Master's thesis

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

Bianca Kjellberg and Sondre Valstad Johansen

Economic Performance of Heating and Ventilation Systems in Energy Retrofit of Detached Houses

Kostnadseffektivitet for varme- og ventilasjonssystem ved energioppgradering av eneboliger

Master's thesis in Energy and Environmental Engineering
Supervisor: Laurent Georges
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Abstract

In the Paris Agreement of 2015, Norway agreed on aiming at a 50% reduction of greenhouse gas emissions by 2030. According to Statistisk Sentralbyrå, private households were responsible for around 23% of Norway's energy consumption in 2019 [1]. More than half of these private households were wooden dwellings. This means that there is a significant potential for energy savings if these wooden dwellings were to undergo an energy retrofit.

The objective of this master's thesis has been to evaluate the cost-, energy- and environmental performance of different HVAC-combinations that could potentially be implemented in Norwegian wooden detached dwellings. This is investigated because of the potential for considerable energy savings and for the purpose of enlightening end users. Ultimately, the thesis hopefully contributes to reaching the national climate target. The impact of the prebound and rebound effects on the cost effectiveness will also be explored.

This master's thesis is related to the NTNU/SINTEF's project named OPPTRE. The OPPTRE-project aims at proposing a nearly Zero Energy Building (nZEB) level for deep energy retrofit of wooden detached dwellings. There are six houses in the OPPTRE-project, representative of the typical Norwegian architectural style. Two of these houses are in this master's thesis going to be analyzed and deep energy retrofitted to three levels of energy efficiency of the building envelope.

Different methods are used to evaluate the three performance aspects of this study. The standard NS-EN 15459 (2017) was mainly used for the cost performance assessment. Concerning the energy performance, simulations in the energy simulation software IDA ICE were done. The key output from the simulations is the annual energy consumption of the building. To assess the environmental impact, CO_2-factors are used to convert the energy consumption into the equivalent CO_2-emissions from the different HVAC-combinations. The prebound and rebound effects are explored through compensation in energy consumption. This implies calculating with lower energy consumption in the existing house and higher energy consumption in the retrofitted scenarios.

This thesis shows that deep energy retrofitting detached wooden dwellings can contribute to reducing the energy use of the Norwegian building stock through cost-effective and energy-efficient measures with low environmental impact. In conclusion, several of the considered HVAC-combinations could be optimal, depending on the energy efficiency of the building envelope and type of detached wooden dwelling. The results indicated additionally that which combinations are optimal, depended on the weighing of the investment's cost effectiveness, energy efficiency and environmental impact.

Sammendrag

I forbindelse med Parisavtalen i 2015, satte Norge seg som mål å redusere drivhusgassene med 50% innen 2030. I 2019 gikk 23% av Norges energiforbruk til private husholdninger ifølge Statistisk Sentralbyrå [1]. Videre er mer enn halvparten av dem eneboliger bygget av tre. Dette betyr at det eksisterer et betydelig energisparingspotensial hvis alle disse boligene ble energioppgradert.

Målet med denne masteroppgaven har vært å evaluere kostnads-, energi- og miljøytelsen til forskjellige VVS-løsninger som potensielt kan implementeres i norske trehus. Dette blir undersøkt på grunn av det store energibesparelsespotensialet, av den hensikt å informere sluttbrukere og til slutt å bidra til å nå det nasjonale klimamålet. Hvordan "prebound" og "rebound"-effektene påvirker kostnadseffektiviteten vil også bli undersøkt.

Denne masteroppgaven er relatert til NTNU/SINTEFs OPPTRE-prosjekt. OPPTRE-prosjektet har som mål å foreslå et nesten nullenerginivå ved renovasjon av eneboliger bygget av tre. Det er seks hus i OPPTRE-prosjektet, representative for typisk norsk arkitektonisk stil. To av disse husene skal i denne masteroppgaven analyseres og bygningskroppen skal renoveres til tre nivåer av energieffektivitet.

Ulike metoder brukes til å evaluere de tre ytelsesaspektene i denne studien. Standarden NS-EN 15459 (2017) ble hovedsakelig brukt til kostnadseffektivitetsanalysen. Når det gjelder energiytelsen, ble det gjort simuleringer i energisimuleringsprogramvaren IDA ICE. Nøkkelresultatet fra simuleringen er bygningens årlige energibruk. For å vurdere miljøpåvirkningen brukes CO_2-faktorer for å konvertere energiforbruket til tilsvarende CO_2-utslipp fra de forskjellige VVS-løsningene. "Prebound"- og "rebound"-effektene utforskes gjennom kompensasjon i energiforbruket. Dette innebærer lavere energiforbruk i det eksisterende huset og høyere energiforbruk i de renoverte scenariene.

Masteroppgaven belyser at renovering av eneboliger kan bidra til å redusere energibruken i den norske bygningsmassen ved å investere i kostnads- og energieffektive tiltak med lav miljøpåvirkning. Man kan konkludere med at flere av de utvalgte VVS-kombinasjonene er optimale, avhengig av energieffektiviteten til bygningskroppen og type enebolig. Resultatene indikerte i tillegg at optimal kombinasjon avhenger av hvordan man veier investeringens kostnadseffektivitet, energieffektivitet og miljøpåvirkning opp mot hverandre.

Description of master's agreement

Economic performance of Heating and Ventilation systems in Energy Retrofit of Detached Houses

The master's thesis is related to the research project OPPTRE (https://opptre.no/). OPPTRE aims to propose a nearly Zero Energy Building (nZEB) level for the renovation of wooden dwellings. The scope is wooden dwellings, responsible for more than half of the total energy use in the Norwegian building stock. Energy retrofitting these houses can contribute significantly to the national target of 10 TWh/year energy saving by 2030 for existing buildings.

The project aims at comparing the energy and cost performance of heating and ventilation systems (HVAC) for deep energy retrofit of detached houses. The objective is to understand the trade-offs, pros and cons of the different HVAC-technologies. For instance, technologies with higher energy efficiency are often characterized by significantly higher investment costs that can be difficult to pay back when the building insulation level is improved. Alternatively, cheap solutions are cost-effective in highly-insulated buildings, but with low energy efficiency. Finally, the analysis will be done considering the difference between the measured energy use and the simulated energy use to take into account the so-called prebound and rebound effects. This is done for the purpose of evaluating how these effects will influence the cost performance of the HVAC-systems.

The following tasks are to be considered.

1. Collect data for the cost performance assessment for each HVAC technology: investment and maintenance costs, typical inflation and discount rates, technology operational lifetime, typical measured and simulated energy efficiency. It should also be mentioned if the investment costs and efficiencies are expected to decrease significantly in the next decades (like PV).

2. Develop a detailed building simulation model in IDA ICE of two of the detached houses of the OPPTRE-project. Determine whether field measurements can provide reliable information about the energy prebound effect.

3. Make an analysis of energy use, GHG emissions and cost performance of the HVAC systems in the simulated buildings for different levels of insulation. Derive conclusions from the analysis of results.

Acknowledgements

We want to thank our supervisor Laurent Georges and co-supervisor Vegard Heide for exceptional support and guidance during the work of this master's thesis. Further, we would also like to give our thanks to Rambøll for providing us with IDA ICE-files, giving us a flying start on the project. Lastly, we want to thank Jørn Stene for his expertise on heat pumps.

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- Øystein Strøm, K. Lund AS

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Abbreviations

AHU Air handling unit

CAV Constant air volume

COP Coefficient of performance

DHW Domestic hot water

DOT Dimensioned outdoor temperature

EAHP Exhaust air heat pump

ESBO Early Stage Building Optimization

GHG Greenhouse gas

GSHP Ground source heat pump

HVAC Heating, ventilation and air-condition

NIA Net internal area

NVE Norwegian Water Resources and Energy Directorate

nZEB Nearly Zero Energy Building

PV Photovoltaic

SCOP Seasonal coefficient of performance

SEC Specific energy consumption

SFP Specific fan performance

SPF Seasonal performance factor

SSB Statistisk sentralbyrå

Introduction

1.1 Background

Together with 194 countries, Norway committed in 2015 to United Nation's Paris Agreement. One of the main objects of this agreement is to limit global warming so that the temperature does not increase by more than 2 degrees by 2030. To reach this goal, all parties of the Paris Agreement must reduce their greenhouse gas (GHG) emissions. Norway agreed on aiming at a 50% reduction of GHG emissions by 2030 [2].

A strategy used for reducing the GHG emissions of a nation is decreasing the national energy consumption. In wooden detached dwellings, this can be done by an energy retrofit and implementing energy-efficient heating systems. In 2019, private households were responsible for around 23% of Norway's energy consumption according to Statistisk Sentralbyrå [1]. More than half of these private households were wooden dwellings. This means that there is a significant potential for energy savings if these wooden dwellings were to undergo an energy retrofit.

NTNU/SINTEF's ongoing research project, OPPTRE, is exploring this potential for energy savings. OPPTRE aims to propose a nearly Zero Energy Building (nZEB) level for the retrofit of six detached wooden dwellings. It employs a multidisciplinary approach, cooperating across several work packages to cover all the aspects of building performance. One of these disciplines is regarding Heating, Ventilation and Air-Conditioning (HVAC) systems and energy use [3]. This includes a large variation in technologies such as heat pumps, hydronic heating systems, solar thermal collectors, photovoltaic (PV) panels, ventilation systems, etc. However, in most cases, this is a major investment for the end user. Consequently, a question is raised about how to choose the optimal solution: should it be based on profit for the end user, energy efficiency, or with respect to the environment?

The main objective of this master's thesis will be to evaluate these three aspects together: cost-, energy-, and environmental performance of different HVAC-systems. To investigate this, several combinations of HVAC-technologies will be established, simulated and evaluated for two of the OPPTRE dwellings. To get a realistic cost analysis representing the Norwegian market, gathering data on investment costs and performances of HVAC-technologies is essential. The cost performance is evaluated by using the standard NS-EN 15459 (2017) to calculate global costs and payback time. Together with energy consumption and the environmental impact, one will get an idea of which combination is best suited for different levels of insulation in the two considered case houses. This is done for the purpose of enlightening end users and finally contributing to reaching the national climate target.

Energy consumption of a building can be analyzed by performing simulations in a simulation program or by considering field measurements. Simplified simulation models, the lack of quality in input parameters and unforeseen circumstances in the real building may cause a deviation in the results between simulations and field measurements. For instance, this includes the use of standardized conditions such as a uniform indoor temperature and variation in occupancy behavior. This difference contributes to what is defined as the building performance gap. The *prebound* and *rebound* effects are consequences connected to the occupancy behaviour leading to the performance gap [4]. As this could influence energy consumption, it could also affect the cost performance. Therefore, this gap will be evaluated in an additional analysis with respect to cost effectiveness and energy efficiency.

1.2 Research question

Based on the master's agreement and in consultation with our supervisors, the following research question is formulated:

How can deep energy retrofitting detached wooden dwellings contribute to reducing the energy use in the Norwegian building stock through cost-effective, energy-efficient measures with low environmental impact?

To answer this question the following sub-questions are considered:

- How are the considered buildings and HVAC-technologies implemented in the simulation program IDA ICE?
- How do different levels of building envelope energy efficiency affect the optimal HVAC-combination in terms of cost effectiveness and energy consumption?
- Which HVAC-combinations are optimal considering global costs, payback time, energy consumption and environmental impact?
- How do the effects of prebound and rebound affect the cost effectiveness and energy efficiency of different HVAC-combinations?

1.3 Scope

This thesis aims to evaluate the cost-, energy-, and environmental performance of different HVAC-systems. In the scope of this master's thesis, it has been decided to analyze the systems in a Norwegian context, limited to deep energy retrofit of detached wooden dwellings. As defined in the research question, the energy efficiency of an HVAC-combination will be evaluated for a house that undergoes a *deep energy retrofit*. For the purpose of this thesis, the term *deep energy retrofit* is defined as retrofitting the entire building, including the building envelope and HVAC-system.

To give a representation of the Norwegian building stock, two case houses with three different levels of insulation are reviewed. However, the results will not apply to all Norwegian wooden dwellings, since every house is very different. Personal preferences are discussed, but not included in the conclusion. The results from this study will in turn indicate the most cost-effective and energy-efficient HVAC-combination, not necessarily the optimal choice for every end user.

Instead of considering an average price for an HVAC-technology, a span of costs is explored in the cost analysis. There is often a large price range of technologies. By including a cost span, one will get an idea of the profitability of both the cheap solutions and the more expensive ones.

The cost analysis in this master's thesis is solely focused on the costs of different HVAC-technologies. Even though different retrofit scenarios of the building envelope are reviewed, the costs of upgrading the building envelope are not regarded at any point throughout this thesis. In other words, we assume that the case house envelopes are supposed to be undergoing an energy-retrofit regardless of the costs. The analysis of different scenarios is done to represent the diversity of the Norwegian building stock with respect to deep energy retrofit.

All HVAC-technologies are considered with a variety of models and sizes, except for the compact heat pump. It has been decided to only consider two models of the compact heat pump. These are the Econordic W4 and Econordic WH4, both supplied by the HVAC-manufacturer Flexit AS. There are other compact heat pumps available on the market. However, each compact heat pump includes different technologies and functions and can therefore not be implemented equally in a simulation program.

In the energy analysis, the case houses are to be simulated in the dynamic simulation program IDA ICE. It has been decided to perform standardized modeling of the houses, with standard schedules and parameter values together with information provided by the OPPTRE-project. Further specifications can be found in Section 4.1.

In the research question, low environmental impact is referring to low carbon footprint. CO_2-emissions of the different HVAC-combinations will therefore be discussed in this thesis. However, the CO_2-emissions will be considered for operation only, not for the whole life cycle. Furthermore, only electricity will be considered as primary energy carrier. There is a wood stove in the existing case houses, but wood as an energy carrier is not regarded in this master's thesis.

1.4 Outline of thesis

The master thesis is a direct continuation of the specialization project done during the fall of 2020. Literature review and methodology from the specialization project have been revised and further developed during the work of this thesis.

A brief introduction to the Norwegian context is already given and the remainder of this thesis is organized as follows. The relevant existing contributions and theory will be presented first in a literature review, followed by a description of the initial conditions: Case houses, scenarios, HVAC-technologies and HVAC-combinations. Then, the method used to evaluate the cost-, energy- and environmental performance of different HVAC-technologies is described. Included in the methodology is a presentation of the simulation software used to assess the energy performance. In addition, descriptions of the following are included: how data is collected, how the cost performance assessment is done, and how energy consumption is converted into an environmental performance. Thereafter, the main cost-, energy- and environmental performance results are presented and discussed. The prebound and rebound effects are taken into account in an additional analysis. In the discussion, sensitivity analyses are done on the electricity price and the discount rate. A conclusion is drawn based on the discussion and the preferred HVAC-combination for each scenario is presented. Finally, suggestions for further work are provided.

Theory

2.1 Existing contributions

To analyze and validate the results of this master's thesis, a literature review on existing contributions is required. This will make way for comparison between the conclusion of other relevant articles and the conclusion of this thesis. The following articles have been studied and briefly summarized in this section:

- Georges et al. "Environmental and economic performance of heating systems for energy-efficient dwellings: Case of passive and low-energy single-family houses" (2011) [5]
- Obyn and Moeseke. "Comparison and discussion of heating systems for single-family homes in the framework of renovation" (2014) [6]
- Heide et al. "Review of HVAC strategies for energy renovation of detached houses towards nZEB in cold climates" (2019) [7]
- Ekström and Blomsterberg "Renovation of Swedish single-family houses to passive house standard – Analyses of energy savings potential" (2016) [8]
- Ekström et al. "Cost-effective passive house renovation packages for Swedish single-family houses from the 1960s and 1970s" (2017) [9]
- NVE "Varmepumper i energisystemet" (2016) [10]
- NVE "Kostnader i energisektoren" (2015) [11]

Georges et al. (2011) conducted a study investigating the equilibrium between cost effectiveness and environmental performance of heating systems in newly built Belgian detached houses. The economic analysis was conducted based on the European standard EN 15459 (2007), called the global cost method. Finding the energy and environmental performance followed a methodology that complies with the European standards EN 15316 (2007) and EN 15603 (2008). The major findings deducted in this research were optimal heating systems for a standard house with large demands for space heating: a standard heat pump (an air to water heat pump and or ground source heat pump (GSHP)) or a wood pellet boiler. In passive houses, the most attractive solutions had moderate investment costs along with good environmental performances, such as a compact heat pump with high seasonal performance factor (SPF), a wood log boiler, a wood hydro-stove and combining solar thermal collectors with a standard wood stove. [5]

A couple of years after Georges et al.'s study was published, Obyn and Moeseke (2014) published a similar article concerning Belgian detached houses. They aimed to evaluate and compare different HVAC-systems in the framework of energy-efficient renovation. This was done to identify which solution best meets relevant economic and environmental objectives. However, instead of solely focusing on new constructions they also studied the profitability of replacing old heating systems. Furthermore, they performed a dynamic energy analysis based on a real reference case, rather than standards applied to a constructed representative case. Obyn and Moeseke found that for highly insulated houses, the energy performance is not the most important factor when choosing which heating system to install. For existing houses, the optimal solution was found when the entire existing system was conserved, in preference to a replacement of the heating system during the retrofit. [6]

Another relevant article for the development of this master's thesis was written by Heide et al. (2019). This article provides a review of HVAC-strategies for energy retrofit of detached houses towards nZEB in cold climates. Heide et al. investigate research publications while focusing on the complexity, robustness, integration of the solution in the building structure, energy performance, indoor environment, the possibility to create thermal zoning, and life cycle costs. Eventually, it was found that no heating system appeared to be an obvious and universal choice. However, whether a solution is common in the Norwegian building stock or not, seemed to be a crucial factor when choosing a system. When a technology already exists in the building, it will lower the investment costs significantly. Further, the assumed occupant preferences and occupant behavior seem to be important for the final choice of system. [7]

The articles by Georges et al. and Obyn and Moeseke, are highly relevant as both evaluate cost- and energy effectiveness for different HVAC-technologies, resembling the main objective of this master's thesis. Some of the methods used in those studies and the methods used in this thesis are identical. However, both studies are done with a Belgian building stock, climate, market prices and energy mix of the grid. We are on the other hand looking at the Norwegian context. The results found in these two studies are therefore to be considered with respect to different circumstances.

Heide et al.'s review gives an indication of the pros and cons of different HVAC-strategies for an energy retrofit towards nZEB in cold climates. While the study has examined prior research publications, it may be interesting to contemplate the impact of real market prices instead of an average value of the market. Hence, this master's thesis is taking a span of investment costs into account.

Ekström and Blomsterberg (2016) conducted a study in 2016 exploring the energy savings potential of renovating Swedish single-family houses to passive house level. Considering four reference houses, they performed a step-by-step simulation, implementing one energy saving measure at a time. This was done to show how the steps affected each other, and to show the variation in results depending on the shape of the house and the composition of the building envelope. Their results showed a reduction of the final energy use by 65-75% for the four reference houses considered. Not all parts of the building envelope could be improved to a passive house level, but it was shown that there is a great energy savings potential in deep energy retrofitting buildings. [8]

Ekström et al. (2017) conducted a study evaluating the cost effectiveness of renovating Swedish single-family houses to passive house level, compared to maintaining the existing building or renovating to building regulation level. This evaluation was done by performing a life cycle cost analysis of several passive house renovation packages on two reference houses. Three different levels of renovation were defined, representing different levels of energy efficiency, from minimum requirements to passive house requirements. At each level, energy-efficient measures were implemented correspondingly. The first step towards evaluating the cost effectiveness was to look at the energy savings potential of each energy-efficient measure at each level of renovation. Then, the cost effectiveness of different heat generation systems and local renewable energy production was evaluated. Local renewable energy production is in the study referring to the possibility for solar thermal collectors covering 50% of domestic hot water (DHW) and photovoltaic (PV) panels, both limited to the size of the reference house's roof. [9]

There are some interesting findings in this study. Energy-efficient measures at the passive house level are not necessarily sufficient to reach the passive house standard regarding specific energy demand. This implies that investing in either better-performing measures or local renewable energy sources would have to be done to achieve a passive house standard. Further, the location of the house also seems to affect whether the house fulfills the passive house standard, due to the climate's impact on energy use. [9]

Overall, the cost effectiveness of the renovation package is largely dependent on the heat generation system used in the house. When direct electric heating is considered, the passive house package is the most cost-effective. This also applies when using the other heat generation systems, but then the passive house package is no longer more profitable than the second strictest renovation level. The individual measure that was the least cost-effective was retrofitting the windows. On the other hand, the most cost-effective individual measure was installing a ground source heat pump (GSHP). Even though the GSHP had the highest investment costs, it also induced the lowest energy costs. When the renovation packages were combined with different heat generation systems, exhaust air heat pumps were presented as being the most cost-effective alternative. The PV-system seems to be profitable in the considered houses considering all types of heat generation. The study is concluded by stating that it may be more cost-effective to invest in a passive house renovation package rather than a less energy-efficient renovation package with renewable energy. However, it is important to evaluate each case individually as several factors affect the conclusion of which solution is most cost-effective. [9]

The Norwegian Water Resources and Energy Directorate (NVE) has made several reports throughout the last decade focusing on the investment cost and performances of different HVAC-technologies. In this master's thesis, two articles have been used to collect important data such as maintenance costs and lifetime expectancy. Some of NVE's data on investment costs have also been used for comparison to the market prices collected for this thesis. One of the articles used in this thesis is called "Varmepumper i energisystemet" (2016) [10]. This article describes the results of a cost analysis looking at energy savings when replacing an oil boiler with a GSHP or an air to water heat pump. The other report used in this thesis is NVE's cost report from 2015 [11], which consists of Levelized Cost of Energy (LCOE) calculations for different technologies.

2.2 Standards

The standards used in this master's thesis are all aiming for international standardization of the methodology for the assessment of energy building performance. To perform the cost performance assessment, the standard NS-EN 15459 (2017) was used as a base for the methodology. This is because it describes the economic evaluation procedure for energy systems in buildings [12], which is one of the main objectives of this study. Further, the following standards were used as references for input values when realistic data from the case houses or other required information was not available: SN-NSPEK 3031 (2020): "Energy performance in buildings" [13], NS 3700 (2013): "Criteria for passive house level for residential buildings" [14], and NS-EN ISO 7730 (2005): "Analytical decision and interpretation of thermal comfort" [15].

2.3 Collecting data

Online research, reading relevant articles and utilizing the data provided by our supervisors, are all important measures to obtain a solid foundation on which the research question can be answered. To get specific market prices, contacting suppliers may be necessary. This also applies to other data such as capacities and energy performance of technologies. Economic data such as electricity price, inflation rate and discount rate are important to study thoroughly, in order to get a realistic result. The references used for collecting prices and performance data are given in Appendix A.

2.3.1 Investment costs and energy performance of technologies

In order to carry out a cost performance assessment, investment costs of the evaluated HVAC-technologies have to be established. The collection of these investment costs is done by online research and contacting suppliers of the different technologies being assessed. As this thesis is limited to Norwegian dwellings and climate, the gathered investment costs mainly reflect the Norwegian market.

Investment costs of an HVAC-technology may vary a lot and depend on several aspects such as efficiency, power, quality, aesthetics and durability. Included in the investment costs are the initial costs of a new product (i.e., the cost of the unit itself) and the cost of installation by professionals. Some investment costs are harder to find than others as they depend on either area, length, or general infrastructure, like hydronic floor heating and ventilation ducts. Therefore, providing suppliers with real case houses may be necessary to retrieve offers on a holistic installation. Efficiencies and performance data of the different HVAC-technologies can either be found in the same way as the investment costs, by contacting manufacturers and suppliers, or by looking at technical brochures and product sheets.

