moreover, floor heating was sized according to typical design heat rates defined by Byggforskserien, representing scenario 2. As it is more energy efficient to use the mentioned heating units for space heating, in comparison to using ventilation heating, the heating coil in the air handling unit was completely turned off. When turning off the heating coil, the temperature distributions in the zones remained adequate and comfortable. Since the buildings are located in Hønefoss, a cooling system is unnecessary, and the cooling coils were therefore removed. Furthermore, by avoiding cooling coils, the air handling units will be simplified, and the investment costs can thereby be reduced.

Once the complete models were constructed, simulations were conducted using the IDA ICE software. The objective was to achieve the optimal indoor environment, considering various setpoint temperatures for different types of rooms. Firstly, a standard temperature range of 22 - 24°C, as defined by FHI, was investigated. Secondly, specific setpoint temperatures for each zone, as specified by Fjordkraft, were tested. It was determined that the recommendations provided by Fjordkraft offered the most favorable option in terms of thermal comfort. External shading, in combination with PI regulated opening control of windows, was necessary to obtain these preferred temperature levels.

After analyzing the simulated results, it was found that all building types experienced a decrease in energy demand of less than 10% when passive house measures were implemented. This was much lower than the initial expectation. The minimal energy savings can prevent the solution from being viable, and it was therefore crucial to consider the investment costs of passive house measures in comparison to the total energy savings.

The payback period is an indicator of how economically favorable an energy system is. This parameter was therefore calculated for all of the building types and for both scenarios. For a passive house, the investment cost is approximately 300 000 - 367 000 NOK higher than for building a TEK17 house. In relation to the simulated results, saved costs between 500 - 3000 NOK/(unit year) were obtained with an electricity price of 1.888 NOK/kWh. Consequently, the calculated payback period was between 124 - 720 years for all the buildings analyzed. As a result, it was not possible to recoup the passive house investment costs within the building's expected lifetime of approximately 60 years. Therefore, the investment costs for passive house measures could not be justified, and investing in passive house measures is thereby not advisable for the project at Tanberghøgda.

The evaluated heating systems were compared with regard to high energy efficiency and thermal comfort. By replacing the radiators with floor heating, the heating demand increased with 60% and 72% for the single family house and the row house, respectively. This provided a basis for further investigation to discover the reason behind this increase. It was discovered that the floor heating caused high internal heat transfer from the heated to the unheated zones. This resulted in the necessity for a higher frequency of aeration through opening of windows to maintain the desired setpoint temperatures. Further, a significant discovery was that the simulation results given by IDA ICE contradicted the theoretical definition of infiltration heat losses. The simulated infiltration heat losses accounted for losses attributed to opening of windows, which are not considered unintentional, and therefore deviate from the definition of infiltration.

When a heat pump was implemented to the models with floor heating, a reduction of 51% and 63% was obtained, when compared to the floor heating models without a heat pump. This applied to the single family house and the row house, respectively. Finally, the scenario with floor heating in combination with a heat pump resulted in a reduction of 22% for the single family house and 36% for the row house, compared to the scenario with radiators. Based on these results, the scenario with floor heating in combination with a heat pump was the most favorable, and is therefore the recommended heating solution.

8.1 Further work

There was an evident pattern for the energy consumption in the single family house and the row house, when radiators were replaced with a floor heating system. Based on this particular pattern, it was assumed that the apartment building would follow a similar trend. However, this assumption requires additional research and analysis, and can be the basis for further work.

The simulation of the Hunton construction was limited to the reference scenario of the single family house. This choice was made due to the closely aligned results observed between the Hunton and the TEK17 construction in this scenario. However, it is important to emphasize that the Hunton construction represents a realistic building solution incorporating authentic materials supplied by Hunton. To achieve a comprehensive representation of the Tanberghøgda project, the Hunton construction can be implemented across all building types.

When the economic analysis of the passive house was conducted, it is important to note that the calculations were intentionally simplified. While the analysis provided valuable insights into the financial aspects of the project, it should be acknowledged that a more comprehensive and detailed assessment could be pursued in future investigations. By expanding the analysis, a more holistic understanding of the economic viability can be obtained.