2.3.2 Inflation rate and discount rate

Future cash flows such as energy costs, maintenance costs and replacement costs are important for the cost analysis. To establish the present value of a future cash flow, discounting is necessary. The discounting procedure is done by using a discount rate, which is a rate describing how much the value of money increases per year. This is almost the same definition as the rate of inflation. However, discounting also takes into account the alternatives of an increase in value. For instance, the discount rate includes the interest rates of saving in a bank or investing the money in something else in addition to the inflation rate. This is to find the most realistic present value of future costs.

Standard NS-EN 15459 (2017) states that the real discount rate is the actualization rate reduced from the inflation rate [12]. The actualization rate is defined as the performance of money when it is placed on the market. This thesis concentrates on private households, which means that the investments are most likely financed by either bank savings/loans or equity funds. The discount rate is dynamic and depends on many different factors such as the inflation rate, the government interest rate, the bank's interest rate, possible individual investment deals, etc. It is therefore hard to pinpoint an exact and realistic discount rate for the calculation period.

In Norway, government regulations help maintain stable inflation. Norges Bank (Bank of Norway) is therefore targeting an inflation rate of 2% [16]. The inflation rates of the past can be found by looking at the consumer price index (KPI). KPI is an index developed by SSB and describes the growth of value in products and services consumed by private dwellings over the last decades [17]. From 2010 to 2020, the KPI states that the average increase of price was at 2.24%. Another way of measuring inflation is through government bonds. From 2009 to 2019 the Norwegian government bonds' average interest rate was at 1.49% [18], reflecting nearly risk-free return while considering the price increase. This can be interpreted as the market not trusting the inflation will reach the target set by Norges Bank. All of the presented inflation rates will be taken into consideration when determining an inflation rate for the cost analysis.

2.3.3 Electricity price

The electricity price is overall lower in Norway compared to the rest of Europe [19]. This is due to Norway being in a unique position as regards renewable energy with a high share of the power production originating from hydronic power plants [20]. For Norwegian households, the mean total cost of power and grid rent, including all charges, has been 0.95 NOK/kWh over the past nine years [21]. This cost consists of several different components including electricity price, grid tariff, taxes and other fees [22]. Some of these components are annual fixed costs [NOK] and others are varying with the amount of energy consumed [NOK/kWh].

2.4 HVAC-technologies

HVAC is short for heating, ventilation and air conditioning and the term includes a various number of technologies: heat pumps, hydronic heating systems, solar thermal collectors, PV panels and ventilation systems among others. Some technologies relevant to Norwegian dwellings are presented in this section.

2.4.1 Heat pumps

In 2019, over 100 000 heat pumps were installed in Norway, with air to air heat pumps being the main contributor. Of all the installed air to air heat pumps, 36% were new installations and the remaining were replacements or installation of additional heat pumps [23]. There are already more than a million heat pumps installed in total across the country [24], indicating that heat pumps are popular heating solutions.

The air to air heat pump is the most common heat pump in Norway and consists of one outdoor unit and one indoor unit. In addition, some outdoor unit models have the possibility of delivering heat through multiple indoor units. The heat pump retrieves energy from the outside air and uses this to heat the air inside. Today, air to air heat pumps come with a filter and can therefore be installed in most houses, no matter the outdoor air quality. This makes the heat pump suitable for even polluted areas, such as houses along trafficked highways. The main benefit of these heat pumps is the fact that they introduce a better indoor climate with lower electricity consumption compared to traditional heating systems. They can also be used for cooling and operate while the outside temperature is as low as -25 °C. [25]

Even though air to air heat pumps are operational at very low temperatures, the heating capacity is decreased, and energy will be used on defrosting the outdoor unit. This means an additional heating source is needed during the coldest days of winter. Another disadvantage is the noise level of the heat pump's outdoor unit. Due to noise, the units should not be placed next to bedroom windows or other frequently occupied outdoor areas. All in all, installing an air to air heat pump is a common option. One unit will during a normal year produce 2-3 times more energy than it consumes. [26]

Another type of heat pump using the outdoor air is an air to water heat pump. This heat pump covers space heating through hydronic heating systems. Typical hydronic heating systems are radiators, floor heating or fan convectors. There is one unit outside and one larger unit inside which is connected to a centralized hot water tank. The largest benefit of this heat pump is that it can be used for both space heating and heating of domestic hot water (DHW), resulting in a high performance factor. It is also possible to use this heat pump for cooling through for example fan convectors. However, as with air to air heat pumps, an air to water heat pump is neither very efficient at very low temperatures. The same reduction in efficiency occurs during hot summer days when the cooling capacity for an air to water heat pump decreases. This implies a need for additional peak heating during winters and additional cooling measures during hot summer days. Furthermore, the level of noise leads to the heat pump being somewhat restricted as to where it should be placed. [27]

Ground source heat pumps (GSHP) are more complex than air source heat pumps. This type of heat pump utilizes the heat in the ground outside the house instead of the surrounding air. The four main heat sources of a GSHP are solid ground, seawater, soil ground and groundwater. In Norway, the most common GSHP utilizes the heat in the solid ground through energy wells. To install a GSHP of this type, energy wells have to be put in boreholes being usually at least 100 meters deep. Then, these energy wells are connected to a heat pump system transferring the heat to hydronic systems. [28]

Exhaust air heat pumps (EAHP) are specialized air to water heat pumps that utilize heat from the extract air or the exhaust air of a building (usually bathrooms, kitchens and laundry rooms) and transfer the heat to a hydronic heating distribution system. In this thesis, an exhaust air heat pump utilizing the extract air is considered, apart from the compact heat pump. Throughout the year, the temperature of the extract air of a building is relatively constant. Hence, the seasonal performance factor (SPF) of an exhaust air heat pump is relatively high. As it retrieves heat from the extract air, the volume of the available extract air limits the heating capacity.

By extracting air, the EAHP creates negative pressure in the building. This negative pressure is forcing fresh air to flow into the building through vents and cracks. The ventilation strategy when using an EAHP is therefore called mechanical. A consequence is that the supply air may be cold and create drafts flowing into the building at ambient temperature. This effect can be reduced by installing ventilation radiators.

The amount of installed EAHPs in Norway has increased significantly over the past ten years, from around 500 sold EAHPs in 2010 to 1 900 newly installed EAHPs in 2016 [10]. In Sweden, the market is both larger and more developed. According to Energimyndigheten, in 2018, 17 000 EAHPs were newly installed in Swedish homes [29]. Several factors could explain why the EAHP market is larger in Sweden than in Norway. There is for instance a longer tradition of hydronic heating systems and district heating in Sweden [30]. When the hydronic heating system already exists in a dwelling, the investment costs of an EAHP installation are significantly reduced. This results in EAHPs being a more commercial and attractive option for the end user. As mentioned in Section 2.3.3, Norway has overall cheaper electricity prices than the rest of Europe. This often makes electricity the favorable energy carrier from an economic point of view and may be one of the reasons why the Norwegian market for EAHP is currently relatively small [30].

A compact heat pump is an HVAC-technology combining several technologies into one compact indoor unit. It is an indoor climate central, with a heat pump, controlling several parts of the heating, ventilation and air conditioning of a building [31]. There are many different types of compact heat pumps and most of them can be adapted to the building's needs. The most standard solution combines an exhaust air heat pump with a balanced ventilation system [7].

The compact heat pumps that are evaluated in this thesis are called Econordic W4 and Econordic WH4 and are delivered by the manufacturer Flexit AS. These models look identical, but Econordic W4 does not cover space heating. An illustration of the indoor unit is shown in Figure 2.1. This indoor climate central consists of four modules, a ventilation module, a heat pump, a hot water tank and an installation module. In the ventilation module, there is a rotary heat exchanger with a temperature efficiency of 84%. The ventilation module retrieves heat from the extract air and transmits the heat to the fresh supply air on its way into the house. The remaining heat in the exhaust air from the heat exchanger is used as heat source for the heat pump together with outdoor air. The heat pump is delivering heat to a hot water tank, which transfers heat to the DHW and/or space heating (depending on the Econordic model). The installation module is originally empty in order to fit additional modules or equipment such as a distribution cabinet. [32]

Figure 2.1: *Flexit's Econordic indoor climate central [32]*

2.4.2 Hydronic heating systems

Hydronic heating systems use hot water for space heating. There are several heating sources for the water, such as heat pumps, bio boilers and electric boilers. The heat is then transferred to the room through either floor heating, radiators, or fan convectors among others. [33]

One way of utilizing the sun's energy for heating purposes is by installing solar thermal collectors. Even though there are fewer sunny days in Norway compared to other parts of the world, these collectors may still collect a substantial amount of heat throughout the year. Together with a heat pump, they can cover large parts of the heating demands. If the solar thermal collector is collecting enough heat, the heat pump does not have to operate at maximum capacity. This means a prolonged lifetime for the heat pump. A solar thermal collector is about 3 times more efficient than PV panels. [34]

Hydronic floor heating is a hot water piping system underneath the floor. Controlling the temperature can either be done by local thermostats or by a centralized control system. The hot water can for instance come from a wood stove water jacket, a bio boiler, or a heat pump. Hydronic floor heating has the advantage of running at low temperatures. This is because of the piping system covering a large area, compared to a radiator. In combination with either an air to water heat pump or GSHP, hydronic floor heating will make the heat pumps more efficient and in turn induce more energy savings than radiators. [33]

Other ways of distributing heat in hydronic systems are through radiators and fan convectors. Radiators are a common sight in both office and apartment buildings and are often connected to a district heating system. When district heating is not an option, the radiators can be combined with solar collectors, heat pumps or a wood stove water jacket [33]. The same applies to fan convectors distributing the heat with fans blowing air across heated piping inside the convector. An important difference between these two distribution systems is that the fan convector can emit the same heat with a lower water temperature. On occasion, having a distribution system including both radiators and fan convectors can cause problems due to the different water temperatures [35].

2.4.3 Direct electric heating

It is possible to cover the space heating demand by using direct electric heating through electric panel heaters and electric floor heating. Panel heaters are found everywhere and can be cheap and easy to install. Electric floor heating is most common in bathrooms and can be installed as heating foils underneath parquet and wood flooring, or electric cables underneath tiles and in concrete. However, direct electric heating may lead to substantial energy costs as it is strictly dependent on electricity prices and heating demand.

Reducing the energy costs can be done by implementing on-site electricity production. For instance, by utilizing the sun's energy directly through photovoltaic (PV) panels. Through the photovoltaic effect, electrons start moving which in turn creates electricity that can be used. One PV panel consists of several solar cells and several PV panels make up a PV facility. By the end of 2018, a total accumulated effect capacity of 68 MWp had been installed in Norway [36]. Electricity produced on-site will reduce the need for electricity drawn from the power grid and therefore lead to lower energy costs.

2.4.4 Ventilation systems

Ventilation systems are important to maintain a healthy indoor climate with clean and fresh air. A commonly used ventilation strategy in Norway is natural ventilation. Natural ventilation is mainly caused by buoyancy and driving pressure forces. In dwellings, this often involves opening windows to cross-ventilate or opening ventilation hatches. During winter, this will cause heat loss. Therefore, more advanced ventilation systems have become more common in detached houses, such as balanced ventilation, single-room ventilation, compact heat pumps and EAHP. Balanced ventilation systems extract used warm air from bathrooms, kitchen and laundry room into a heat exchanger. At the same time fresh outdoor air is cleansed, filtered and transferred to the heat exchanger where the heat from the extracted air is exchanged. Then, the heated fresh air is supplied evenly to the living room and bedrooms and the exhaust air is transferred outside. About 70 to 90% of the heat in the extract air can be recovered by heat exchangers, transferred to the fresh air and distributed evenly around the building. [37]

2.4.5 Financial support

For private individuals, investing in a deep energy retrofit could become expensive. In turn, an energy retrofit is a step towards a more sustainable house for the end user. ENOVA is a governmentally owned organization working on developing Norway in direction of a low-emission society. Therefore, many energy-efficient technology upgrades are subsidized to make the investments more affordable for the end user [38]. When the market of a technology is well established, ENOVA may decide on either decreasing or abolishing the subsidies. From July 1st. 2021, new reductions in financial support are to be enforced. For instance, the support for air to water heat pumps and exhaust air heat pumps is removed, while it is reduced for solar thermal collectors. Table 2.1 shows the HVAC-technologies supported by ENOVA as of 01.07.2021 with the new support rates [39].

Table 2.1: *ENOVA support for technologies as of 01.07.2021 [39]*

Technology	Support [NOK]
Ground source heat pump	10 000
Solar thermal collector	5 000 + 200 NOK pr. m^2 (1)
PV panels	7 500 + 1 250 NOK pr. kW (2)
Balanced ventilation	10 000
Hydronic distribution system	10 000
Bio boiler	10 000
Heat recovery of grey water	2 500
Accumulator tank	5 000

2.5 Nearly Zero Energy Building (nZEB)

As mentioned in the introduction, the OPPTRE-project aims to propose a nearly Zero Energy Building level for retrofit of detached wooden dwellings. nZEB implies a "Technically and reasonable achievable primary energy use higher than zero kWh/(m^2 year)", according to Stene et al. [40]. This would then be achieved by combining energy-efficient measures and technologies utilizing renewable energy. However, there is no universal definition on how to become an nZEB regulated building.

Rambøll together with I. Andresen developed a proposal for the Norwegian nZEB requirements in 2013, on behalf of the Norwegian Directorate of Building Quality (Direktoratet for byggkvalitet). In this proposal, it was suggested that an nZEB regulated building in the Norwegian context should have 70% lower energy consumption than the TEK10-level [41]. The energy consumption should correspond to the net supplied energy of the building. TEK10 is now outdated and replaced by TEK17, thus the requirements had to be revised. In the criteria of FutureBuilt-projects from 2018, new requirements of energy consumption are proposed. For dwellings, the energy consumption was proposed to be at a maximum of 40 kWh/m^2 [42]. It must be stressed that a national definition of nZEB is still under development and that the FutureBuilt criteria is still only a proposal. Nevertheless, it gives an idea of what the requirements may look like in the future.

2.6 Carbon footprint

The CO_2-emissions from different energy carriers are converted to fit into a common ground of comparison by using CO_2-factors. Each energy carrier has a corresponding CO_2-factor that represents the magnitude of emissions. By adding these up it is possible to derive the total CO_2-factor for the energy mix delivered to the building [43]. In this master's thesis, the purpose is not to evaluate the realistic development of CO_2-emissions. The aim is rather to give an idea of which HVAC-combination performs best from an environmental perspective.

[1] Up to 25 m^2
[2] Up to 15 kW

Norway is in a unique position with the highest share of renewable energy production in Europe, as mentioned in Section 2.3.3. In other European countries, non-renewable energy sources such as gas and coal are more commonly used. The Norwegian and European grids are closely connected with export/import of energy. Despite this close connection, a climate declaration report done by NVE in 2019 shows that 94% of the energy consumed in Norway, still originates from renewable sources. Because of the high renewable ratio, the CO_2-factor of the Norwegian energy mix is significantly low. According to NVE, the average CO_2-factor of the Norwegian energy mix is 17 gCO_2/kWh, whereas the average CO_2-factor of the European energy mix is 300 gCO_2/kWh [43].

According to NVE's recent report on long-term power market analysis (2020), the energy consumption in Norway is expected to increase from 137 TWh in 2020 to 163 TWh in 2040. This increase is mainly a result of the electrification of several sectors, among others the transport sector. Thus, to balance the consumption and production of energy and to secure a well-functioning power system, the exchange capacity between the Nordic countries and the rest of Europe is due to expand [44]. In terms of CO_2-factors, this means that the energy mix causing the low CO_2-factor in Norway will be even more mixed with the European power grid. Hence, the CO_2-factor in Norway is expected to increase. Nevertheless, ambitious climate goals are demanding a reduction in fossil power production in Europe [45]. This means that the CO_2-factor of the European electricity mix may also be reduced. The standard NS 3720 (2018), "Method for greenhouse gas calculations for buildings" proposes a CO_2-factor of 138 gCO_2/kWh to use in greenhouse gas calculations for buildings in a scenario where the Norwegian energy market is mixed with the European power grid [46]. This complies with ZEB Research Centre, which has employed the assumption of an average future extrapolated CO_2-factor of 132 gCO_2/kWh in 2050 [44].

As pointed out by Stene et al. (2018), the methods used to calculate the extrapolated CO_2-factor may vary from study to study [40]. This is a result of not having defined the size of energy losses when estimating embodied energy and CO_2-emissions. Consequently, it is not given that 138 gCO_2/kWh will be the future CO_2-factor [40]. The factor will probably be highly affected by how much Europe manages to phase out fossil power production [47].

As electricity is the only primary energy carrier considered in the scope of the environmental analysis in this thesis, the relationship between energy delivered and CO_2 emitted during operation is proportional. Therefore, we are not considering any specific CO_2-factor and will use energy efficiency as a measure of the environmental impact.

2.7 Prebound effect and rebound effect

According to Kohury et al. (2017), three main factors are affecting the gap between measured and simulated building performance. Firstly, the gap may appear due to inaccuracies when applying standard parameter values instead of realistic data. Secondly, a gap may be induced due to most of the input data being dependent on decisions made by the model operator of the simulation program. Lastly, there are uncertainties related to the quality of execution, operation, monitoring and user behavior. [4]

The *prebound* and *rebound* effects are consequences of the occupancy behaviour, leading to the performance gap [4]. In 2012, Sunikka-Blank et al. (2012) conducted an extensive study on calculated and measured energy consumption for 3400 German households. They discovered that occupants living in high energy demand buildings consume roughly 30% less heating energy than the calculated energy consumption. This is called the *prebound effect*, meaning the real energy use is often lower than the calculated energy use in poor energy quality buildings. The reason for this is that the occupants tend to behave more economically in a building with poor energy quality [48]. In low-energy and passive houses, the opposite effect occurs and the measured energy consumption is higher than the calculated energy consumption. This is called the *rebound effect* and is due to increased comfort expectations and the low additional costs of increased temperatures in reality compared to the calculated scenario [20][48] [49].

Sandberg et al. (2017) studied the prebound and rebound effects of a Norwegian dwelling stock [20]. Both calculated energy use and measured energy use for the dwelling stock were registered. Figure 2.2 shows the trend that appeared for the different buildings in the dwelling stock, marked as a red dotted line. The trend describes that buildings with calculated energy consumption less than 100 kWh/m^2 are exposed to the rebound effect. When the calculated energy use is more than 100 kWh/m^2, the buildings tend to be exposed to the prebound effect. Sandberg et al. created a trendline, Equation (2.1), describing how a dwelling with a specific calculated energy use is exposed to prebound and rebound effects. In the study, the trendline is used to define a thermal adaptation factor, which then is used to compensate for the two effects to get a more realistic picture of a building's energy consumption. This is especially important to analyze before a building is either built or renovated.

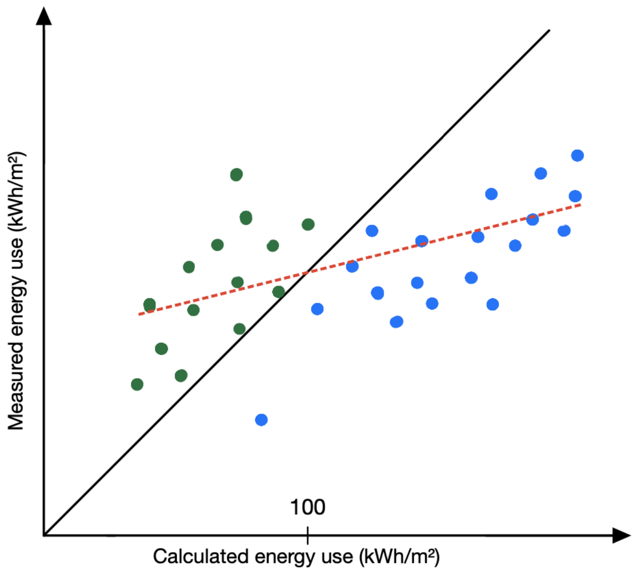

Figure 2.2: *Thermal adaptation factor trendline, made with inspiration from Sandberg (2017) [20]*

$$y = 0.47x + 53.02 \tag{2.1}$$

where: y = Measured energy use
x = Calculated energy use

Another study, conducted by Borg (2015), also analyzes these two effects for a Norwegian dwelling stock. The results indicated the same trends as the results of Sunikka-Blank et al. and Sandberg et al. showed. Borg estimated the prebound effect to be around 20-25%, demonstrating that the calculated energy consumption is higher than the actual consumption. The results of the rebound effect were however more uncertain due to the lack of measurements [50]. Nevertheless, Borg found the same overall trend in the rebound effect as Sunikka-Blank et al. and Sandberg et al.; low-energy and passive houses tend to have a higher measured energy consumption than calculated.

These two effects are dependent on the sociocultural factors related to heating practices, according to Galvin et al. (2015) [49]. This implies that there may be differences in the prebound/rebound effects when different countries are studied.

Initial conditions

In this chapter, the considered case houses, building envelope scenarios, HVAC-technologies and HVAC-combinations are defined and presented.

3.1 Description of the case houses

Two case houses form the base used for evaluating the energy consumption of different HVAC-combinations in detached wooden dwellings. Since this master's thesis is related to the OPPTRE-project, two of the six dwellings in the project will be analyzed, one house in Kristiansand and one house in Malvik. A part of the OPPTRE-project was to propose renovated versions of each of the six dwellings [3]. These proposals were developed in an architect competition in 2019/2020 by several architect- and engineering teams. Each team was responsible for one of the detached wooden dwellings in the OPPTRE-project. Their task was to come up with solutions for renovating the given dwelling, with an aim of reaching the nZEB-target. Both the existing house and the renovation proposal will be reviewed in this study.

The case house in Kristiansand was built in 1972 with a net internal area (NIA) of 196 m^2. It is a single-family house for 4 people that spans two floors. It was one of the largest of the dwellings in the OPPTRE-project and is representative of typical family houses built in the 1960s/1970s. It has a cold attic and a pitched roof. The renovation proposal suggests filling the recesses of the building mass. This will increase the indoor area to 214 m^2 (NIA) and make the building shape more compact. Further, the renovation proposal suggested integrating a studio apartment in the basement. Figure 3.1 shows a photo of the existing Kristiansand house (3.1a) and a sketch of the renovation proposal (3.1b).

(a) *Kristiansand: Existing house - Foto: OPPTRE*

(b) *Kristiansand: Renovated - Sketch: OPPTRE*

Figure 3.1: *Kristiansand - Existing and renovated building envelope [51]*

The Malvik case house is 164 m^2 (NIA) and was built in 1957. The existing house spans three floors consisting of two heated floors and an unheated basement. In addition, there is a small attic used for storage. Regarding the building envelope, the existing house has a squared base. The renovation proposal broadens this base with an annex and a roof dormer, increasing the net internal area to 193 m^2 (NIA). This makes the building body of the renovation proposal of the Malvik house more complex than the renovation proposal of the Kristiansand house. Furthermore, the renovation proposal suggests elevating the small attic so that the ceiling on the second floor stretches up to the roof. Lastly, the unheated basement is upgraded to become partly heated keeping a minimum temperature of 10 °C. Figure 3.2 shows a photo of the existing Malvik house (3.2a) and a sketch of the renovation proposal (3.2b).

(a) *Malvik: Existing house - Foto: OPPTRE*

(b) *Malvik: Renovated - Sketch: OPPTRE*

Figure 3.2: *Malvik - Existing and renovated building envelope [52]*

None of the existing case houses have hydronic distribution systems, nor are they connected to a district heating system. The original heating systems in both case houses consist of direct electric heating and a wood stove for peak heating purposes. The wood stove will not be considered in this thesis, as the simulation procedure is complex.

By choosing these two distinct dwellings we can cover a broader specter in the cost performance assessment than if we were to study two similar units. The results may show that one HVAC-combination is better suited for the Kristiansand house, while another is better for the Malvik house. It must be stressed that studying even more dwellings would have made the study representative for an even larger building stock. Due to the time limit, this was not possible for this master's thesis.

3.2 Studied scenarios

Four scenarios are studied for the building envelopes of the two case houses in this thesis. The scenarios are referring to different levels of energy efficiency of the building envelope. The scenarios studied for the two case houses in this thesis are: EXISTING, TEK10÷, OPPTRE and PASSIVE. These are to be simulated in IDA ICE. Scenario EXISTING is simulated to pose as a reference case for the cost analysis. Scenarios TEK10÷, OPPTRE and PASSIVE are simulated for the purpose of analyzing the energy efficiency of different HVAC-combinations in different retrofitted building envelopes. When it comes to the building shape, scenario EXISTING preserves the geometry of the existing houses. TEK10÷, OPPTRE and PASSIVE have the same geometry based on the renovation proposals in the architect competition. The reason for selecting several retrofitted scenarios is to get a broader perspective of which HVAC-combination is better. These scenarios are representative of dwellings with both lower and higher energy demands. Table 3.1 and 3.2 show the most important input parameters used for the different scenarios in the IDA ICE simulation models of the Kristiansand house and Malvik house, respectively.

Table 3.1: *Input parameters - Kristiansand house*

KRISTIANSAND		EXISTING	TEK10÷	OPPTRE	PASSIVE
U-values [W/m^{2}K]	External walls	0.45	0.22	0.18	0.11
	Internal walls	0.47	0.47	0.47	0.47
	Roof	2.23	0.18	0.18	0.085
	Separating floor b/f_1 [1]	0.50	0.47	0.47	0.47
	Separating floor f_1/a [2]	0.50	0.09	0.09	0.09
	Basement wall	0.87	0.18	0.14	0.11
	Basement floor	0.54	0.18	0.18	0.08
	Door	2.96	1.60	1.00	0.80
	Windows (U/LT/g)	2.54/81/76	1.60/74/70	1.00/73/54	0.80/73/54
Thermal bridge	[W/mK per envelope m^2]	0.07	0.07	0.05	0.03
Infiltration	at 50 Pa - [1/h]	6.00	3.00	1.50	0.60
DHW use	[kWh/(m^2 year)]	25	25	25	25
SFP	[kW/(m^3/s)]	2	1.5	1.5	1.5

Table 3.2: *Input parameters - Malvik house*

MALVIK		EXISTING	TEK10÷	OPPTRE	PASSIVE
U-values [W/m^{2}K]	External walls	0.44	0.22	0.17	0.11
	Internal walls	0.60	0.47	0.47	0.47
	Roof	0.30	0.18	0.14	0.085
	Separating floor b/f_1 [1]	1.49	0.21	0.21	0.21
	Separating floor f_1/f_2 [3]	0.23	0.23	0.23	0.23
	Basement wall	3.48	0.33	0.33	0.11
	Basement floor	4.37	4.37	4.37	1.00
	Door	2.54	1.60	1.00	0.80
	Windows (U/LT/g)	2.55/81/76	1.60/74/70	1.00/73/54	0.80/73/54
Thermal bridge	[W/mK per envelope m^2]	0.06	0.07	0.05	0.03
Infiltration	at 50 Pa - [1/h]	6.00	3.00	1.50	0.60
DHW use	[kWh/(m^2 year)]	25	25	25	25
SFP	[kW/(m^3/s)]	2	1.5	1.5	1.5

3.2.1 EXISTING

EXISTING is based on the existing case houses with original U-values of the building envelope. The HVAC-combination implemented in scenario EXISTING consists of electric panel heaters and electric floor heating. This scenario will lead to the highest energy demand due to lower energy conservation in the building envelope and lower efficiency of the heating system. The energy efficiency of an HVAC-combination will be evaluated for a house that undergoes a *deep energy retrofit*. As the building envelope in this scenario remains unretrofitted, the scenario will only work as a reference case for the cost analysis.

[1] Separating floor between basement and first floor
[2] Separating floor between first floor and attic
[3] Separating floor between first and second floor

3.2.2 TEK10÷

The retrofitted scenario TEK10÷ is based on the minimum requirements found in the TEK10-regulations [53]. This means that the U-values of the building envelope, thermal bridges and infiltration are all set accordingly. The U-value for separating floor was not mentioned in the TEK10-regulations and was therefore set to the same as in scenario OPPTRE. Consequently, the two case houses do not have the same U-values for separating floors, as seen in Table 3.1 and Table 3.2. Scenario TEK10÷ is introduced in order for the results of this thesis to be applicable for a larger building stock.

3.2.3 OPPTRE

The retrofitted scenario OPPTRE is simulated with most of the suggested renovation measures from OPPTRE's architect competition. For both case houses the architect and engineering teams suggested an upgrade of the building shape, infiltration, thermal bridges, insulation level, windows and doors. As the teams in the architect competition were responsible for renovating their respective dwelling, the renovation proposals for the houses in Kristiansand and Malvik are differing. Askim/Lantto arkitekter AS and T. A. Vik created the proposal for the Kristiansand house [52]. For the Malvik house, Arkitektbrygga, Bjørke Arkitektur AS, Fasting arkitekter AS, RF Arkitektur, Byggmester Hans Helseth AS and Rambøll Trondheim created the proposal [51]. Thus, it is possible to observe from Table 3.1 and Table 3.2 that some of the parameter values depart from one another: U-values for external walls, roof, separating floors, basement wall and basement floor. On the other hand, some parameter values have been modified for the purpose of facilitating the comparison of the two case houses. Infiltration has been set to 1.5 1/h in both case houses, thermal bridges have been set to 0.05 W/mK, and U-values of windows have been set to 1 W/m^{2}K. All in all, the level of energy efficiency in this scenario corresponds to a level in between scenario TEK10÷ and PASSIVE.

3.2.4 PASSIVE

The retrofitted scenario PASSIVE is based on components in the passive house standard, NS 3700 (2013) [14]. This standard introduces the strictest requirements for the level of insulation, thermal bridges, infiltration, etc. Some parameters are not defined in the passive house standard, for instance U-values of separating floors. Therefore, it was decided to maintain the same U-values as in scenario OPPTRE for separating floors as shown in Table 3.1 and Table 3.2.

It needs to be stressed that the U-value of the basement floor in the Malvik house is not coinciding with the passive house standard. The reason for this is that the basement floor was not prioritized and upgraded from the existing house to the renovation proposal. Even though this master's thesis does not consider the investment costs of the building envelope, an upgrade of the basement floor to passive house level was assumed to be unrealistic and unnecessary. Scenario PASSIVE will lead to the lowest energy demand due to greater energy conservation and higher efficiency of the heating systems.

The standard NS 3700 (2013) also sets a requirement of the highest specific energy demand for heating purposes allowed in a passive house. However, since not all components of the standard are followed, scenario PASSIVE does not fulfill the requirements of highest specific energy demand. As pointed out in Ekström et al.'s study, energy-efficient measures at the passive house level themselves are not necessarily sufficient to reach the passive house standard regarding specific energy demand [9].

3.3 Studied HVAC-technologies

In order to do a cost performance assessment, there are several initial decisions that have to be made. One is to determine which HVAC-technologies are going to be included in the assessment. In Table 3.3, the selected technologies are presented. The data collection for each of these technologies includes investment costs, maintenance costs, lifetime expectancies, performance and efficiencies. These technologies have been selected because of their relevance to Norwegian detached wooden dwellings and the OPPTRE-project alongside consultation with our supervisors.

Table 3.3: *HVAC-technologies in the scope of this master's thesis*

Heat sources	Distribution	Ventilation systems
Air to air heat pump	Hydronic floor heating	Balanced ventilation
Air to water heat pump	Electric floor heating	
Ground source heat pump with energy well	Fan convectors	
Exhaust air heat pump	Electric panel heaters	
Compact heat pump (Econordic W4/WH4)		
Solar thermal collectors		

3.4 Studied HVAC-combinations

The selected HVAC-technologies are appropriately put into relevant combinations applicable to detached wooden dwellings, which in turn will be implemented and simulated in IDA-ICE. This is done in order to use the energy consumption output to calculate the energy costs and analyze the energy efficiency of a combination. The HVAC-combinations that are considered in this master's thesis are presented in Table 3.4 and will be further described.

Table 3.4: *Studied HVAC-combinations*

Combination	Space heating	DHW heating	Ventilation system
A2A	Air to air heat pump Electric panel heaters Electric floor heating	Electric heating coil	Balanced ventilation
A2AsolarDHW	Air to air heat pump Electric panel heaters Electric floor heating	Solar thermal panels Electric heating coil	Balanced ventilation
A2W	Air to water heat pump Fan convectors Hydronic floor heating	Air to water heat pump	Balanced ventilation
CHPW4	Compact heat pump Econordic W4 Electric panel heaters Electric floor heating	Econordic W4	Econordic W4 (Balanced ventilation)
CHPWH4	Compact heat pump Econordic WH4 Fan convectors Hydronic floor heating	Econordic WH4	Econordic WH4 (Balanced ventilation)
EAHPDHW	Exhaust air heat pump Electric panel heaters Electric floor heating	Exhaust air heat pump	Mechanical extract ventilation
EAHPCombi	Exhaust air heat pump Fan convectors Hydronic floor heating	Exhaust air heat pump	Mechanical extract ventilation
GSHP	Ground source heat pump Fan convectors Hydronic floor heating	Ground source heat pump	Balanced ventilation

3.4.1 A2A

The first combination consists of an air to air heat pump delivering heat to the main living room in each case house. When the heating capacity of the air to air heat pump is not sufficient to cover the heating demand in the specific room, an electric panel heater will cover the peak load. Electric panel heaters and electric floor heating are used to heat the rest of the rooms in the houses to cover the space heating demand. The DHW is heated with electricity through an electric heating coil and balanced ventilation was chosen as ventilation strategy.

3.4.2 A2AsolarDHW

This combination consists of an air to air heat pump in the same way as combination A2A. An electric panel heater covers the peak load in the living room when the air to air heat pump is not able to deliver enough heat. The rest of the space heating is covered by electric panel heaters and electric floor heating. In difference to combination A2A the DHW demand is partly covered by flat plate solar thermal collectors. Following a rule of thumb, the solar thermal collectors were sized to cover approximately 50% of the DHW heating demand. The rest of the DHW heating demand will be covered by an electric heating coil. The sizing process of the solar thermal collectors will be described in detail in Section 4.2.1. There is also a balanced ventilation system in this combination.

3.4.3 A2W

Combination A2W consists of an air to water heat pump delivering heat to a centralized hydronic heating system. It has been decided that space heating is to be distributed through fan convectors and hydronic floor heating. The floor heating will be placed in bathrooms, in WCs and in the entrance, whereas fan convectors will cover the space heating in the rest of the house. The DHW heating demand is also mostly covered by the heat pump. When the heat pump is not able to deliver enough heat, an electric boiler will supplement the heating system and cover the peak load. Finally, balanced ventilation was chosen as ventilation strategy for this combination.

3.4.4 CHPW4

In this combination, space heating is covered by electric panel heaters and electric floor heating. The DHW heating demand is however covered by the compact heat pump Econordic W4. The ventilation system is integrated as a part of the compact heat pump and is based on a balanced ventilation strategy. There is an electric heating coil that heats the supply air if the heat recovery unit is not able to provide the correct temperature.

3.4.5 CHPWH4

In contrast to combination CHPW4, the compact heat pump in combination CHPWH4 can cover space heating. As described in Section 2.4.1, the Econordic WH4 retrieves heat from the extract air and delivers heat to a centralized heating system. The hydronic distribution system is equal to the one used in combination A2W: hydronic floor heating in bathrooms, in WCs and in the entrance and fan convectors in the rest of the house. If the heat pump is not able to deliver enough heat, an electric boiler will supplement the heating system and cover the peak load. The ventilation system of this combination is equal to combination CHPW4.

3.4.6 EAHPDHW

Combination EAHPDHW will be somewhat similar to combination CHPW4, having a heat pump covering the DHW heating demand and electric panel heaters/electric floor heating covering the space heating demand. In this combination, there is an exhaust air heat pump providing heat to the DHW system. The EAHP-unit includes a fan extracting air from kitchens, bathrooms, etc. Air is supplied directly through vents and leakages. In other words, a mechanical extract ventilation system.

3.4.7 EAHPCombi

EAHPCombi consists of an exhaust air heat pump covering both DHW heating and space heating. The heat pump will provide heat to a centralized hot water tank. Then the water will be distributed throughout the house with hydronic floor heating in the bathrooms, in the WCs and in the entrance and fan convectors in the rest of the house. As explained in Section 2.4.1, the volume of the available extract air is limiting the heating capacity of the exhaust air heat pump. Consequently, it was decided to have an electric boiler covering the peak load when the exhaust air heat pump is not delivering enough heat. The ventilation strategy is the same as in combination EAHPCombi.

3.4.8 GHSP

Combination GSHP consists of a ground source heat pump with an energy well as heat source. Through a centralized heating system, the heat pump will deliver heat to a hydronic distribution system which will cover the space heating demand. There is hydronic floor heating in the bathrooms, in the WCs and in the entrance. The rest of the space heating is covered by fan convectors. When the heat pump is not able to deliver enough heat, an electric boiler will supplement the heating system and cover the peak load. Balanced ventilation was chosen as ventilation strategy for this combination.

Methodology

This chapter describes the procedures and methods used in this master's thesis. First, the implementation procedure in IDA ICE is described followed by the methodology of the cost performance assessment. The cost performance assessment is divided into the establishment of investment costs, and a description of the approach used for calculating global costs and payback times. Finally, the method of considering the prebound and rebound effects is described.

4.1 Modelling in IDA ICE

The following section turns to the research question and describes how the considered buildings and HVAC-technologies were implemented in the simulation program IDA ICE.

4.1.1 Choice of simulation software - IDA ICE

In this master's thesis, the case houses and heating systems were investigated using the building performance simulation software IDA ICE 4.8. This is a program applying dynamic and multi-zone simulations of indoor environment and energy use [54]. The case houses in Kristiansand and Malvik were both simulated with detailed models and different zones for each room. In this thesis, the energy consumption of the buildings was the key output from the simulations. It was decided to use IDA ICE for energy simulations as the dynamic application allows for an evaluation of buildings with more realistic behavior compared to a static calculation tool.

4.1.2 Standardized modelling and assumptions

Because of unavailable information, for the sake of simplicity, and due to the time limit of this master's thesis, standardized models were simulated. Many of the input parameters applied in IDA ICE were taken directly from the description of the existing houses and the renovation proposals described in the OPPTRE-project [51][52]. Standards were used for the remaining data input: The Norwegian standard SN-NSPEK 3031 (2020) and the regulation TEK17 (2017) were used for simulating all scenarios, EXISTING, TEK10÷, OPPTRE and PASSIVE. Additionally, the minimum requirements of TEK10 (2010) were used for scenario TEK10÷ and the Norwegian standard NS 3700 (2013) was used for simulating scenario PASSIVE.

There were some significant differences between the Malvik and Kristiansand simulation models. A fully developed IDA ICE file of the Malvik house was made by Rambøll during the architect contest. Rambøll was kind enough to provide us with this model for further simulations in this master's thesis. Consequently, the Malvik model contained more detailed information compared to the Kristiansand model. There was more detailed information on the pressure coefficients and the thermal bridges in both the existing house and the renovation proposal. This information was assumed to be correct because the model had been revised by several competent people in the architect competition. As this detailed information was not available for the Kristiansand house, a standardized approach was adopted. In this case, the pressure coefficients were set to be "Semi exposed" in IDA ICE, and thermal bridges were based on standards [13].

Defining heated zones

As part of the standardized approach, it has been assumed that all zones are heated except the attic in the retrofitted scenarios of the Kristiansand house, and the basement and small attic in scenario EXISTING of the Malvik house. The heated areas are shown in Table 4.1. Compared to scenario EXISTING, the total heated area of the Kristiansand house was somewhat increased in the three retrofitted scenarios as the indoor area was broadened. In the Malvik house, the total heated area was significantly increased as the basement in the retrofitted scenarios was regarded as heated. The standard set point temperatures were set according to SN-NSPEK 3031 (2020). In the heated zones the set point temperatures were 20 °C between 08:00 - 16:00 and 22 °C the rest of the day [13].

Table 4.1: *Heated areas [m^2] of the case houses*

Case houses	Kristiansand	Malvik
Heated area [m^2]: EXISTING	196	103
Heated area [m^2]: TEK10÷, OPPTRE and PASSIVE	214	193

In the architect competition, it was decided that the basement of the Malvik house was to be kept at a lower temperature than the rest of the house, 10 °C compared to 20/22 °C, to save energy. The renovation proposal for the basement reflected that choice, with relatively high U-values of the basement floor and walls. Hence, the basement floor and walls in the simulated Malvik house in scenario OPPTRE also had high U-values. There would be large heat losses through the floor and walls if the basement temperature was equal to the temperature in the rest of the house. Therefore, it was decided to keep the low temperature in the Malvik basement for scenario OPPTRE. However, the temperature was not set to be 10 °C as suggested in the architect competition, but 15 °C, as the basement was regarded as partly used. For comparative purposes, it has also been decided to simulate with a set point temperature of 15 °C in the Malvik basement, in scenarios TEK10÷ and PASSIVE.

Ventilation

A standardized approach was also adopted as regards airflow rates for ventilation. The standard SN-NSPEK 3031 (2020) was used as a base for deciding airflow rates. In SN-NSPEK 3031 (2020), there is a requirement of having at least 1.2 m^3/h m^2 air supplied for zones with continuous occupancy [13]. In the zones without continuous occupancy, i.e. storage rooms or cold basements, it was decided to deviate from the standard and follow a requirement from the regulation TEK17. Therefore, in the zones without continuous occupancy, it was decided to have supply air of 0.7 m^3/h m^2 [55]. Based on these two requirements the total supplied airflow rate was determined. Equation (4.1) describes the relationship that gives the total supplied airflow rate. The supplied airflow rates in the respective case houses are given in Table 4.2.

$$\text{Total supply} = 1.2\frac{\text{m}^3}{\text{h m}^2} \cdot \text{Area of zones w/ cont. occupancy} + 0.7\frac{\text{m}^3}{\text{h m}^2} \cdot \text{Area of zones w/o cont. occupancy} \quad (4.1)$$

Table 4.2: *Supplied airflow rates of the case houses*

Case house	Kristiansand	Malvik
Supplied airflow [m^3/h m^2]: EXISTING	225.8	150.8
Supplied airflow [m^3/h m^2]: TEK10 ÷, OPPTRE and PASSIVE	245.5	182.2

The supplied air was distributed in zones such as living rooms, bedrooms, staircases, entrances, storage rooms and technical rooms. In zones such as bathrooms, kitchens and toilets, the air was solely extracted. Since the total supplied airflow was dimensioned for all zones, including the ones where the air is solely extracted, the excess air had to be distributed somewhere else. As part of the standardized approach, it was decided that the excess air would be distributed in the bedrooms, as this is the common practice.

In IDA ICE, all combinations were simulated with the same ventilation strategy based on CAV, the total airflow rate calculated in Equation (4.1) and the principle of balanced ventilation. Firstly, CAV was chosen in IDA ICE as part of the standardized model, as CAV is a common ventilation strategy in newly built residential buildings. Then, in order to balance the ventilation system, the same amount of air was supplied and extracted. This way the total supplied air in Table 4.2 also corresponds to the total extracted air in each case house. In this thesis, the amount of extracted air in each of the respective zones was set based on the relative size of the zone and on discretion. For instance, more air was extracted in kitchens and large bathrooms than in small toilets.

A standard air handling unit (AHU) was implemented in IDA ICE and represented the control center for the ventilation system. In the AHU, there was an electric heating coil, an electric cooling coil, a heat recovery unit and fans. It was assumed that there was no need for cooling of the ventilation air. Thus, the cooling coil was turned off. The heat recovery unit was assumed to be a rotary heat exchanger. In IDA ICE, a temperature limit of the heat recovery unit was implemented, such that the supply air never gets heated to more than 18 °C. If the temperature reached above 18 °C, the efficiency of the heat recovery unit started to decrease. This was done to avoid overheating during summer. The combinations with ordinary balanced ventilation systems, A2A/A2AsolarDHW/A2W/GSHP, had heat recovery units with a temperature efficiency of 80%. Combinations CHPWH4 and CHPW4 had heat recovery units with a temperature efficiency of 84%. Due to the ventilation system connected to an EAHP, combinations EAHPDHW and EAHPCombi had the efficiency of the heat recovery unit set to zero.

The electric heating coil was heating the supply air after the heat recovery unit. It was implemented in such a way that it would start operating when the temperature of the incoming air was below 16 degrees. The heating coil would then heat the incoming air to reach the set point temperature of the zones. It was assumed that in all combinations the heating coil was electric as the ventilation heating demand usually does not make up a large part of the total heating demand.

Specific fan performance (SFP) was chosen with respect to the standards SN-NSPEK 3031 (2020) [13] and NS 3700 (2013) [14]. This is shown in the tables showing the input parameters of the IDA ICE simulation models, Table 3.1 and Table 3.2.

It is important to stress that in the scenario EXISTING, the airflow rates of balanced ventilation were used in the simulations. However, the electric heating coil was turned off and the efficiency of the heat recovery unit was set to zero. The fans were still turned on to simulate the heat loss from a natural ventilation system. For scenario EXISTING, pressure differences between the outside and the inside were the driving forces for the airflow in the building, i.e., infiltration. As stated earlier, the pressure coefficients for Kristiansand were assumed to be "Semi exposed", whereas in the model of the Malvik case house the pressure coefficients were based on Rambøll's calculations.

Climate files

A climate file used in IDA ICE contains hourly values of the following parameters: relative humidity, dry bulb temperature, airspeed, rain, wind information, solar radiation for different orientations, barometric pressure and cloudiness. These values represent data for a typical year and contain the composite weighing of a set of parameters deriving from a period of 18 years. This results in a set of climate and weather data, containing monthly data from different years [56].

For comparative reasons, it was decided to have identical climate files when simulating both case houses, even though they in reality are situated different places. Therefore, the two case houses were both simulated with the climate of Oslo, Gardermoen. The dimensioning outdoor temperature (DOT) at Gardermoen is -22 °C.

Modeling of internal gains

The presence of occupants and electric appliances entails heat gain in the energy balance of a building. These gains affect both thermal comfort and energy consumption for heating purposes. If there are a lot of people present, less heating is necessary. Therefore, the internal gains are important for an energy simulation. In this thesis, lighting, equipment and occupant loads were modeled according to the standard SN-NSPEK 3031 (2020). The daily schedules and intensities throughout the day of the internal gains can be found in Appendix B.1.

Table 4.3 shows the hourly proportion of assumed energy demand being supplied to the zone as heat. These percentages were set according to SN-NSPEK 3031 (2020).

Table 4.3: *Energy demand supplied to the zone as heat [13]*

Occupancy	Lighting	Equipment
100%	100%	60%

The occupancy heat gain was calculated in IDA ICE based on the number of people and the activity level. The activity level was set equally in both case houses studied in this master's thesis. As they are both residential buildings, the activity level was set to 1.2 MET [15]. The number of occupants was 2 in the Malvik house and 4 in the Kristiansand house.

Domestic hot water (DHW)

The daily profile of DHW was set according to SN-NSPEK 3031 (2020) and can be found in Appendix B.1. Table 3.1 and Table 3.2 show the average usage of DHW for all scenarios, which was set to be 25 kWh/(m^2 year) [13]. Following the passive house standard for scenario PASSIVE, the average DHW usage should originally be 29.8 kWh/(m^2 year) [14]. However, as part of the standardized approach, it was decided to assume the same DHW usage in all scenarios.