With the aim to reduce the increased heat losses in the models with floor heating, a possible solution could be to place the unheated zones on the first floor, and the heated zones on the ground floor. This proposal can create the basis for further investigation. Lastly, more measures can be implemented in the models, such as Variable Air Volume systems (VAV), night set back control, super insulated windows and doors, or solar panels. This will be necessary to satisfy the maximum calculated space heating demand of 15 kWh/(m^2year) for the passive residential buildings.

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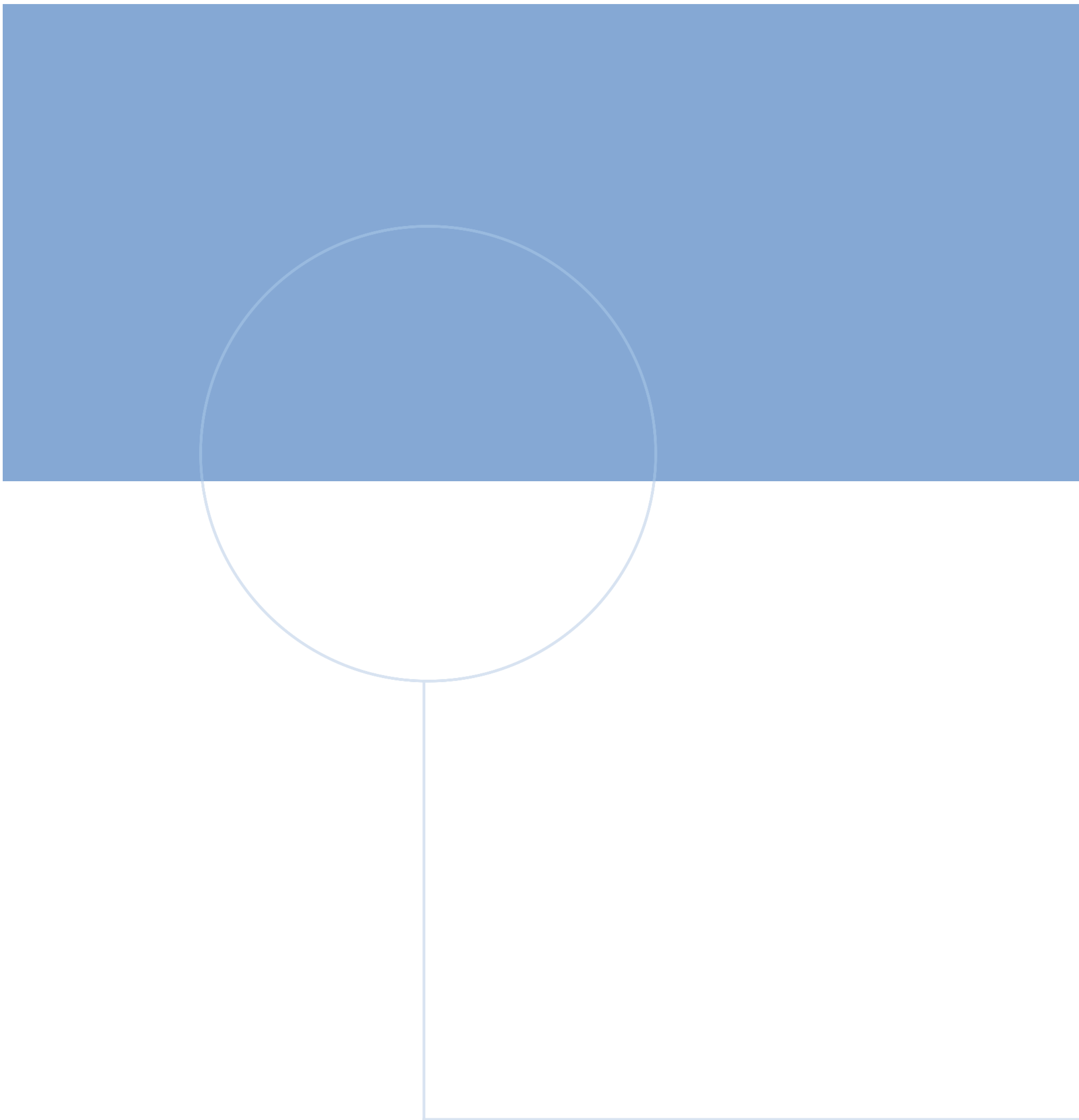

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