Weather compensating curve

For the combinations with centralized hydronic heating (A2W/GSHP/CHPWH4/EAHPcombi), a weather compensation curve was implemented in IDA ICE. A weather compensation curve enables the boiler to respond to the outside temperature changes and adjust the heat emitting systems accordingly. With conventional control, the heat emitting systems will only respond after the building has become too hot or too cold. However, the weather compensated control enables a faster response to changes for the purpose of maintaining a constant indoor temperature [57]. In this thesis, it was assumed that the supply temperature of the heat emitting systems was 40 °C at DOT, and 20 °C at an ambient temperature of 20 °C. Figure 4.1 illustrates the assumed weather compensation curve used in this master's thesis.

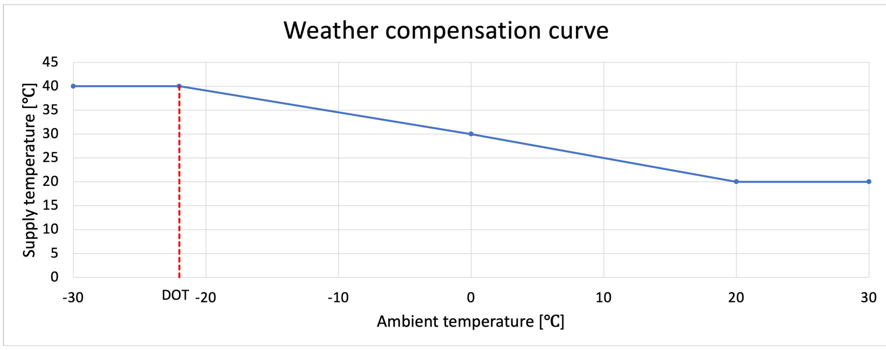

Figure 4.1: *Weather compensation curve*

4.1.3 Modeling of HVAC-technologies in IDA ICE

In this section, the modeling of the different HVAC-technologies in IDA ICE will be described. Some of the considered HVAC-technologies are already integrated into the IDA ICE database, making them easy to implement correctly in the simulations. Other technologies had to be simplified with a decoupled approach.

Later, in Section 4.2.1, the process of dimensioning the heat pumps, energy well, solar thermal collectors and heat distribution systems will be described.

Ground source heat pump

Among the considered HVAC-technologies, ground source heat pump (GSHP) was one of the technologies already integrated into IDA ICE with a standard model in the Early Stage Building Optimization plant, also called ESBO-plant. For simplicity's sake, it was decided to use this standard model of the GSHP in the simulations. The ESBO-plant is the default energy supply plant in IDA ICE and established a centralized heating system. This meant that heat from the GSHP was delivered to a hot water tank before it got distributed to the different zones through a hydronic heating system. The amount of energy that the heat pump was unable to deliver was covered by an electric boiler connected to the centralized heating system.

Air to water heat pump

It was also decided to implement the already integrated model of an air to water (A2W) heat pump in the IDA ICE models. Like the GSHP, the A2W heat pump is found in the ESBO-plant. Hence, a centralized heating system was established with an electric boiler delivering peak heating.

Air to air heat pump

A standard model of an air to air heat pump exists in the IDA ICE database and was implemented in the simulation models. In reality, air to air heat pumps are often implemented in a zone with continuous occupancy, typically a living room. Thus, it was decided to place the heat pump in the living room in the simulations as well. In order to deliver sufficient heat in that zone, an electric panel heater was placed in the same zone with a capacity large enough to cover the peak demand. In IDA ICE, this was controlled by having the set point of the panel heater one degree lower than the set point of the heat pump. When the heat pump was not able to deliver enough heat to the room, the temperature was decreasing, resulting in the electric panel heater being turned on.

Hot water tank

A hot water tank for storage and DHW was also implemented in the simulation models. It has been assumed that every detached dwelling has a hot water tank. A hot water tank will lower the demand for heating power of the DHW. Hence, if a hot water tank is not modeled in IDA ICE, it will result in unrealistically high heating power. Following the standard SN-NSPEK 3031 (2020) for sizing a hot water storage tank, gave the volumes V = 196 L and V = 184 L for the Kristiansand house and Malvik house, respectively [13]. Subsequently, a volume of 200 L was chosen as the standard size for the two case houses. The only exception was the combination with solar thermal collectors, A2AsolarDHW, where the volume was set to 300L. It was decided to have a larger hot water tank in A2AsolarDHW to facilitate the uncertainty of the heat production depending on the sun conditions. The insulation level of the tank is chosen to be moderate. In table 4.4, the hot water tank properties used in the simulations are listed.

Table 4.4: *Hot water tank properties in IDA ICE*

Case house	Kristiansand and Malvik
Volume tank, standard	200 L
Volume tank, combination A2AsolarDHW	300 L
Insulation level	0.6 W/m^2 °C

Exhaust air heat pump

The default energy supply plant (ESBO) does not support exhaust air heat pumps nor compact heat pumps. It is possible to implement these systems in IDA ICE, but this procedure is advanced and requires detailed information from the manufacturer and can be time-consuming. Therefore, it was decided to evaluate the components not supported by ESBO, in a decoupled approach outside of IDA ICE. The decoupled approach is faster and more compatible with the available manufacturer data. The output of the decoupled approach was the energy consumption of the exhaust air heat pump and peak heating. Together with the output for lighting, equipment and HVAC-auxiliary from IDA ICE, the total energy consumption of the building can be calculated.

In order to find the amount of energy consumed by the exhaust air heat pump one has to estimate how much energy it is possible to retrieve from the heat source. As mentioned in Section 2.4, an exhaust air heat pump utilizes heat in the extract air of the ventilation system. The nominal airflow of the extract air $\dot{V}$ for the respective building, the specific heat at a constant pressure of air C_p, the density of air ρ, and temperatures of the extract air in T_{in} and out T_{out} of the evaporator were all known parameters. With these parameters, the maximum power of the evaporator $P_{max,e}$ was derived. As the temperature of the extract air is constantly around 20 °C, T_{in} was set to 20 °C. It was assumed that the heat pump can cool air down to -15 °C, which is why T_{out} was set to -15 °C [9]. Equation (4.2) shows this relation and gives the maximum power of the evaporator. The equation indicates how much heat it is possible to retrieve from the exhaust air in the ventilation system.

$$P_{max,e} = \dot{V} \cdot \rho \cdot C_p \cdot (T_{in} - T_{out}) \tag{4.2}$$

where: $P_{max,e}$ = Maximum evaporator capacity
$\dot{V}$ = Ventilation airflow rate
ρ = Density of air (1.225 kg/m^3)
C_p = Specific heat capacity are of air (1 kJ/kgK.)
T_{in} = The constant temperature at 20 °C
T_{out} = The lowest air temperature at -15 °C

The maximum evaporator capacity was calculated for both case houses. These capacities are shown in Table 4.5. The difference in evaporator capacity appears due to distinct airflow rates in the two case houses for all retrofitted scenarios.

The Coefficient of Performance (COP) was assumed to be constant due to the constant temperature of the extract air. With this assumption, the maximum capacity of the condenser was possible to derive. Equation (4.3) describes the relation between the maximum capacity of the condenser, maximum capacity of the evaporator and the constant COP. This relation indicates how much heat the heat pump can deliver based on the respective COP and airflow. The calculated maximum capacities of the condenser are shown in Table 4.5.

$$P_{max,c} = P_{max,e} \frac{COP}{COP - 1} \tag{4.3}$$

where: $P_{max,c}$ = Maximum condenser capacity
COP = Coefficient of performance

Table 4.5: *Maximum evaporator and condenser capacity of the EAHP based on total airflow rates*

Case house	**Krisitansand**	**Malvik**
Total airflow rate	245.5 m^3/h	182.2 m^3/h
$P_{max,e}$	2924 W	2170 W
$P_{max,c}$	4195 W	3113 W

In the decoupled approach for the exhaust air heat pump, the next action was to compare the maximum possible heat delivered by the heat pump with the actual demand at every time step. Therefore, the heating power delivered to the DHW and zones at every time step, P_d(t), was logged in IDA ICE. The exhaust air heat pump was in this thesis considered in two ways. In the first case, combination EAHPCombi, the heat pump covers both space heating and heating of DHW. Hence, P_d(t) is the sum of the heating power delivered to the heating coil (connected to the hydronic distribution system) and DHW. In the second case, combination EAHPDHW, the heat pump only covers the heating demand for DHW, meaning that P_d(t) only represents the heating power delivered to DHW.

The IDA ICE simulation models with exhaust air heat pumps were simplified as regards heating systems, with electric heat emitters in every heated zone and 100% efficiency. However, the cost performance analysis took the real heat distribution systems in these two combinations into consideration. These distribution systems were hydronic space heating in combination EAHPCombi and electric space heating in EAHPDHW.

As mentioned, the maximum capacity of the condenser was compared with the logged power, P_d(t), at each time step. If P_d(t) was less than $P_{max,c}$, it implied that the EAHP was able to deliver a sufficient amount of heat at that time. However, if P_d(t) was larger than $P_{max,c}$, it implied that the EAHP had reached its maximum capacity and the power of the condenser was limited to $P_{max,c}$. When the power of the condenser was limited, an additional heating source was needed to cover the power demand. It was decided to consider an electric boiler with an efficiency of 100% as peak heating source.

The power consumed by the compressor at each time step is given by Equation (4.4). P_{cond}(t) represents the power of the condenser at each time step, which is either P_d(t) or the maximum condenser capacity depending on whether P_d(t) is above or below $P_{max,c}$.

$$P_{com}(t) = \frac{P_{cond}(t)}{COP} \tag{4.4}$$

where: $P_{com}(t)$ = The power needed for the compressor at each time step
$P_{cond}(t)$ = Power of the condenser at each time step
COP = Coefficient of performance

In the cost analysis, the annual energy cost of a combination was needed (i.e. the amount of electricity consumed by the heat pump and the electric boiler in combination EAHP). As mentioned, there was a need for a peak heating source when the power of the condenser was limited. The electricity consumed by the peak heating source, given in Equation (4.5), was calculated by first finding the difference in power at each time step, P_d(t) - P_{cond}(t). Then, this difference was multiplied with the time interval to find the electricity consumed at each time step. Finally, the electricity consumed at each time step was summed to obtain the total annual electricity consumed by the electric boiler.

$$E_{peak} = \sum_{t=0} (P_d(t) - P_{cond}(t)) \cdot \Delta t \tag{4.5}$$

where: E_{peak} = Total amount of electricity used by the electric boiler
$P_{cond}(t)$ = Power of the condenser at each time step
$P_d(t)$ = Logged power of the condenser at each time step
Δt = Time step

As described in Equation (4.6), by summing up the electricity consumed by the compressor at each time step, it was possible to obtain the total amount of electricity consumed by the heat pumps.

$$E_{hp} = \sum_{t=0} P_{com}(t) \cdot \Delta t \tag{4.6}$$

where: E_{hp} = Total amount of electricity consumed by the heat pump
$P_{com}(t)$ = Power needed by the compressor at each time step
Δt = Time step

The annual electricity consumption of the heat pump, electric boiler, lighting, equipment and HVAC auxiliary, made up the total annual electricity consumption of the case houses in a specific scenario.

Compact heat pump

A standard compact heat pump often consists of an exhaust air heat pump and a balanced ventilation system [7], as mentioned in Section 2.4.1. Some models of the heat pump can cover both DHW heating and space heating, and some models can only cover DHW heating. In this thesis, both models were considered. The two considered compact heat pumps resemble Flexit AS' two indoor climate centrals Econordic WH4 and Econordic W4. Econordic WH4 covers space heating, whereas Econordic W4 does not. In contrast to the combinations with an exhaust air heat pump, the combinations with a compact heat pump were implemented with heat recovery in the ventilation system. The airflow rates of both case houses were based on SN-NSPEK 3031 (2020) and are explained further in Section 4.1.2. The efficiency of heat recovery and COP, given in Table 4.6, were based on the performance of the two compact heat pumps Econordic WH4 and Econordic W4.

Table 4.6: *Properties of Econordic W4 and Econordic WH4 [58]*

Model	Econordic W4 and Econordic WH4
Temperature efficiency heat recovery	84%
COP heat pump	3.15

The energy consumption of both compact heat pumps was evaluated in a decoupled approach. Econordic WH4 was evaluated in the same way as the exhaust air heat pump covering both DHW and space heating, and Econordic W4 was evaluated in the same way as the exhaust air heat pump solely delivering heat to DHW. Similar methods were applied because an exhaust air heat pump often is a part of the compact heat pump system [7]. It should be stressed that the Econordic models in reality utilize the outdoor air in addition to the exhaust air. This was not considered in the chosen decoupled approach, which leads to the heating capacities being limited by the airflow rates.

Heat distribution systems

In these sections, the implementation of the heat distribution systems will be described. Apart from the heat pumps, there were four heat distribution systems considered in this thesis: electric panel heaters, electric floor heating, fan convectors and hydronic floor heating. In IDA ICE these systems are called *electric radiator*, *electric floor heating*, *simple fan coil* and *heating and cooling floor*, respectively.

All four heat distribution systems were dimensioned in the same way in IDA ICE. First, ideal heaters were implemented in every heated zone. Then, a heating load simulation was run outputting the heating power demand for each of the zones on the coldest day (i.e. at DOT). This indicates the minimum heating power the respective room units require to cover the heating demand on the coldest day.

There were some differences in the modeling of the four heat distribution systems. Electric floor heating and hydronic floor heating were both implemented in the bathrooms, WCs and entrances. The areas of floor heating for the two case houses are given in Table 4.7. In Appendix B.2, there is an overview of the specific rooms in which floor heating was implemented.

It was decided to have flow control of the hydronic floor heating. A PI controller would then be steering the flow and amount of heat delivered at each time step. When the air temperature of the zone becomes lower than the set point temperature, the controller will give a signal and the flow control valve will open accordingly.

As regards electric panel heaters and fan convectors, one unit was placed in the remaining heated zones, except bedrooms. It was decided to not have any heating units in the bedroom. However, the bedroom doors were assumed open, and the heating unit in the room/zone next to the respective bedroom was dimensioned to cover the bedroom's heating demands. The number of electric panel heaters and fan convectors in each case house is given in Table 4.7. The electric panel heaters are implemented with an efficiency of 100%. It should be mentioned that the quantities of fan convectors implemented in IDA ICE are not the same as regarded in the cost analysis. The reason for this will be described more thoroughly in Section 4.2.1.

Table 4.7: *Heat distribution systems, area and quantity in IDA ICE*

Case house	**Kristiansand**	**Malvik**
Area el. floor heating [m^2]	25.6	26.9
Area hyd. floor heating [m^2]	25.6	26.9
Quantity el. panel heaters	8	10
Quantity fan convectors	8	10

Solar thermal collectors

The ESBO-plant in IDA ICE made it possible to easily define and implement a standard model of solar thermal collectors. It was decided to use a flat plate "Generic solar collector". The area of the collectors was adjusted to fit the particular case house, 6 m^2 for the Malvik house and 12 m^2 for the Kristiansand house. Further information on how these two areas were determined can be read in Section 4.2.1. The solar thermal collectors were placed on the sunniest rooftop of each case house, facing the same way as the roof. In the Kristiansand house, the sunniest rooftop is facing southwest, whereas the sunniest rooftop in the Malvik house is facing south. The angles of the collectors were set according to the angle of the roofs.

4.2 Establishing investment cost spans

After creating the simulation models in IDA ICE, the next step towards answering the research question was to gather investment costs for the different HVAC-technologies with associated capacities and performances. With investment costs gathered for specific capacities, one is able to investigate which capacity is the best size for each scenario as regards cost effectiveness and energy efficiency. These specific investment cost spans were then used in the global cost calculations to give a more precise picture of the actual cost effectiveness of deep energy retrofitting the two case houses. The process of gathering data was unique for almost every HVAC-technology and will be presented in detail in this section.

It should be stressed that the investment costs of a hot water tank were not considered for any of the combinations, except A2AsolarDHW. A hot water tank was assumed to be reusable from the existing houses, not requiring a new investment.

The investment cost spans considered for each technology, scenario and case house are presented in Appendix A.1, Figure A.1.

4.2.1 Sizing heating systems and deciding investment cost spans

To give a better representation of the investment costs, a span of costs was considered instead of only considering a mean value. These investment cost spans were determined by data collected mostly from the Norwegian market. The sources of the data collected on investment costs are given in Appendix A.

For the air to air, air to water and ground source heat pumps, the collected data on investment costs were clustered into groups based on capacity. Each group represented several models within the same capacity range. The reason for clustering the capacities into groups was to facilitate the sizing process and reduce the number of necessary simulations. A capacity span of approximately 1-2 kW was permitted in each group.

Air to air heat pump

The 127 reviewed air to air heat pump models had capacities ranging from 3.3 kW to 10.6 kW with associated investment costs spanning from 14 000 NOK to 49 000 NOK including installation. For the majority of the air to air heat pumps the installation cost was either included or stated on the suppliers' web page. It was decided to consider the standard nominal COP with an outdoor temperature of 7 °C for this thesis. These COP values were found in the product sheets of the different heat pump models. Based on the data collection, the capacities simulated for each scenario were now the following six: 4.5 kW, 5.5 kW, 6.4 kW, 7.4 kW, 8.7 kW and 10 kW. The simulated COP at each capacity was determined based on the mean COP of the models in the respective group.

Each of the six capacities with adjoining COPs was implemented in IDA ICE and simulated for all scenarios in both case houses. The output from the simulations was used to find a Seasonal Performance Factor (SPF) and coverage factor of the heat pump for each of the capacity groups. The case houses' energy consumption for each of the six capacity groups was also registered for each scenario.

After completing all the simulations, a capacity group was selected for each scenario. This required a simple cost analysis to look at how the savings in energy costs would affect the global costs compared to investing in a cheaper air to air heat pump model with lower capacity. The energy costs were multiplied with the calculation period of 20 years and an electricity cost of 1,2 NOK to account for the environmental impact and inflation. Together with the coverage factor and SPF data, an optimal capacity for each scenario was determined.

In the case of air to air heat pump, the lowest capacity of 4,5 was the best suited for all scenarios. Even with a higher electricity price, the savings in energy costs were not large enough to make up for the increased investment cost of a greater capacity. Furthermore, the coverage degree increased about 1% if one were to purchase the more expensive 10 kW model. The same applied to the SPF, which did not improve enough to make a larger capacity more energy-efficient. There was no reason for overdimensioning the heat pump as this would induce larger investment costs. Taking SPF and coverage factor into consideration, the lowest capacity group fitted all scenarios. The chosen capacity for the heat pump led to coverage factors in the retrofitted scenarios being between 10-18% and 12-19% for the Kristiansand house and Malvik house, respectively.

Air to water heat pump

As regards air to water heat pumps, the 23 reviewed models that had data on investment costs, ranged from 6.5 kW to 14.1 kW in capacity. Alongside the investment costs and the designated maximum capacity, COP values could be extracted from the heat pump models' product sheets. The COP used in this thesis was the standard nominal COP with an outdoor temperature of 7 °C and water temperature of 35 °C. Using information solely based on the Norwegian market was not sufficient to get a large enough selection. Thus, Swedish sources were also considered. Installation costs were based on NVE's cost report from 2015 [11], due to the lack of such information online.

Looking at both the Norwegian and Swedish prices, it was clear that the prices on the Swedish market overall were lower. Therefore, a market conversion factor was found based on the data collected for the air to water heat pumps. This factor implied that the Norwegian prices were approximately 25% higher and the Swedish prices were adjusted accordingly.

The same procedure as for air to air heat pump, was applied for the air to water heat pump. The following capacity groups were considered for this technology: 7.3 kW, 9 kW, 10.9 kW and 13.2 kW, and the average COP of each group was the one used for simulation purposes.

A simple cost analysis of the different capacity groups showed that the investment costs were more dominant than the energy costs during the whole calculation period. For scenario TEK10÷, the impact on costs of increasing the capacity from the lowest to the second lowest, was not substantial. That is why the most energy-efficient and cost-effective heat pump capacity was 9 kW for scenario TEK10÷. For the rest of the scenarios, the 7.3 kW heat pump was selected. Both SPF and coverage factor were taken into account when dimensioning the heat pump capacities. The two capacity groups had different investment cost spans. This is due to a large installed capacity having a greater cost of the unit. The chosen capacities for the heat pump led to coverage factors in the retrofitted scenarios being between 96-97% for the Kristiansand house and 95-97% for the Malvik house.

Both K. Lund AS and RoMyClima AS provided estimates of a complete installation of an air to water heat pump. This made it possible to compare the cost span including installation with the market prices for private customers.

Ground source heat pump with energy well

The process of collecting data on ground source heat pumps (GSHPs) was quite similar to air to water heat pumps. Both Norwegian and Swedish investment costs were collected to get sufficient data representative of the market. A comparison of the different markets indicated that Norwegian prices were approximately 25% higher than the Swedish, equivalent to the air to water heat pumps. Therefore, the same market conversion factor was used. Installation costs were based on NVE's cost report from 2015 [11].

GSHPs utilize the ground as heat source. An investment cost span must therefore include the investment of an energy well. It was decided to use prices given at different lengths (150 m, 200 m, 250 m), provided by Værås Brønnbåring AS [59], in order to get precise investment costs for the scenarios.

The depth of the well was also needed for the simulations alongside capacity and COP of the heat pump. The capacity groups determined from the data collection of the GSHP were: 5.5 kW, 8.2 kW, 9.5 kW and 10.3 kW. As with the air to air and air to water heat pumps, the COP of each capacity group was the mean value of COPs within the respective group. The literature states that the depth varies between 80-350 meters depending on ground properties and demand [60][61][62]. Therefore, a depth of 150 m was chosen for the lowest capacity group, 200 m for the two capacity groups in between and 250 m for the highest capacity group. It is worth mentioning that simulations with a 50 m increase in the depths of the energy wells were conducted and showed that the primary assumed lengths were sufficient.

After the simplified cost analysis and considering both the SPFs and coverage factors, the 8.2 kW heat pump with 200 m energy well was selected for scenario TEK10÷ in both case houses. In addition, the 8.2 kW heat pump was selected for scenario OPPTRE in the Kristiansand house. The remaining 3 scenarios had such a low heating demand that the 5.5 kW heat pump with 150 m energy well was assumed sufficient. The chosen capacities for the heat pump led to coverage factors in the retrofitted scenarios being about 98% and 97-98% for the Kristiansand house and Malvik house, respectively.

Exhaust air heat pump

When looking at the Norwegian market for exhaust air heat pumps (EAHPs), we quickly realized that there were few prices to collect for this thesis. Therefore, both the Swedish and Danish markets had to be researched in order to establish a cost span. A market conversion factor of 1.25 was assumed for EAHP as the Norwegian prices were approximately 25% higher. This is the same factor used for GSHPs and air to water heat pumps. As regards the relationship between the Swedish and Danish markets for EAHP, the conversion factor was assumed to be 1. This was due to at least two models of EAHP having about the same cost both in the Danish and Swedish markets. This resulted in the Danish prices being increased by 25% as well as the Swedish, to be comparable to the Norwegian prices.

Since two different types of EAHP were considered, there were two different approaches when establishing an investment cost span. Most of the EAHP models in our data collection were heat pumps with the ability to cover both space heating and DHW heating. Due to the limited airflow of a house, the maximum heating capacity of the heat pump is restricted. The airflow of the Kristiansand house resulted in a maximum capacity of 4.3 kW, whereas the airflow of the Malvik house resulted in a maximum capacity of 3.2 kW.

The investment cost span of the EAHP covering solely DHW heating derived from two models, NIBE F110 and Vanvex 260. These were assumed suitable for both case houses, resulting in the same investment cost spans. The investment cost span of the EAHP covering both space heating and DHW heating derived from several models. Due to different maximum capacities, two different capacity groups were used for the case houses. This resulted in different investment cost spans for the Malvik and Kristiansand case houses.

A standard installation cost originating from the Swedish market [63] was included in the investment cost spans. In order to find the Norwegian installation cost, the conversion factor 1.25 was assumed to apply for installation costs as well. An EAHP installation requires ventilation ducts for air extraction. As such, the cost of ducts (15 000 NOK) was retrieved from the investment costs of balanced ventilation and added to the investment cost spans of the EAHPs.

Compact heat pump

As described in Section 2.4.1, the two compact heat pump systems from Flexit AS are indoor climate centrals in which there is a hot water tank, a heat exchanger and a heat pump. In addition, the indoor climate centrals are connected to a ventilation system and a hydronic heat distribution system. In other words, it is an extensive installation, customized to the house where it is to be installed. We contacted several vendors of these two installations trying to receive offers on the two case houses used in this thesis. Unfortunately, most vendors we contacted replied that they did not have time to make us an offer due to general work load.

Only two vendors provided us with offers for the compact heat pumps Econordic W4 and Econordic WH4, Knut Olav Gaaseby at Ski Boligventilasjon AS and Per Christian Gustavsen at Byggventilasjon AS. The information from these two vendors was used to establish the investment cost spans of the two compact heat pumps. The price estimates they provided us included the central itself, design of the ventilation system, materials for piping and installation of the central and ventilation system. It is important to stress that a separate ventilation aggregate for the studio apartment in the Kristiansand house, was not considered in the investment cost span of the compact heat pumps.

On the Norwegian market, two prices were found for the central itself, not including installation or a ventilation system. These prices derived from Ventdel.no and Byggmakker. The price of the ventilation system given by Ski Boligventilasjon AS and Byggventilasjon AS were isolated and added to the unit price from Ventdel.no and Byggmakker. The total cost based on Ventdel.no's unit price was in the same range as the two other total offers. On the other hand, the total cost based on Byggmakker's unit price was way higher, about 100 000 NOK more. Hence, it was decided to disregard Byggmakker's price in this thesis.

Balanced ventilation

To get a span of investment costs for customized balanced ventilation systems, several vendors were contacted. We received two offers, from Per Christian Gustavsen at Byggventilasjon AS and Alexander Wabakken at Moe Ventilasjon AS. The investment cost span for balanced ventilation was therefore based on these two offers. Based on the two case houses, both offers included system design, pipes, ventilation aggregate and installation. Since the Kristiansand house has a small studio apartment in the basement of the retrofitted scenarios, the cost of an extra ventilation aggregate was included in the investment cost. Hence, the investment costs of balanced ventilation in the Kristiansand house were larger than in the Malvik house.

Electric panel heaters

In IDA ICE, the heating power of the electric panel heaters was dimensioned as described in Section 4.1.3. Instead of gathering data on electric panel heaters with capacities matching each heating power given in the simulations, it was decided to solely consider two sizes of capacities for the cost assessment, 500 W and 2000 W. Depending on the heating demand in each room, either a 500 W panel heater or a 2000 W panel heater was selected. The quantities of each type of panel heater used in the cost performance assessment, are shown in Table 4.8.

The investment costs were calculated based on prices collected from the Norwegian market. An electric panel heater of 2000 W had greater investment costs than an electric panel heater of 500 W. These investment costs were multiplied with the respective number of units for the two case houses to establish a total investment cost span. Due to having two more electric panel heaters in the Malvik house, there were two spans of investment costs, one for each case house.

Table 4.8: *Quantities used to establish investment costs*

Case house	Kristiansand	Malvik
Number of 500 W units	6	8
Number of 2000 W units	2	2

It is important to stress that by selecting only two sizes of capacities to establish the investment cost span of electric panel heaters, some rooms may end up having an over- or undersized heating unit. However, it was assumed that these effects are balanced such that the overall heating capacity is sufficient.

Electric floor heating

For electric floor heating, the number of rooms in which this technology is installed and their respective area, have to be determined. Due to difficulties in retrieving an estimate online for the two case houses, we contacted some suppliers directly with the data on floor areas. GK Elektro was the only supplier at that time, that was available to give an exact offer on electric floor heating for the two case houses. The offer included installation, thermostats and electric heating cables. Due to this specific offer, we chose to move forward with a single investment cost for each house, removing the span from this technology. Nevertheless, we compared the offer with our online research and found that it coincided with the information we could gather. The exact areas of each room with floor heating, are given in Appendix B.2.

Hydronic floor heating

The investment costs of hydronic floor heating depend on a variety of factors such as area, type of pipes, control system, etc. There were not many suppliers being able to propose an investment cost span for the case houses in Kristiansand and Malvik. However, Varmetema AS is developing an investment cost calculator for their HVAC-systems. Included in the calculator is their hydronic floor heating solution with their own control unit, called Alpha-center. Jan Håvard Bratlie introduced us to their systems and we decided that they were suitable for the relevant HVAC-combinations considered in this thesis as they are easily connected with different heat pumps. The investment cost calculator includes everything a customer needs in order to install a functioning hydronic floor heating system, such as installation by a plumber, transport, equipment, etc. The input parameters are the respective areas of the rooms in which the hydronic floor heating is to be installed, the type of floor construction in each room, and the control unit solution. Doing so for the Malvik and Kristiansand case houses, two different investment costs of hydronic floor heating were established. As with electric floor heating, a span was not considered for hydronic floor heating.

Fan convectors

Fan convectors tend to be relatively large and noisy. However, they are often efficient when it comes to heat distribution. Hence, there is no need for a fan convector in every room. Based on the floor plan of the two case houses, it was decided to only consider three fan convectors in the cost performance assessment of each case house. Based on prices provided by five different Norwegian vendors, a common investment cost span for fan convectors was made for both case houses.

Solar thermal collectors

When the solar thermal collectors are to solely cover the heating of DHW, a commonly known rule of thumb states that the coverage factor should be around 50%. This is the same coverage factor as used in Ekström et al.'s study from 2017 [9]. Based on this rule of thumb, simulations were done iteratively to determine which area gave the most reasonable coverage factor. This resulted in collector areas of 12 m^2 for the Kristiansand house and 6 m^2 for the Malvik house. Hence, prices of these specific areas were collected and two different investment cost spans were established. The investment cost spans include the cost of a new hot water tank, due to the required volume of 300 L. Both solar thermal collectors and the hot water tank have investment costs based on the following information sources: Varmeshop.no [64], NVE's cost report from 2015 [11] and a report developed by Asplan Viak and Norsk solenergiforening (2015) [65].

4.3 Cost performance assessment

The cost performance assessment is at the heart of this project, and all results originate from the initial decisions made prior to the analysis. After gathering all the data needed, a standard for economic performance was applied as the main method for calculating the final results. Some of the data needed for the calculations derived from the simulation output of IDA ICE. The standard used for the cost performance assessment was the Norwegian and European standard *NS-EN 15459-1:2017 Energy performance of buildings - Economic evaluation procedure for energy systems in buildings - Part 1: Calculation procedures, Module M1-14* [12]. This standard gave standardized instructions on how to do a cost analysis of energy systems in a building. It also provided some of the main input values and equations for the calculations and described the steps required to obtain the results.

Step 1 was to gather the financial data needed for the calculations. This included the duration of the calculation period, inflation rate and discount rate. In addition to these parameters, the standard stated that the rate of development of human operation costs and the rate of development of energy price were to be determined. Regarding these two rates, it was decided to deviate from the standard. The rate of development of human operation costs was not considered in this project. Further, the rate of development of energy price was set to be equal to the inflation rate. Another deviation from the standard is the decision of disregarding disposal costs and CO_2-emission costs, due to difficult data collection.

Step 2 was to identify the systems to be considered in the economic calculations and collecting project data such as maintenance costs, lifetime expectancies and efficiencies. Step 3 was to gather the different investment costs of HVAC-technologies, including installation costs. Step 4 was to determine the energy costs which in this project was based on the price of electricity and energy consumption of each combination in the retrofitted scenarios. Then there were the two final steps, 5 and 6, which gave the main output for discussion. Step 5 was calculating the global costs of a system and step 6 was calculating the payback time of a system. All steps will be described more thoroughly in this chapter.

4.3.1 Calculation period

In the scope of this master's thesis, the calculation period was set to be 20 years. This was done to give a fair representation of all the lifetime expectancies of the technologies considered in the combinations. For instance, all heat pumps have lifetime expectancies of 15-20 years, a balanced ventilation system has 20 years and solar thermal collectors have 25 years as seen in Appendix A.1, Figure A.1.

4.3.2 Determining maintenance costs and lifetime expectancies

Maintenance costs were in the cost performance calculations set as a percentage of investment costs. This data was in general difficult to retrieve from the market. Most of these percentages were therefore gathered from the standard NS-EN 15459 (2017) [12]. Further, a few suppliers have given an estimation of maintenance costs in NOK per year, which was easily converted into a percentage of the investment costs. Lifetime expectancy data was for the most part also collected from the standard. For those technologies that were not listed in the standard, a literature review had to be done.

4.3.3 Determining electricity price, inflation rate and discount rate

The electricity price was based on data over the past nine years, rounded up from 0.95 NOK/kWh to 1 NOK/kWh [21]. In the discussion part of this thesis, the effects of increasing the electricity price by 0.5 NOK/kWh will be analyzed. This increase was based on future predictions and uncertainties, as mentioned in Section 2.3.3

Since higher inflation will result in lower present values, the cautionary principle was applied. This principle implies that the inflation rate used for calculations should be higher than the real inflation rate. The inflation rate in this master's thesis was therefore set to be 2%, which equals the Norwegian target of inflation.

The government recommendation for the discount rate of a normal-sized public project with normal risk is 4% for a calculation period between 0 and 40 years [66]. The objective of this thesis was to assess private investments in a deep energy retrofit with low risk. Therefore, the initial discount rate for the cost performance assessment was set to be 3%, which is 1% higher than the inflation rate. Since this is an uncertain variable, the sensitivity of the discount rate will be discussed in Section 6.5.2.

Alternative way of determining the discount rate

The discount rate for energy systems can also be determined by other means. Equation (4.7) from the compendium "TEP 4235 Energy Management in Buildings" applies to private investments with external financing [67]. Using this equation, different discount rates can be used in the cost performance assessment to establish the sensitivity of this parameter. In this master's thesis, the relative price fluctuation factor was set to be zero. This was done because the development of energy price as a basis is equal to the inflation rate (Section 4.3). To obtain the nominal financing interest rate for private investments, the rate should be set equal to the bank's loan interest rate or savings interest rate depending on the project. If the investment is financed internally (e.g., bank savings), the tax factor is eliminated. The nominal interest rate is then determined by the interest rates of the alternative investment opportunities.

$$r = \frac{1}{1+e} \cdot \left[\frac{r_n(1-s)-i}{1+i} - e \right] \tag{4.7}$$

where: r = The discount rate
e = Relative price fluctuation factor (index deviation)
r_n = Nominal financing interest rate (interest rate on loans, alternative investment interest rates)
s = Tax factor (marginal tax)
i = General inflation

4.3.4 Calculation of global costs

The calculation procedure described in standard NS-EN 15459 (2017) provides a set of equations to use for the cost performance assessment [12]. The equations consist of several parameters that are to be described in this section. Due to the complexity of the combinations and the different parameters, such as the investment cost spans, a calculation program has been developed in Excel based on the equations. Table A.2 in Appendix A.2 shows the combination investment costs considered in the calculation of global costs. The main results outputted of the Excel program are global costs and payback time. Table 4.9 shows a summary of the parameters needed for the calculation program.

Table 4.9: *Parameter values used as input for calculation of cost performance*

Parameter	Value
Calculation period (TC) [years]	20
Inflation rate [%]	2
Real discount rate [%]	3
Present value factor at the end of TC [-]	14.88
Discount factor at the end of TC [-]	0.55
Electricity price [NOK/kWh]	1

Discount factor

The discount factor D_f_i is used to discount the residual value or replacement cost of a technology in a year i back to the starting year. RAT_{disc} is the discount rate used in this master's thesis. If a technology needs to be replaced, Equation (4.8) is used with i as the year of replacement. For the equation of residual value, Equation (4.10), a discount factor with i set as the calculation period has to be used. With a discount rate of 3% and a calculation period of 20 years, the discount factor at the end of the calculation period was 0.55, shown in Table 4.9.

$$D\_f_i = \left(\frac{1}{1 + RAT_{disc}}\right)^i \tag{4.8}$$

where: D_f_i = The discount factor
RAT_{disc} = The discount rate
i = Number of years from starting year

Present value factor

The present value factor $PVAL\_f_{TC}$ is an annuity factor that depends on the discount rate RAT_{disc}. This factor is used to find the reduction of value of annual costs throughout the calculation period TC. With a discount rate of 3% and a calculation period of 20 years Equation (4.9) outputted a present value factor of 14.88, as shown in Table 4.9.

$$PVAL\_f_{TC} = \frac{1 - (1 + RAT_{disc})^{-TC}}{RAT_{disc}} \tag{4.9}$$

where: $PVAL\_f_{TC}$ = The present value factor
RAT_{disc} = The discount rate
TC = The calculation period j

Residual value

The residual value VAL_{fin} is determined by discounting the straight-line depreciation of the initial investment V_0 until the end of the calculation period. In this master's thesis, the lifetime expectancy LS of a technology is never twice as low as the calculation period, meaning only one possible replacement is considered. When the lifetime expectancy is lower than the calculation period, a discounted replacement cost will be included in global costs. If so, the replacement cost is considered as the initial investment cost in the calculation of residual value. When the lifetime expectancy of a technology or a replaced technology coincides with the calculation period, the residual value is zero. Otherwise, Equation (4.10) is used to find the residual value at the end of the calculation period for a specific technology.

$$VAL_{fin} = V_0 \cdot (1 + RAT_{pr})^{n \cdot LS} \cdot \left[1 - \frac{(TC - n \cdot LS)}{LS}\right] \cdot D\_f_{TC} \tag{4.10}$$

where:
VAL_{fin} = The residual value
V_0 = The initial investment
RAT_{pr} = The rate of development of technology price
n = The number of replacements throughout the calculation period
LS = The lifetime expectancy
D_f_{TC} = The discount factor at end of calculation period

In Equation (4.10) the development rate of technology price RAT_{pr} was set equal to the inflation. As mentioned, the number of replacements n will always be zero or one in this master's thesis. D_f_{TC} is the discount factor at the end of the calculation period TC.

This equation deviates a bit from the standard, as the standard NS-EN 15459 (2017) seems to have made a different interpretation of linear depreciation compared to our intuition. The fraction of the initial investment cost or replacement cost that remains at the end of the calculation period is the residual value, according to our intuition. Whereas the equation given in standard NS-EN 15459 (2017) outputs the fraction of the investment cost already depreciated within the calculation period [12].

To give an example: A calculation period of 20 years and a technology with a lifetime expectancy of 15 years is considered. Consequently, the technology must be replaced after 15 years. At the end of the calculation period, 10 years are remaining of the replaced technology's lifetime expectancy. Our intuition is that the residual value is at what price one can possibly resell the technology at the end of the calculation period. This corresponds to 2/3 of the last investment cost. By using the standard this turns out to be 1/3 of the last investment cost. This represents the number of years between the last replacement and the end of the calculation period.

Global costs equation

Global costs, CG, is a measure of the costs of the whole life cycle (i.e., calculation period) induced by a collection of different components. The collections considered in this master's thesis were HVAC-combinations. There was a span of investment costs which led to a span in global costs producing three results per combination. This means that a total of 18 results of global costs were calculated per considered combination.

$$CG = CO_{INIT} + \sum_{j} \left[\sum_{i=1}^{TC} \left[CO_{a(i)}(j) \cdot \left(1 + RAT_{xx(i)}(j)\right) \cdot D\_f(i) \right] - VAL_{fin_{TC}}(j) \right] \tag{4.11}$$

where:
CG = The global costs (referred to starting year T_0)
CO_{INIT} = The sum of all technologies' investment costs in a combination
$CO_{a(i)}$ = The annual cost year i for technology j
RAT_{xx} = The price development year i for technology j, which is set equal to inflation
$D\_f(i)$ = The discount factor year i
$VAL_{fin_{TC}}$ = The residual value of technology j at the end of calculation period TC

Excel calculation program

To obtain the global cost results, an Excel program performing the calculation was developed. It will now be described in detail. Firstly, it contained one sheet for each combination and one sheet where the common parameters (shown in Table 4.9) are set. This made it easy to change parameters such as discount rate, inflation rate and electricity price. By using the discount rate, the present value factor and discount factor were calculated at the end of the calculation period using Equations (4.8) and (4.9). In the sheet with common parameters, all output from IDA ICE was also included, which was the base for calculations of energy costs. The global costs were calculated by dividing Equation (4.11) into separate calculation steps.

All 8 combination sheets contain the same method of calculating global costs. First, the technologies' investment cost spans, percentages of maintenance costs and lifetime expectancies were input for each combination. Then, the investment cost spans for the whole combination were established by summing the spans of each technology. The next step was to implement the maintenance cost spans, which were multiplied by the present value factor in order to be discounted. Ultimately, the discounted maintenance costs for each technology were summed up for the whole combination. The result was the total discounted maintenance costs for a given combination during the calculation period.

Enova support was subtracted from the investment costs in the combinations generating support. If more than one technology fulfilled the requirements of support from Enova, the sum was considered for the combination. It was also adjusted such that it was not possible to get more support for a single technology than its respective investment costs.

The next step was to calculate the replacement cost of each technology, assuming there was one. If the lifetime expectancy is strictly lower than the calculation period, a replacement cost will be induced. As replacement costs depend on investment costs, this also led to a span in replacement costs. For those technologies inducing replacement, the resulting span was discounted. The discount factor used for discounting the replacement costs is dependent on the year of replacement. In addition, the development of technology price was accounted for, i.e., the inflation rate in this project. If the lifetime expectancy was equal to or larger than the calculation period, the technology's replacement cost was set to zero. By summing the replacement costs of each technology, the span of replacement costs for the whole combination was calculated.

Finally, the calculation of residual values was done for each technology. This was done by using Equation (4.10) if and only if the lifetime expectancy of a technology or a technology's replacement was greater than the calculation period. Otherwise, the residual value was set to zero. The total residual value for a combination was calculated by summing each technology's residual value.

In order to calculate the energy costs, the output from IDA ICE simulations was used. For each combination, there were six different energy costs. This was because of the two case houses each being considered with three different retrofitted scenarios. The annual energy costs for a combination in a specific scenario were found by multiplying the annual simulated energy consumption with the electricity price given in Section 4.3.3 Then, the energy costs were multiplied with the present value factor to find the total discounted energy costs throughout the calculation period.

The global costs for the scenario considered were ultimately found by summing a combination's investment cost, discounted maintenance cost, discounted replacement cost and the respective discounted energy cost and thereafter subtracting the discounted residual value. The global cost spans are created based on the investment cost spans and the respective discounted minimum, maximum and mean values of the maintenance costs, replacement costs and residual values.

4.3.5 Calculation of payback time

Another measure of the cost effectiveness of an HVAC-combination is the payback time PB. This describes how many years it takes until the buyer has saved enough on running costs to cover the initial investment. The running costs are defined as all annual costs after the initial investment. The amount of money saved is the difference between the running cost of the new combination versus the reference case. A new HVAC-installation is most likely to lower the energy demands and therefore lower the energy costs. Equation (4.12) shows the equation given in standard NS-EN 15459 (2017) [12] which includes the discount rate to give a more realistic payback time.

$$PB = \ln\left(\frac{1}{1-\frac{(CO_{INIT}-CO_{INIT,ref})\cdot RAT_{disc}}{CF}}\right)\cdot\frac{1}{\ln\left(1+RAT_{disc}\right)} \tag{4.12}$$

where:
- PB = The payback time
- CO_{INIT} = The initial investment costs for a combination
- $CO_{INIT,ref}$ = The initial investment costs for a reference case, which in this project is set to zero
- RAT_{disc} = The price development for year i for technology j, which is set equal to inflation
- CF = The constant difference of annual running costs between option and reference case

The reference case used in these calculations was scenario EXISTING with the existing HVAC-combination, implying no initial costs. Due to a lack of information on the reference case, the maintenance costs were not considered in the calculations of payback time. This means that the payback time, in this thesis, only depended on the initial investment costs of an HVAC-combination (Table A.2, Appendix A.2), inflation rate and the difference in energy costs between the retrofitted scenarios and scenario EXISTING. For the record, simple payback time in Equation (4.13) has been used as a reference for comparison, reassuring the calculations are done correctly. Simple payback time is found when dividing the investment costs by the difference in energy costs.

$$SPB = \frac{CO_{INIT}}{(CO_{ENERG,ref} - CO_{ENERG})} \tag{4.13}$$

where: SPB = Simple payback time
CO_{INIT} = The initial investment costs for a combination
$CO_{ENERG,ref}$ = The energy costs per year for reference case
CO_{ENERG} = The energy costs per year for the combination and scenario considered

The argument of a logarithmic function needs to be greater than zero. Otherwise, the results will become undefined. This is an important condition in Equation (4.12), describing payback time. Furthermore, if the argument of the logarithmic function in Equation (4.12) is between 0 and 1, the payback time will become negative. If this argument is equal to 1, the payback time will be zero. This means that the argument of the logarithmic function needs to be greater than 1 in order to get a real payback time. Therefore, the condition in Equation (4.14) and the condition in Equation (4.15) need to hold due to the constraints described. If one of these conditions does not hold or the calculated payback time is longer than 50 years, the payback time is set to be a maximum of 50 years.

$$RAT_{disc} > 0\% \tag{4.14}$$

$$\frac{(CO_{INIT}) \cdot RAT_{disc}}{(CO_{ENERG,ref} - CO_{ENERG})} < 1 \tag{4.15}$$

As mentioned in Section 4.1.2, the heated areas of the retrofitted scenarios were increased compared to scenario EXISTING. Therefore, the energy costs per heated area were used in the calculation of payback time to give a fair representation of the payback time of the investment. To be specific, the energy costs of scenario EXISTING were divided by the heated area of the respective existing houses, whereas the energy costs of the retrofitted scenarios were divided by the retrofitted area. The investment costs are divided by the area of the retrofitted scenarios.

4.3.6 Cost effectiveness

The most cost-effective combination depends on the scenario considered. When discussing which combination is the most cost-effective, both the global costs and the payback time of the combinations were considered. To clarify, it is the combination with the lowest global cost results that is the most cost-effective. This is because the global costs is a measure of the total amount of expenses there are during the calculation period when investing in an HVAC-combination. The global costs do not indicate the profitability of an investment. Therefore, payback time needs to be considered in addition to global costs. The shorter the payback time, the shorter it takes until the investment is profitable compared to the existing circumstances. Therefore, low payback time is considered a competitive advantage [68]. However, this does not mean that the other combinations are unprofitable. The profitability is defined by whether the payback time of the combination is longer or shorter than the calculation period. If a payback time is less than the calculation period, the investment is considered profitable compared to the reference case [12]. Hence, an analysis of both the global costs and payback time should give an idea of the most cost-effective combination of the considered scenario.

4.4 Analysis of prebound and rebound effects

In this section, the methodology of considering the prebound and rebound effects is described. To be clear, the effects on the cost performance assessment will be taken into account in its own analysis after presenting the results without prebound and rebound, defined as the original results.

Based on the literature findings in Section 2.7, several studies suggest that the output from simulation and field measurements (performance gap), depends on the energy demand of the building [48][49][50]. In the OPPTRE-project, five of the six detached wooden dwellings had information on measured energy consumption. Unfortunately, the dwelling not measured was the Malvik house, which was used as case house in this thesis. Therefore, the prebound and rebound effects were taken into account through a standardized approach.

Sunikka-Blank et al.'s study is more extensive than Sandberg et al.'s study. However, since the effect is often dependent on the sociocultural circumstances, the degrees of prebound and rebound analyzed in this master's thesis are based on Sandberg et al.'s Norwegian study. First, the "measured energy consumption" of the buildings was calculated based on the thermal adaptation factor trend line described in Equation (2.1) (from Section 2.7). Then, by using the relations described in Equation (4.16) and (4.17), the prebound and rebound effects were found. For the sake of simplicity, one thermal adaptation factor was considered for the existing houses and one factor was considered for all the retrofitted scenarios.

The prebound effect is a phenomenon that may occur for houses with high energy demand, i.e., scenario EXISTING. To find the "measured energy consumption" corresponding to the existing houses, the mean value of the calculated energy consumption of the Kristiansand and Malvik case houses was estimated. Then inserting the "measured" and calculated energy consumption into Equation (4.16) resulted in a prebound effect of 23%. Accordingly, the prebound effect will be compensated for by decreasing the calculated energy consumption by 23% for each house in scenario EXISTING.

$$\text{Prebound factor} = 1 - \frac{\text{"Measured" energy consumption}}{\text{Calculated energy consumption}} = 0.23 \tag{4.16}$$

As regards the retrofitted scenarios, the mean calculated energy consumption was based on all scenarios and combinations. Similarly, the mean calculated energy consumption was inserted into Sandberg et al.'s trend line, Equation (2.1) and the "measured energy consumption" was found. The rebound factor was then calculated to be 25%, based on Equation (4.17). Thence, the rebound effect was taken into account by increasing the calculated energy consumption of scenarios TEK10÷, OPPTRE and PASSIVE with 25%.

$$\text{Rebound factor} = \frac{\text{"Measured" energy consumption}}{\text{Calculated energy consumption}} - 1 = 0.25 \tag{4.17}$$

Results

In the following chapter, the output of the simulations is to be presented. Then, the results of the cost performance assessment are introduced, both global costs and payback time. Lastly, the effects of prebound and rebound will be presented.

5.1 Energy analysis

The output of the IDA ICE simulations considered in this thesis is the total energy consumption in kWh per year and annual specific energy consumption (SEC) in kWh per heated area of each combination. The simulation outputs were used to retrieve an estimation of energy costs. These results are defined as the original results without the effects of prebound and rebound.

5.1.1 Simulation output of scenario EXISTING

In Table 5.1, the energy consumption of the existing houses is shown. It is possible to notice that the total energy consumption in the Malvik house is lower than in the Kristiansand house. This is because the Malvik house is smaller. However, the specific energy consumption shows the opposite. The Malvik house has a higher specific energy consumption than the Kristiansand house because of the poorly insulated basement leading to large heat losses. Additionally, the unheated basement is not accounted for when dividing by the heated area, leading to greater specific energy consumption.

Table 5.1: *Simulated annual energy consumption of the existing houses used for calculations of payback time*

Existing case house	Kristiansand	Malvik
Total energy consumption [kWh/year]	32920	18207
Specific energy consumption [kWh/m^2/year]	246	292

5.1.2 Simulation output of the retrofitted scenarios

Figure 5.1 illustrates the specific energy consumption when each of the combinations is implemented in the different scenarios. The specific energy consumption is given in kWh per heated area per year. The heated areas are based on the retrofitted case houses as defined in Section 3.1.

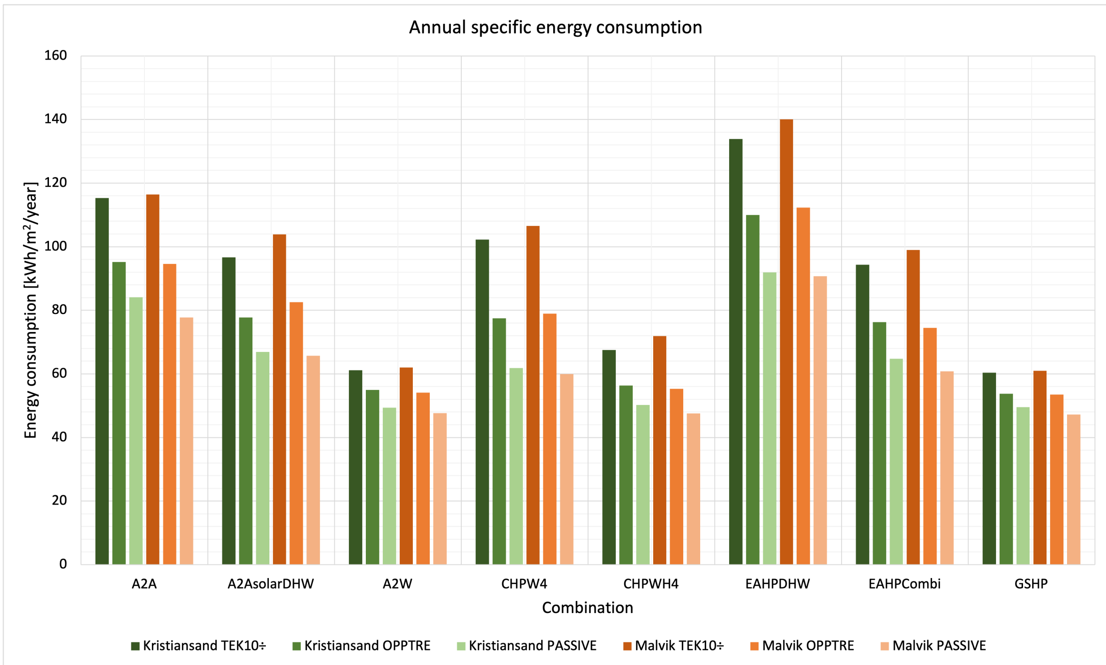

Figure 5.1: *Simulation output: Annual specific energy consumption [kWh/m^2]*

From Figure 5.1, it is possible to see that scenario TEK10÷ leads to the highest specific energy consumption for all combinations, whereas scenario PASSIVE leads to the lowest. The combinations inducing the overall lowest specific energy consumption are combinations A2W, CHPWH4 and GSHP. This is true for both case houses. On the other hand, the combinations A2A and EAHPDHW are leading to the highest overall specific energy consumption. Furthermore, it is possible to see that some of the combinations are more affected as regards energy consumption when changing scenario. This applies to both houses and includes the combinations A2A, A2AsolarDHW, CHPW4, EAHPDHW and EAHPCombi.

It is also possible to notice some individual differences between the case houses in Figure 5.1. For all combinations in TEK10÷, the Malvik house has higher specific energy consumption. On the contrary, the Kristiansand house has higher specific energy consumption for all combinations in PASSIVE. Regarding scenario OPPTRE, the question of which of the case houses has the highest/lowest specific energy consumption depends on the combination.

The nZEB requirement of energy consumption was proposed to be at a maximum of 40 kWh/m^2 [42]. Looking at Figure 5.1, none of the combinations in neither of the scenarios nor case houses are able to fulfill the nZEB requirement. However, as mentioned in Section 2.5, this is only a proposal as the nZEB definition is still under development. It should be pointed out that some combinations in scenario PASSIVE are close to fulfilling the nZEb requirement of energy consumption: A2W, CHPWH4 and GSHP in both case houses.

5.2 Global costs

Two figures were made to illustrate the original results of the global costs calculations without the effects of prebound and rebound, one figure for each case house. In common for the two figures is the layout. The figures show the global costs of an HVAC-combination compared to the energy consumption of the case house where this is implemented. For each combination, there are three marked points. For these three points, the energy consumption is the same, only the global costs are varying due to the span in investment costs. The three points represent the minimum, maximum and mean investment costs. The lowest point is the minimum global cost of the HVAC-combination. The highest point is the maximum global cost, and the point in between is referring to the global cost of the mean market investment cost. The three retrofitted scenarios are shown in the figures and have different indicators, TEK10÷ is represented by circles, OPPTRE is represented by triangles and PASSIVE is represented by crosses.

5.2.1 Kristiansand

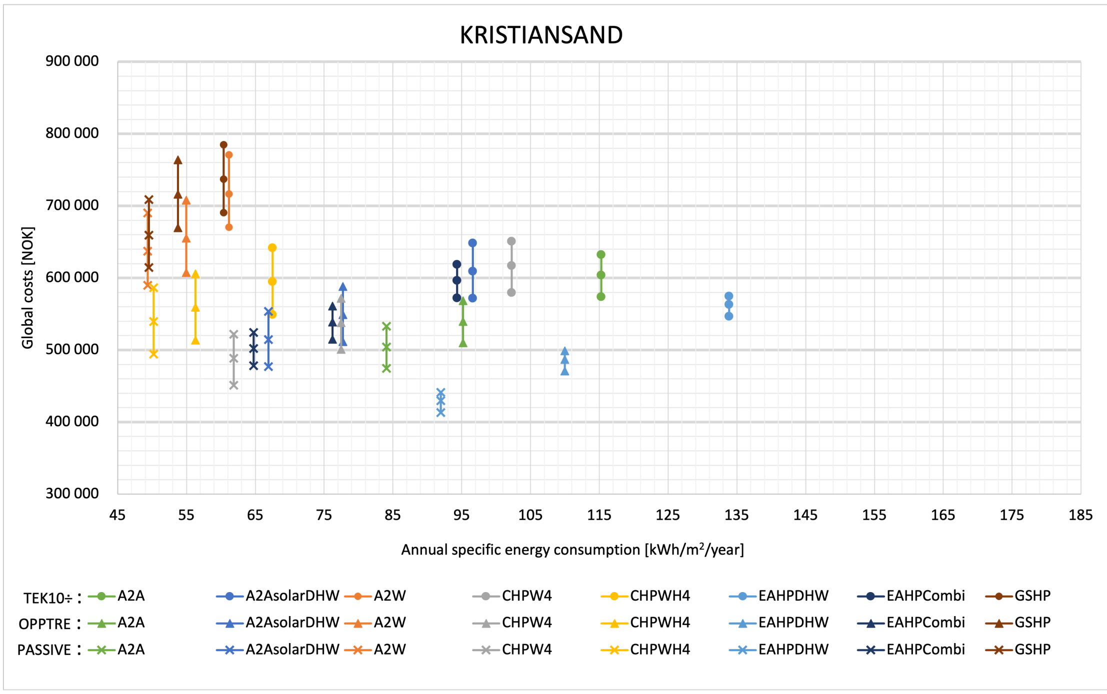

Figure 5.2: *Global costs - Kristiansand house*

Figure 5.2 shows the global costs of each HVAC-combination for the Kristiansand house. The combination with the overall lowest global costs is EAHPDHW in scenario PASSIVE. In addition to EAHPDHW, combinations CHPW4, A2A and A2AsolarDHW are also competitive as regards global costs. EAHPDHW is also the combination with the lowest global costs in OPPTRE, but none of the other combinations are competitive as regards global costs in this scenario. On the other hand, there are several competitive combinations in scenario TEK10÷. The combinations with the lowest global costs in this scenario are EAHPDHW, CHPWH4, A2A, EAHPCombi, A2AsolarDHW and CHPW4. The highest global costs are induced by GSHP and A2W in all three scenarios. It is possible to see from Figure 5.2 that GSHP, A2W and CHPWH4 have relatively similar energy costs in OPPTRE and PASSIVE. However, in TEK10÷, the energy costs of CHPWH4 are significantly higher.

When changing scenario from TEK10÷ to OPPTRE and from OPPTRE to PASSIVE, the energy consumption, i.e. the energy cost, for each combination is reduced. Hence, the global costs are also reduced when changing scenarios from TEK10÷ to OPPTRE and from OPPTRE to PASSIVE. The combinations with the greatest difference in global costs when changing the scenario are EAHPDHW and A2A. In contrast, the global costs of the combinations A2W and GSHP do not change significantly when changing scenario.

5.2.2 Malvik

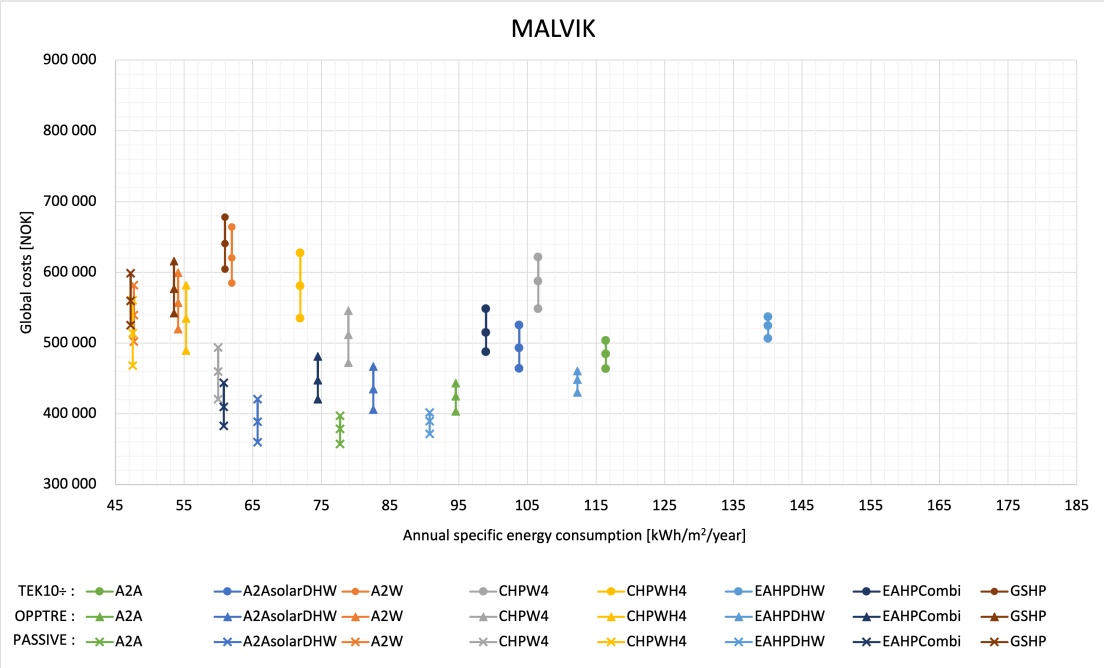

Figure 5.3: *Global costs - Malvik house*

Figure 5.3 shows the global costs of each HVAC-combination for the Malvik house. The combinations with the lowest global costs in scenario PASSIVE are combination A2A, A2AsolarDHW and EAHPDHW. These combinations also have the overall lowest global costs. In OPPTRE, the combinations with the lowest global costs are A2A, A2Asolar, EAHPDHW and EAHPCombi. These combinations are also competitive as regards global costs in TEK10÷. The highest global costs are induced by GSHP, A2W and CHPWH4 in all scenarios. As for the Kristiansand house, it is possible to see that GSHP, A2W and CHPWH4 have relatively similar energy costs in OPPTRE and PASSIVE. In scenario TEK10÷ (Malvik house), the energy costs of CHPWH4 are significantly greater than the energy costs of CHPWH4 in the Kristiansand house.

Similar to the Kristiansand house, when changing scenario from TEK10÷ to OPPTRE and from OPPTRE to PASSIVE, the energy costs of each combination are reduced. Hence, the global costs are also reduced when changing scenario from TEK10÷ to OPPTRE and from OPPTRE to PASSIVE. The combinations with the greatest difference in global costs when changing scenario are EAHPDHW, A2A and CHPW4. In contrast, the global costs of combinations A2W and GSHP do not change significantly when changing scenario.

5.3 Payback time

The original payback time results of the three retrofitted scenarios of Kristiansand and Malvik are shown in Figure 5.4, without the effects of prebound and rebound. Each combination has a span of investment costs which leads to a span in the payback time, calculated as described in Section 4.3. The payback time span from the minimum payback time of a combination's minimum investment cost, to the maximum payback time of a combination's maximum investment cost. In the middle of the span, there is a line indicating the payback time of a combination's mean investment cost.

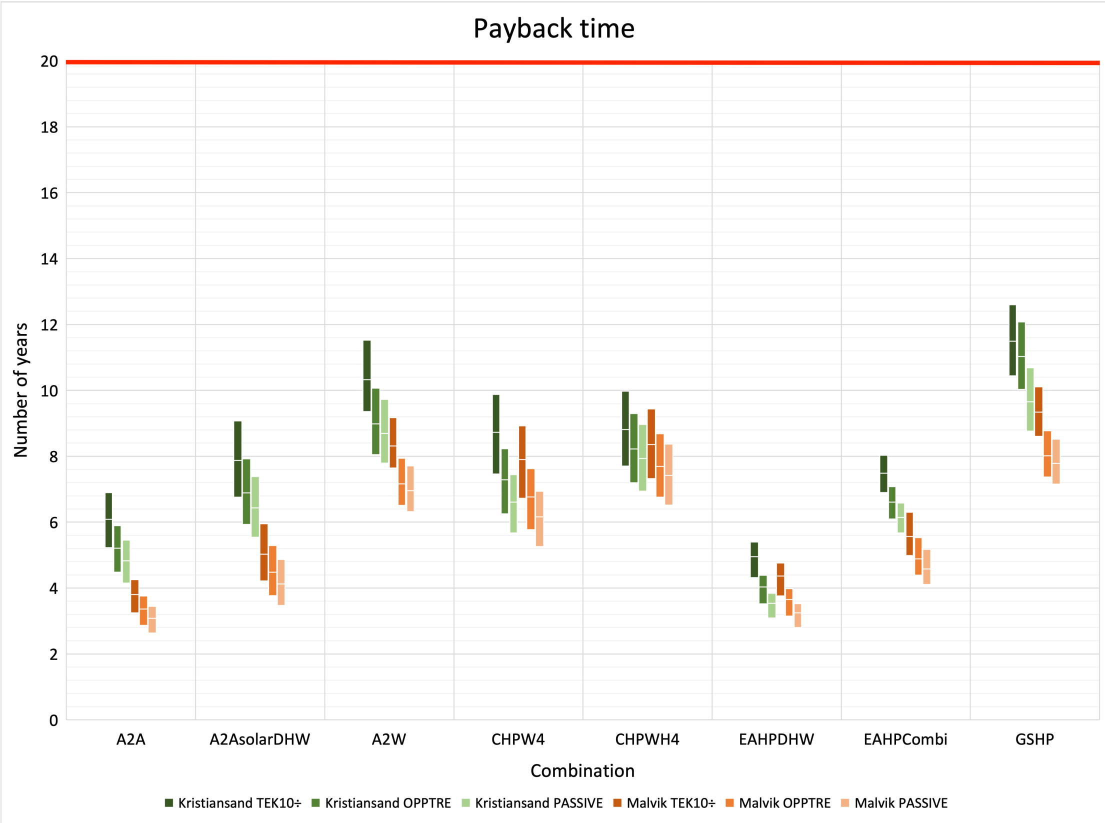

Figure 5.4: *Payback time - Kristiansand house and Malvik house*

5.3.1 Kristiansand

The most competitive combination as regards payback time is EAHPDHW in all scenarios of the Kristiansand house. The shortest payback time overall belongs to EAHPDHW in scenario PASSIVE and is spanning from 2.8 to 3.4 years. The longest overall payback time is induced by the maximum investment cost of GSHP in scenario TEK10÷. Combination GSHP has longest payback time in OPPTRE and PASSIVE as well. Still, all combinations in all the retrofitted scenarios are profitable as the payback time does not exceed the calculation period of 20 years.

When changing scenario from the least energy-efficient scenario (TEK10÷) to the most energy-efficient scenario (PASSIVE) it is possible to notice a significant improvement in payback time. Combination CHPW4 has the greatest improvement in payback time when changing scenario.

5.3.2 Malvik

In the Malvik house, the combination with the shortest payback time is combination A2A in all three retrofitted scenarios. Combinations A2AsolarDHW, EAHPDHW and EAHPCombi, have a payback time competitive to combination A2A. The overall lowest payback time is spanning from 2.6 to 3.5 years and belongs to A2A in scenario PASSIVE. Similar to the Kristiansand house, all combinations in all scenarios are profitable having a payback time below 20 years.

When changing scenario from the least energy-efficient scenario (TEK10÷) to the most energy-efficient scenario (PASSIVE) it is possible to notice a significant improvement in payback time. Just as for the Kristiansand house, combination CHPW4 has the greatest improvement in payback time when changing scenario.

5.4 Analysis of prebound and rebound effects

In this section, the original global cost results are compared to the global cost results when taking the prebound and rebound effects into consideration. The new payback time spans with prebound and rebound will also be presented. As explained in Section 4.4, the prebound effect is affecting scenario EXISTING. The calculation of payback time is the only calculation depending on scenario EXISTING. Hence, the prebound effect only has an impact on the payback time. The rebound effect will have an impact on both the payback time and the global costs, as it affects the energy consumption of the retrofitted scenarios.

5.4.1 Global costs - Prebound and rebound effects

The global costs results when taking the prebound and rebound effects into account are presented for the Kristiansand and Malvik house in Figure 5.5 and Figure 5.6, respectively. In addition to the figures showing the global cost results with prebound and rebound effects, the original results without prebound and rebound effects are also presented. The original results are illustrated in the figure with faded colors.

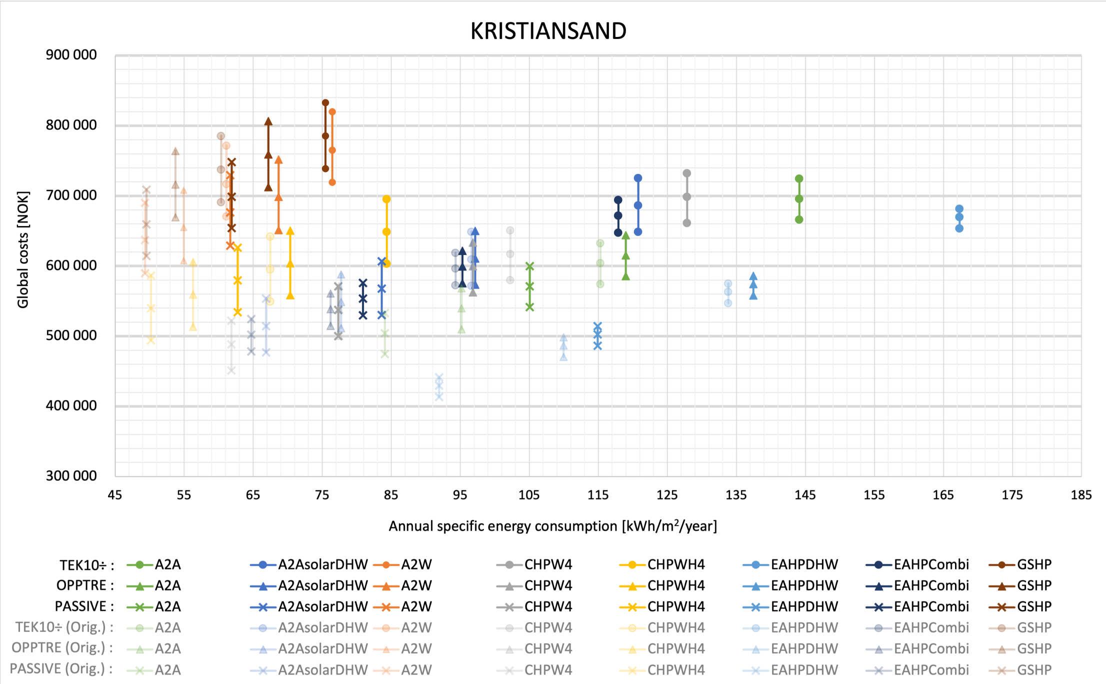

Figure 5.5: *Global costs after considering prebound and rebound effects - Kristiansand house*

Taking the prebound and rebound effects into account results in larger global costs for the Kristiansand house, as seen in Figure 5.5. Compared to the original results, there are differences in which combinations are the most cost-effective. EAHPDHW is still one of the combinations with the lowest global costs in scenario PASSIVE. However, combination CHPW4 has also become competitive in PASSIVE, when the rebound effect is introduced.

The lowest global costs of the combinations in OPPTRE belong to combinations EAHPDHW, EAHP-Combi, CHPW4 and CHPWH4. Compared to the original results, the energy costs of EAHPDHW have increased significantly in OPPTRE. Consequently, the other three combinations, EAHPCombi, CHPW4 and CHPWH4, have become as competitive as EAHPDHW. Lastly, in TEK10÷, almost all combinations have roughly the same global costs, with the exception of combinations A2W and GSHP, having somewhat higher global costs. The lowest global costs in scenario TEK10÷ belongs to combination CHPWH4.

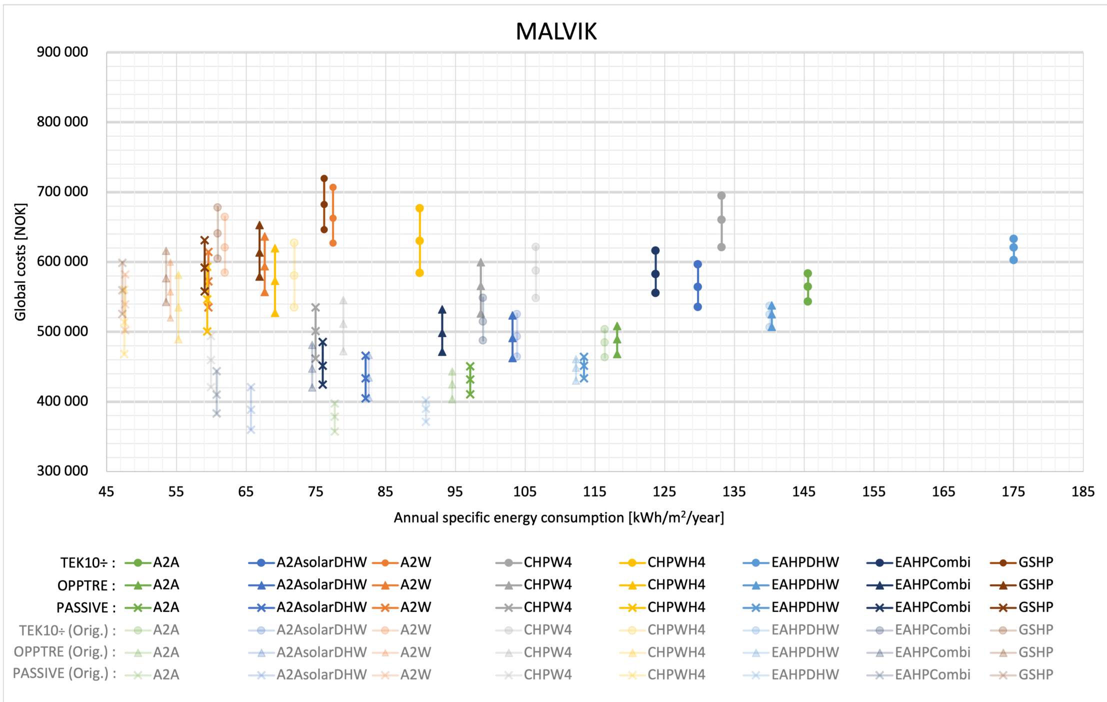

Figure 5.6: *Global costs after considering prebound and rebound effects - Malvik house*

In Figure 5.6, it is possible to see that the global costs (Malvik house) with the rebound effect are greater than in the original results. The lowest global costs are induced by A2A, A2AsolarDHW, EAHPDHW and EAHPCombi in scenario PASSIVE. Compared to the original results, EAHPCombi is now among the most competitive combinations. A2A, A2AsolarDHW and EAHPCombi induce the lowest global costs both in OPPTRE and TEK10÷.

5.4.2 Payback time - Prebound and rebound effects

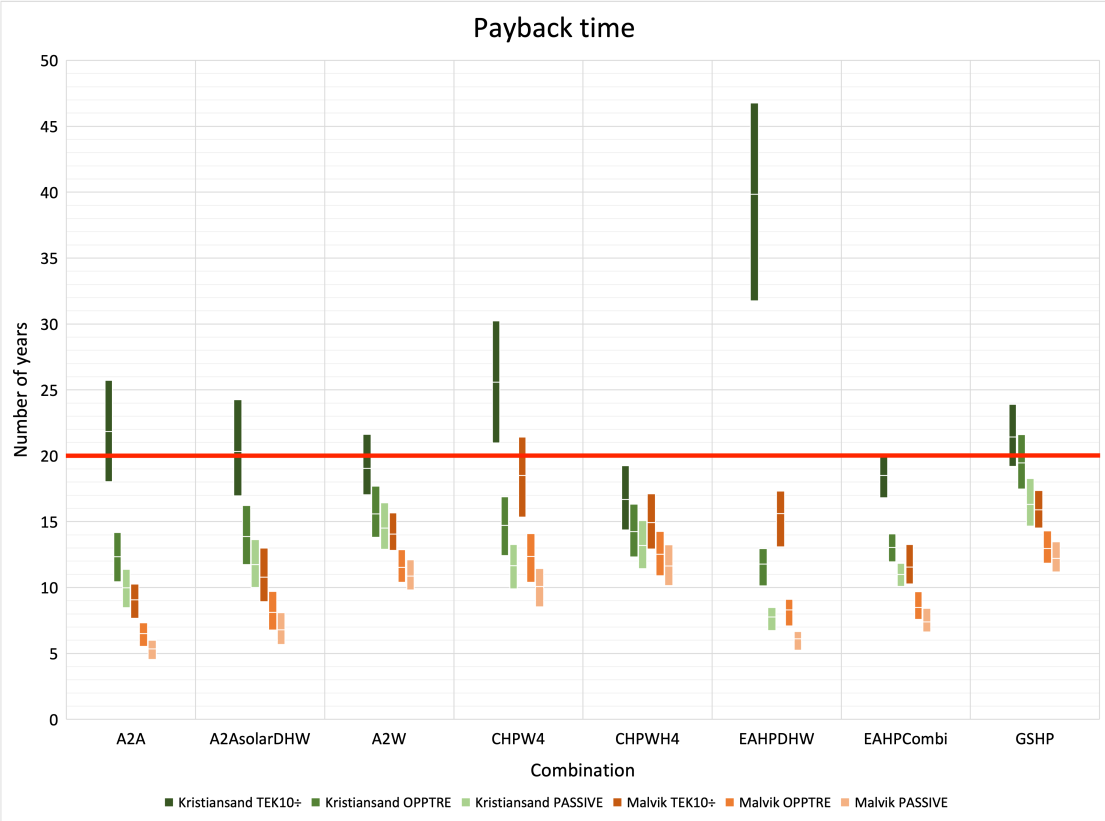

Figure 5.7: *Payback time after considering prebound and rebound effects - Kristiansand house and Malvik house*

Figure 5.7 shows the payback time results when accounting for the prebound and rebound effects. Each combination has a span of investment costs which leads to a span in the payback time, calculated as described in Section 4.3. The payback time span from the minimum payback time of a combination's minimum investment cost, to the maximum payback time of a combination's maximum investment cost. In the middle of the span, there is a line indicating the payback time of a combination's mean investment cost. There is also a red line representing the calculation period of 20 years. If the payback time of a combination's investment exceeds this line, the investment of the respective combination is not profitable.

With prebound and rebound effects accounted for, combination EAHPDHW is still the most competitive as regards payback time in scenarios OPPTRE and PASSIVE of the Kristiansand house. However, compared to the original results, EAHPDHW now has the longest payback time in scenario TEK10÷ and combination CHPWH4 is the most competitive. In fact, combination CHPWH4 is the only combination in scenario TEK10÷ where the whole investment cost span is defined as profitable as the whole span in payback time is within the calculation period.

In scenario OPPTRE, all combinations are completely within the calculation period, except GSHP. Only the lowest and mean investment costs of GSHP are deemed profitable. On the contrary, EAHPDHW is the combination with the overall shortest payback time accompanied by A2A and EAHPCombi. These combinations have a payback time ranging between 10 and 15 years.

All combinations are profitable in scenario PASSIVE of the Kristiansand house. Otherwise, there is not much difference between OPPTRE and PASSIVE in terms of payback time. GSHP has the longest payback time, and EAHPDHW has the shortest. The combination most affected by changing scenario is EAHPDHW.

The payback time results of the Malvik house have also changed with the prebound and rebound effects accounted for. In scenario TEK10÷, combination A2A is now the most competitive with the shortest payback time. Additionally, EAHPDHW and A2AsolarDHW have a relatively short payback time. The least competitive combination in TEK10÷ is CHPW4. This is the only combination with a payback time crossing the red line of profitability. It should be stressed that it is the maximum investment cost of combination CHPW4 which is deemed unprofitable.

Combination A2A is also the most competitive in scenario OPPTRE, but several combinations are close. In fact, the payback time for all combinations in OPPTRE ranges from 5 to 15 years. GSHP, CHPW4 and CHPWH4 are nevertheless the least competitive in scenario OPPTRE. When looking at PASSIVE, combinations GSHP and CHPWH4 are among the least competitive as well. In difference to scenario OPPTRE, the payback time of combination CHPW4 is relatively shorter in PASSIVE compared to combinations GSHP and CHPWH4. In PASSIVE, all combinations with either an air to air heat pump or exhaust air heat pump are competitive in terms of payback time. The combination with the overall shortest payback time is the same as for the other scenarios of the Malvik house, namely A2A.

Discussion

In this section, the results of the cost performance assessment and the energy analysis are discussed. The impact of the prebound and rebound effects, the electricity price uncertainty, the future development of investment costs and the range of discount rates are also explored through discussion and sensitivity analysis.

6.1 Energy analysis

The simulation output of IDA ICE shows a clear trend as regards scenario versus energy consumption in the retrofitted scenarios. As the scenario changes from TEK10÷ to OPPTRE or from OPPTRE to PASSIVE, the energy consumption decreases. This is due to the improved level of insulation and U-values when upgrading the scenario. Consequently, less energy is needed to heat the building. As pointed out in the results, there is a larger difference in energy consumption between TEK10÷ and OPPTRE than OPPTRE and PASSIVE. The reason for this is the deep energy retrofit package of scenario OPPTRE that leads to a level of energy efficiency closer to scenario PASSIVE than TEK10÷.

Combinations with hydronic centralized heating have a low specific energy consumption. This is due to the heat pumps covering large parts of the space heating and DHW. On the contrary, combinations covering the space heating demands with electricity have a high energy consumption, such as EAHPDHW and CHPW4. Both heat pumps in these combinations are only covering the DHW demand, and all of the space heating is therefore covered through either electric floor heating or electric panel heaters. Because of the similarities in how the heating demand is covered, one could guess that the energy consumption of the two combinations would coincide. Nevertheless, CHPW4 has heat recovery in the ventilation system, contributing to lowering the heating demand and reducing the energy consumption.

One of the reasons why the Malvik house has higher specific energy consumption than the Kristiansand house in TEK10÷, is the high U-value of the Malvik basement floor. High U-values lead to larger heat losses through the floor and thus, higher energy consumption. In OPPTRE, there were some differences in which of the case houses had the lowest specific energy consumption. The reason for this is connected to the dimensioning of the heat pumps, which will be further deliberated in the discussion of global costs, Section 6.2.1. Lastly, in PASSIVE, it was pointed out that the Malvik house had lower specific energy consumption than the Kristiansand house. This is because the Malvik basement in PASSIVE is retrofitted compared to TEK10÷ and OPPTRE, and the U-value of the basement floor is reduced significantly. Hence, there is less heat loss through the floor and the energy consumption is reduced.

In the OPPTRE-project, they aimed at proposing a nearly Zero Energy Building (nZEB) level for retrofit of detached wooden dwellings. With the considered scenarios and combinations in this master's thesis, the proposed nZEB requirement of specific energy consumption, mentioned in Section 2.5, was not met. However, this was only a proposal and when a national definition of the nZEB requirements is developed, the energy consumption results have to be revised. To better meet the nZEB-requirements, on-site renewable energy production such as photovoltaic panels (PV), could be introduced.

6.1.1 Environmental analysis

As mentioned in Section 2.6, the relationship between energy delivered and CO_2 emitted during operation is proportional. Because of this relationship, one will get the same results of comparing global costs with CO_2-emissions, as comparing global costs with energy consumption. This means that the combination with the highest energy consumption in operation also will be the combination with the highest CO_2-emissions in operation.

When solely taking CO_2-emission during operation into account, large emissions tied to other stages of the life cycle are left out. Doing a full life cycle analysis could give more realistic results when considering the combination with the lowest environmental impact.

6.2 Cost effectiveness

There are two measures of the cost effectiveness of an HVAC-combination used in this thesis. The first is global costs and the second is payback time. In this section, the results of these measures will be further discussed.

6.2.1 Global costs

Combination EAHPDHW seems to be the overall most cost-effective investment in the Kristiansand house. The global costs of EAHPDHW are very dependent on energy costs as electric panel heaters are covering the space heating demand. However, the investment cost of the combination is low and will therefore induce lower global costs than for example GSHP or A2W. When going from scenario PASSIVE to TEK10÷, it is possible to see that the global costs of EAHPDHW are increased drastically due to the dependency on energy costs.

Looking at combinations A2A, A2AsolarDHW, EAHPCombi, EAHPDHW and CHPW4, they have some of the lowest global costs in all the retrofitted scenarios for the Kristiansand house. In scenario TEK10÷, CHPWH4 is also among the combinations with the lowest global costs. The reason for this may be the initial high investment cost compared to the other combinations, while on the contrary having low energy costs. Therefore, CHPWH4 benefits from having both space heating and DHW covered by the heat pump. This also applies to A2W, EAHPCombi and GSHP as these heat pumps cover most of the space heating lowering the total energy consumption. However, A2W and GSHP both have greater investment costs compared to CHPWH4 and are therefore not among the group with the lowest global costs in TEK10÷.

In the Malvik house, combinations A2A, A2AsolarDHW, A2W and GSHP have a drop in global costs compared to the Kristiansand house. This is mainly because of lower investment costs in balanced ventilation for the Malvik house. The balanced ventilation system in the Kristiansand house includes two aggregates instead of one because of the studio apartment, increasing the investment costs significantly. Combinations EAHPDHW, EAHPCombi, CHPW4 and CHPWH4 do not get affected by this. A2AsolarDHW gets an additional drop in global costs when comparing Kristiansand and Malvik due to the reduction of the investment costs of the solar thermal collectors.

In scenario TEK10÷ and PASSIVE of the Malvik house, the difference in the investment cost of balanced ventilation results in a different optimal combination in terms of global costs compared to the Kristiansand house. In the Malvik house, combinations A2A, A2AsolarDHW and EAHPCombi are more cost-effective than EAHPDHW, which was not the case for Kristiansand. Another reason is that the air to air heat pump is dimensioned equally for both houses, even with different heating demands. The coverage factor of the heat pump is larger in the Malvik house than in the Kristiansand house, as mentioned in Section 4.2.1. As a result, the energy costs are slightly lower, inducing lower global costs.

The effects of dimensioning the ground source heat pump and air to water heat pumps specifically to each scenario and case house can also be seen in the global cost results. In the Kristiansand house, the ground source heat pump in combination GSHP is dimensioned equally in scenarios TEK10÷ and OPPTRE. However, the heat pump in scenario PASSIVE has a lower capacity and shallower energy well resulting in lower investment costs. This can be seen in Figure 5.2 by a larger difference in global costs between scenarios OPPTRE and PASSIVE, compared to TEK10÷ and OPPTRE. For combination A2W, this effect is the opposite due to scenarios OPPTRE and PASSIVE being dimensioned equally and TEK10÷ being dimensioned with greater capacity. In Figure 5.3, the same effect as for combination A2W (Kristiansand house) can be seen on both combinations A2W and GSHP in the Malvik house.

For both case houses, there seems to be a discontinuity with combination CHPWH4 when changing the scenario. In scenarios PASSIVE and OPPTRE, the specific energy consumption of CHPWH is close to combinations A2W and GSHP. However, this is not true for scenario TEK10÷. The relatively large increase in specific energy consumption is a consequence of the constraints in the decoupled approach of the compact heat pumps. As explained in Section 4.1.3, the compact heat pumps are modeled as exhaust air heat pumps in a decoupled approach. This means that the airflow rates decide the maximum heating capacity of the compact heat pumps, even though they also utilize outdoor heat. When the capacity is too low to cover the space heating, electric peak heating is necessary, resulting in larger energy consumption and energy costs. The discontinuity described is a direct result of this, as the combination CHPWH4 does not seem to have sufficient heating capacity in scenario TEK10÷.

6.2.2 Payback time

Many of the reasons discussed in the global cost results can be said to apply for the payback time as well. Due to low investments of combination EAHPDHW, few years are required to pay back the investment. All combinations are profitable in the Kristiansand house, and EAHPDHW is the combination with the overall shortest payback time. This could be different with a higher electricity price as there would be more to gain, in terms of energy cost reduction, on investing in a more energy-efficient and more expensive combination.

As with the global cost results of the Malvik house, several combinations are also competitive in the analysis of payback time. Again, this is due to the differences in the investment cost spans of several HVAC-technologies, especially balanced ventilation. Another reason is the fact that the simulated total energy consumption in the Malvik house is overall lower than in the Kristiansand house for all combinations in all scenarios, due to a smaller heated area. This results in slightly lower energy costs for the retrofitted scenarios of the Malvik house, causing a shorter payback time.

In both case houses, CHPW4 is the combination with the largest difference in payback time between scenarios TEK10÷ and OPPTRE. The investment costs of the HVAC-technologies included in this combination are almost identical for these two case houses. This means that the drop in payback time when increasing the energy efficiency of the building itself is solely based on improved energy conservation.

6.3 The impact of prebound and rebound

In this section, the following research sub-question is assessed: "*How do the effects of prebound and rebound affect the cost effectiveness and energy efficiency of different HVAC-combinations?*". Based on the results in Section 5.4, the appearance of either the prebound and rebound effect leads to higher payback time and lower profitability. The energy costs of scenario EXISTING decreases compared to what is simulated and the energy costs of the retrofitted scenarios increases. Therefore, taking prebound and rebound effects into account will reduce the annual savings in energy costs. Consequently, the energy retrofit will be less profitable than simulated.

In the calculations of global costs, the ratio between energy costs and investment costs is varying from combination to combination. In combinations with lower investment costs, the energy costs tend to become a significant part of the global costs. On the other hand, in combinations with higher investment costs, the energy costs are not that significant. This is why combinations with lower investment costs are more sensitive to changes in energy consumption and the combinations with the highest investment costs are the least sensitive. EAHPDHW is one of the combinations with the highest share of energy costs compared to investment costs. Hence, it is one of the combinations most sensitive to the increase in energy consumption, which again results in higher global costs. It is also possible to see that CHPW4, EAHP-Combi and CHPWH4 have become more competitive compared to the original results in the Kristiansand house. The same applies to the Malvik house.

As the global costs increase when taking prebound and rebound effects into account, the payback time increases accordingly. Therefore, the combinations with a higher share of energy costs compared to investment costs will be exposed to larger changes in payback time. In both case houses, this is the reason why A2A, CHPW4 and EAHPDHW have large differences in payback time when changing scenario from TEK10÷ to OPPTRE, and OPPTRE to PASSIVE.

CHPWH4 is not the most competitive combination in terms of payback time in the original results of scenario TEK10÷ (Kristiansand house). However, it is in fact the only combination profitable when the prebound and rebound effects are considered. This is a valuable argument for considering CHPWH4 as the optimal combination in scenario TEK10÷ of the Kristiansand house. The energy costs of CHPWH4 are low compared to the investment costs, and the payback time of the combination does not change significantly from the original results.

Even when taking prebound and rebound effects into account, almost all combinations are profitable in the Malvik house. The reason for this is mainly due to the combinations not being as dependent on the change in energy costs as the combinations in scenario TEK10÷ of the Kristiansand house. The impact on the profitability is strongly dependent on the degree of prebound and rebound effects in a house. Thus, calculating with accurate effects will give the end user a more realistic perspective on the profitability of an HVAC-combination. The fact that CHPW4 is deemed unprofitable when taking prebound and rebound effects into account in scenario TEK10÷ (Malvik house), should be considered in the discussion of optimal combination.

If measured energy consumption of a house is available, it is possible to use it for comparison when considering prebound and rebound effects. Field measurements were only available for the existing Kristiansand house. Hence, it is only possible to compare the results with the measured energy of the Kristiansand house. The measured energy use of the existing Kristiansand house and the calculated energy use in scenario EXISTING with the prebound effect are given in Table 6.1. It is possible to see that the two values are quite similar. This may be implying that the prebound effect is realistically taken into account in this thesis, which was done by decreasing the energy consumption of scenario EXISTING with 23%.

Table 6.1: *Measured energy consumption and calculated energy consumption in the Kristiansand house scenario EXISTING (with prebound effects)*

Measured energy consumption	**Calculated energy consumption**
184 kWh/m^2	189 kWh/m^2

6.4 Optimal HVAC-combination

In this section, the two following research sub-questions are discussed: "*How do different levels of building envelope energy efficiency affect the optimal HVAC-combination in terms of cost effectiveness and energy consumption?*" and "*Which HVAC-combinations are optimal considering global costs, payback time, energy consumption and environmental impact?*".

Each retrofitted scenario might have different optimal combinations when considering cost effectiveness, energy efficiency and carbon footprint. Before accounting for the prebound and rebound effects, the original results indicate that combination EAHPDHW is the most cost-effective option in all scenarios of the Kristiansand house. However, combination EAHPDHW has about twice the energy consumption of combinations A2W, CHPWH4 and GSHP, or more (depending on scenario). The carbon footprint of EAHPDHW is also the largest, meaning it is the worst option seen from an environmental perspective.

After having paid back the large investment costs of A2W, CHPWH4 and GSHP, one will gain more on the difference in energy costs than EAHPDHW. This means that these expensive combinations will turn out more profitable at one point in the future, due to lower energy consumption. Therefore, only considering the payback time could be misleading when they are all within the calculation period of 20 years.

The hardest decision when determining an optimal combination is how to weigh the different aspects. In this thesis, cost effectiveness is regarded as the most important aspect. This is due to an assumption of the general public usually being more concerned about their economy than the environment. Using this assumption, combination EAHPDHW or CHPWH4 would be the optimal combination for scenarios TEK10÷ and OPPTRE of the Kristiansand house. Including the energy and environmental aspect, EAHPDHW should be omitted because of the high energy consumption. Therefore, CHPWH4 seems to be the most optimal combination in TEK10÷ and OPPTRE. As regards scenario PASSIVE, combination CHPW4 seems to be the optimal combination when looking at both the cost effectiveness, energy efficiency and carbon footprint.

Compared to other combinations with balanced ventilation, CHPW4 and CHPWH4 could be less competitive in the Kristiansand house. This is because the investment cost spans of the compact heat pumps do not include a separate ventilation aggregate for the studio apartment. However, this is included in combinations A2A, A2AsolarDHW, A2W and GSHP. It may be preferred to have a separate aggregate for the ventilation system in the studio apartment, as it enables independent control. This means that the combinations with a compact heat pump may be less competitive as regards personal preferences. However, personal preferences are not considered in the discussion of optimal combination.

In the Malvik house, one can argue that A2AsolarDHW and EAHPCombi are the most optimal combinations for scenario TEK10÷, when weighing cost effectiveness more than energy efficiency. Nevertheless, CHPWH4 does not have that much larger global costs than these two combinations. Weighing carbon footprint and energy efficiency equal to cost effectiveness, it would seem that combination CHPWH4 is the most optimal option. The same trends can be seen in scenario OPPTRE. However, there is a larger difference in global costs between combination CHPWH4 and A2AsolarDHW/EAHPCombi, compared to scenario TEK10÷. There is also a larger difference in specific energy consumption between combinations A2AsolarDHW and EAHPCombi. Due to these differences, combination EAHPcombi could be argued to be the most optimal combination when considering both cost effectiveness and energy efficiency.

There are several combinations being cost-effective in scenario PASSIVE of the Malvik house, such as A2A, A2AsolarDHW, EAHPDHW and EAHPCombi. In terms of energy efficiency and carbon footprint, EAHPCombi would be the most optimal of these combinations. However, the gap in specific energy consumption between EAHPCombi and A2AsolarDHW is not very large and the global costs of A2AsolarDHW are slightly lower, making it somewhat difficult to determine an optimal combination.

In both case houses, combinations EAHPDHW and EAHPCombi could lead to lower indoor comfort, as cold air is directly supplied to the houses through cracks and vents. This is due to the negative pressure being caused by the exhaust air heat pump, as mentioned in Section 2.4.1.

With the prebound and rebound effects accounted for, some changes occur as regards which combinations are optimal. Due to the rebound effect the energy costs are more dominating now that the energy consumption is increased in the retrofitted scenarios. As with the original results, combination CHPWH4 could be considered optimal for scenarios TEK10÷ and OPPTRE of the Kristiansand house. In scenario PASSIVE, combination CHPW4 could also with rebound be considered as optimal. However, CHPWH4 is more energy-efficient and does not have that much higher global costs, meaning it could be an optimal solution as well.

In all scenarios of the Malvik house, the rebound effect makes combinations A2W and GSHP very competitive as regards energy consumption. One could argue that A2W is the optimal combination in TEK10÷, as it is somewhat more cost-effective than GSHP. The situation is different in OPPTRE, where other combinations become more cost-effective as a result of larger energy costs. Combination CHPWH4 could be optimal for scenario OPPTRE, weighing the cost effectiveness more than the energy consumption. The same weighing could be applied for PASSIVE, where combinations A2AsolarDHW, CHPW4 and EAHPCombi are more cost-effective than CHPWH4, even though the energy consumption is larger. Nevertheless, EAHPCombi is the combination with the overall lowest global costs and at the same time with relatively low energy consumption in PASSIVE, arguing that EAHPCombi is the optimal combination.

The optimal combination for one house may not be optimal in another. The results show that there are many differences between the two studied case houses. In general, a detached wooden dwelling can deviate a lot more from these studied case houses. The installation of some combinations is not even possible for some houses. For instance, the installation of a ground source heat pump requires a stable ground where the heat could be extracted, and not all houses are located in such places. It can also be complicated to install a large HVAC-technology if the space is already limited. This means that this study cannot necessarily be generalized to be valid for all detached wooden dwellings.

Regarding existing contributions, Georges et al.'s study [69] came to some of the same conclusions of optimal combination. The study stated that the most attractive solutions for passive houses had moderate investment costs along with good environmental performances. This is also true in all retrofitted scenarios of both case houses in this thesis.

6.5 Parameter sensitivity

The sensitivity of the electricity price and the discount rate is explored in this section. These are dynamic parameters that are dependent on many uncertain variables. That is why it is important to redo the calculations with other values for these parameters. The global costs and payback time of each combination are calculated once more with new parameter values. In addition to showing the new global cost results in the figures, the original results are also presented. The original results are illustrated in the figure with faded colors. Prebound and rebound effects are not considered in the sensitivity analysis.

6.5.1 Variations in electricity price

The electricity price is changing constantly and depends on location, season, weather and the power market in general. When the power grid in Norway is more connected with the European power grid, the local electricity price will depend more on the European power market. Since the European electricity prices are higher, there might be an increase in Norwegian electricity prices as well. The relatively high electricity prices in Europe can be due to countries using less renewable power sources compared to Norway [19].

As mentioned in Section 2.6, ambitious climate goals are demanding a reduction in fossil power production in Europe [45]. This might introduce higher electricity prices for countries producing electricity by the means of fossil energy. However, the European electricity price might also decrease as a result of Europe introducing more renewable power sources. All this uncertainty implies that the sensitivity of the electricity price is important to consider in the discussion of the results.

An increased electricity price will increase the energy costs of each combination. How much the global cost increases, depends on the combination considered. For a combination with large investment costs and low energy costs, an increase in electricity price will not affect the global cost much. However, for a combination where the energy cost makes up a large part of the global costs, the relative increase will be greater. This means that with an increased electricity price, some combinations might end up being cheaper than others in terms of global costs. In this master's thesis, the energy consumption is not dependent on the electricity price, meaning it stays constant in the calculations. However, this is not consistent with the actual occupancy behavior. If the electricity price were to increase by 200%, the electricity bill would be tripled, and a household would most likely begin to consume less power.

The effects of an increase of 0.5 NOK/kWh

The electricity price is probably due to increase at some point. If a relative increase of 0.5 NOK/kWh were to happen, Figure 6.1 and 6.2 show the effects this would have on the global cost results. As regards the effects on payback time, these are shown in Figure 6.3. In general, the increase in the electricity price causes the global costs to increase and the payback time to decrease. This means all combinations become less cost-effective considering global costs, whereas more competitive considering payback time.

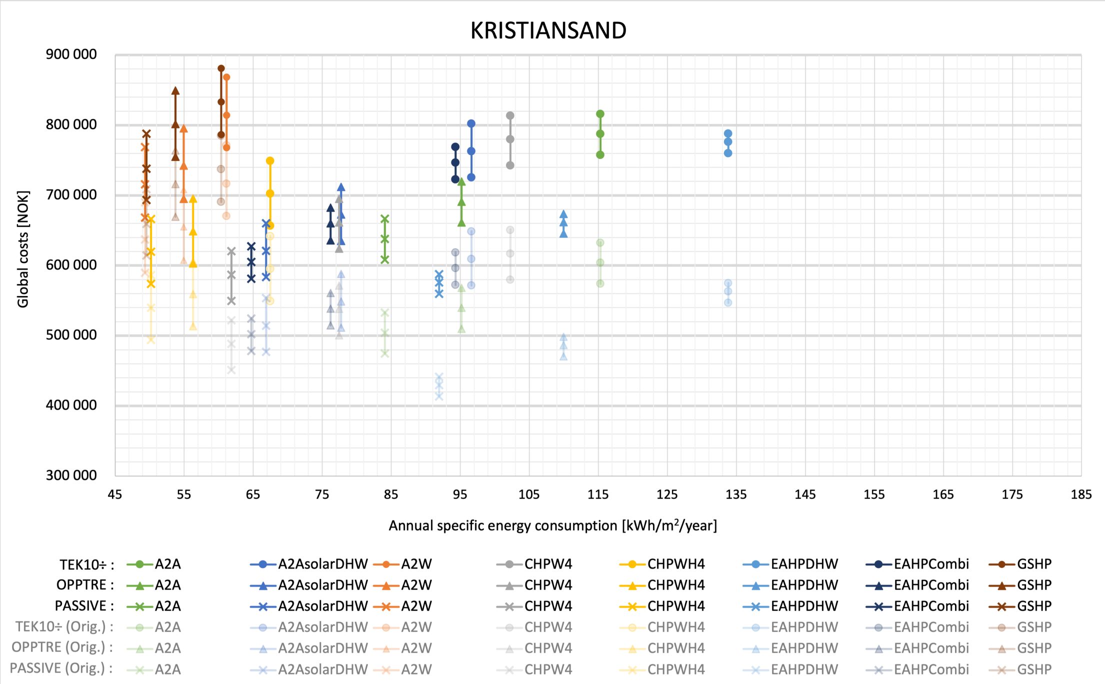

Figure 6.1: *Global costs for the Kristiansand house when increasing the electricity price by 0.5 NOK/kWh*

The Kristiansand house has the overall highest initial global costs for all combinations in all scenarios. It is also the case house having the largest increase in global costs when increasing the price of electricity. This is a direct result of the larger total energy consumption in the Kristiansand house compared to the Malvik house. Combinations with large energy costs such as A2A, CHPW4 and EAHPDHW are more affected by an increase in the electricity price. In scenario TEK10÷ of the Kristiansand house, EAHPDHW is no longer one of the combinations with the lowest global costs. Combination CHPWH4 has the lowest global cost span and simultaneously low specific energy consumption. In scenario OPPTRE, CHPWH4 is also one of the combinations with the lowest global cost span, but CHPW4, EAHPDHW and EAHPCombi are all competitive in terms of cost effectiveness. However, CHPWH4 has the lowest specific energy costs, which together with the cost effectiveness indicate that this combination is the most optimal option.

Comparing two combinations with the same energy consumption, the combination with the lowest overall global costs will be more affected by an increase in electricity price due to the greater dependency on energy costs. An example of this dependency of energy costs is shown when looking at combinations A2A and A2AsolarDHW. These combinations are somewhat similar except for the solar thermal collectors covering about 50% of DHW heating demand in A2AsolarDHW. Before the increase in electricity price, the global cost spans of these combinations are in the same range. Since A2A has a larger specific energy consumption, the situation is slightly different after the increase of electricity price, with a relative increase in the global costs of A2A. It is however not enough to determine which combination is the most cost-effective.

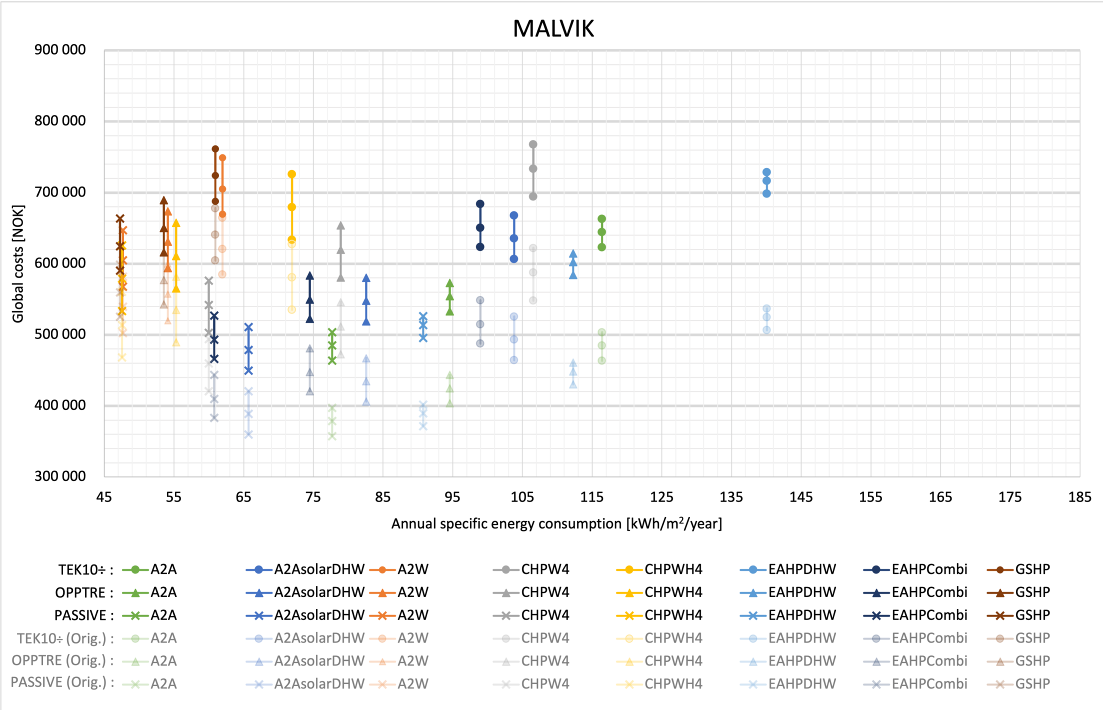

Figure 6.2: *Global costs for the Malvik house when increasing the electricity price by 0.5 NOK/kWh*

Similar to the Kristiansand house, EAHPDHW is less cost-effective in terms of global costs in all scenarios of the Malvik house. On the other hand, combination CHPWH4 is now more competitive, especially in scenarios TEK10÷ and OPPTRE. In scenario PASSIVE, the two combinations A2AsolarDHW and EAHPCombi are still the most competitive. Essentially, the further to the right a combination is in the global costs figures, the more affected they are by the increase in electricity price.

When it comes to payback time, the new electricity price will increase both the energy costs of scenario EXISTING and the retrofitted scenario. As seen in Section 4.1, the specific energy consumption of all retrofitted scenarios in both case houses is less than of the scenarios EXISTING. This means that the energy costs of the existing houses are affected more by an increase in the electricity price than the retrofitted scenarios, leading to improved energy savings. As a result, the payback time of all combinations decreases.

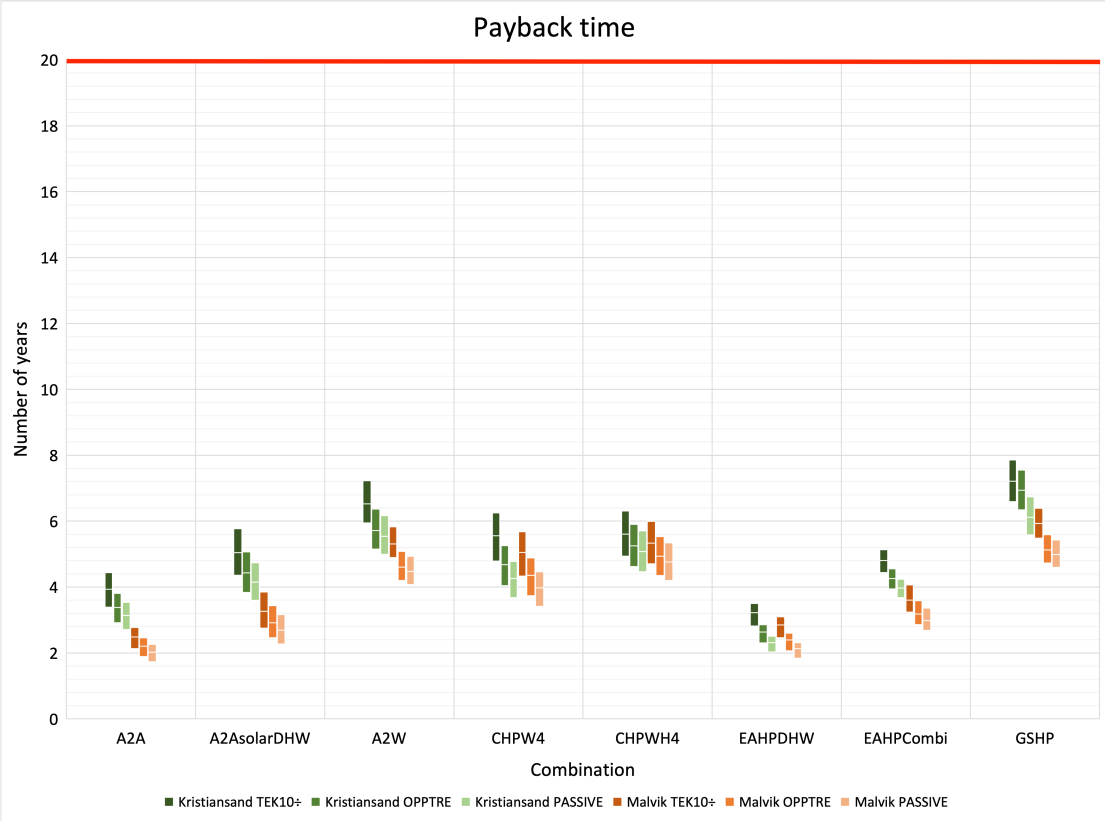

Figure 6.3: *Payback time for both case houses when increasing the electricity price by 0.5 NOK/kWh*

The combinations previously having a long payback time are the ones most affected by the increase in the electricity price. For instance, GSHP had a payback time ranging from 9 to 13 years in the original results of the Kristiansand house. This payback time is now ranging from 5.6 to 8 years. In general, all combinations have a very short payback time considering the major differences in the investment cost spans.

6.5.2 Range of discount rates

As already mentioned, the discount rate is a complicated parameter to determine as a lot of uncertain factors are at play. Initially, the discount rate was set to be 3% due to the recommendations for public projects with normal risks in Section 4.3.3. The same government document states that the discount rate could vary between 0.24% and 11%, which will result in a large variety of global costs and spans in payback time.

Utilizing Equation (4.7) in Section 4.3.3, the discount rate can be calculated from data on the different parameters involved. The marginal tax for general income was 22% in 2019 and 2020 [70]. The inflation rate may change in the years to come, but due to the cautionary principle it is set at today's rate for the calculation period. With a nominal financing interest rate on a consumer loan at about 10%, Equation (4.7) results in a discount rate of 5.69%. However, if a private individual decides to extend the bank loan instead, the interest rate is significantly lower. If the house loan has an interest rate of 3%, the discount rate turns out to be 0.5%. This shows how much the discount rate can vary just by altering the interest rate of a loan.

The effects of increasing the discount rate to 6%

Considering a discount rate resulting from Equation (4.7) with an interest rate of 10% on a consumer loan, the cost performance assessment is redone with a discount rate of 6%. The effects on global costs are shown in Figure 6.4 and 6.5. As regards the effects on payback time, these are shown in Figure 6.6.

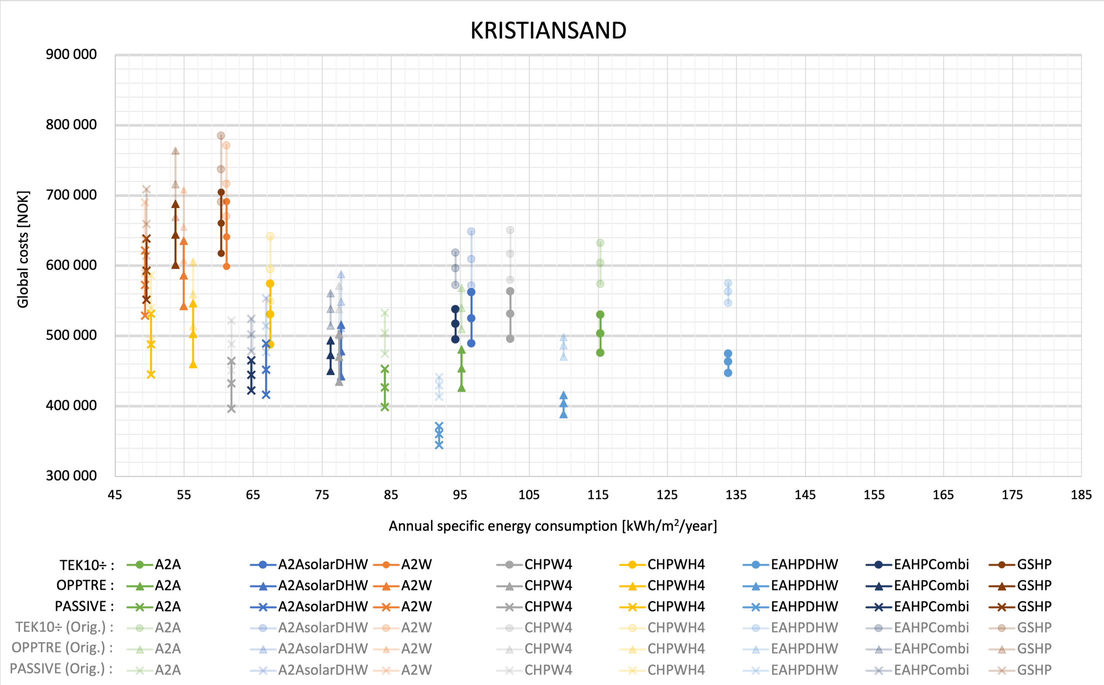

Figure 6.4: *Global costs for the Kristiansand house when increasing the discount rate from 3% to 6%*

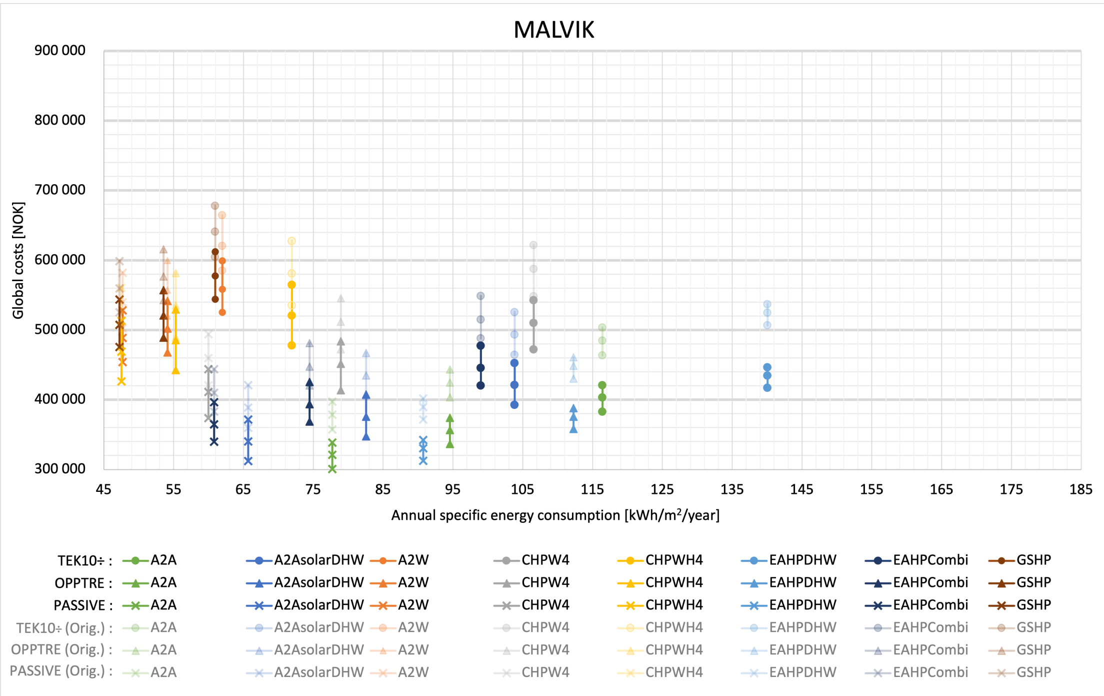

Figure 6.5: *Global costs for the Malvik house when increasing the discount rate from 3% to 6%*

As with an increase in electricity price, there are no effects on the specific energy consumption when altering the discount rate. However, the global costs are now decreasing due to a lower value of future cash flows. Instead of solely affecting the energy costs, the discount rate affects the maintenance costs, the residual values and possible replacement costs as well.

There are no major shifts in which combinations are most cost-effective in terms of global costs. The maintenance costs are given as a percentage of the investment costs. This means that large investment costs result in large maintenance costs. Combinations with great investment costs are therefore more affected by the increase of discount rate.

Combinations with large specific energy consumption will have a decrease in the global costs as well. This is because a high discount rate will reduce future energy costs, which is the opposite effect of increasing the electricity price.

The residual values and replacement costs are also affected by the discount rate. If a combination includes technologies with a lifetime expectancy less than the calculation period, the technologies are due to be replaced within 20 years. Therefore, the combinations with the largest replacement costs will be more affected by the change in discount rate, meaning the global costs will have a larger reduction. The opposite effect occurs for combinations with large residual values. The residual value is a negative value that decreases the global costs. This means that the greater the residual value, the more reduced it is by the increase of discount rate, resulting in greater global costs. This will only apply for combinations including technologies, or replaced technologies, with a lifetime expectancy above the calculation period of 20 years.

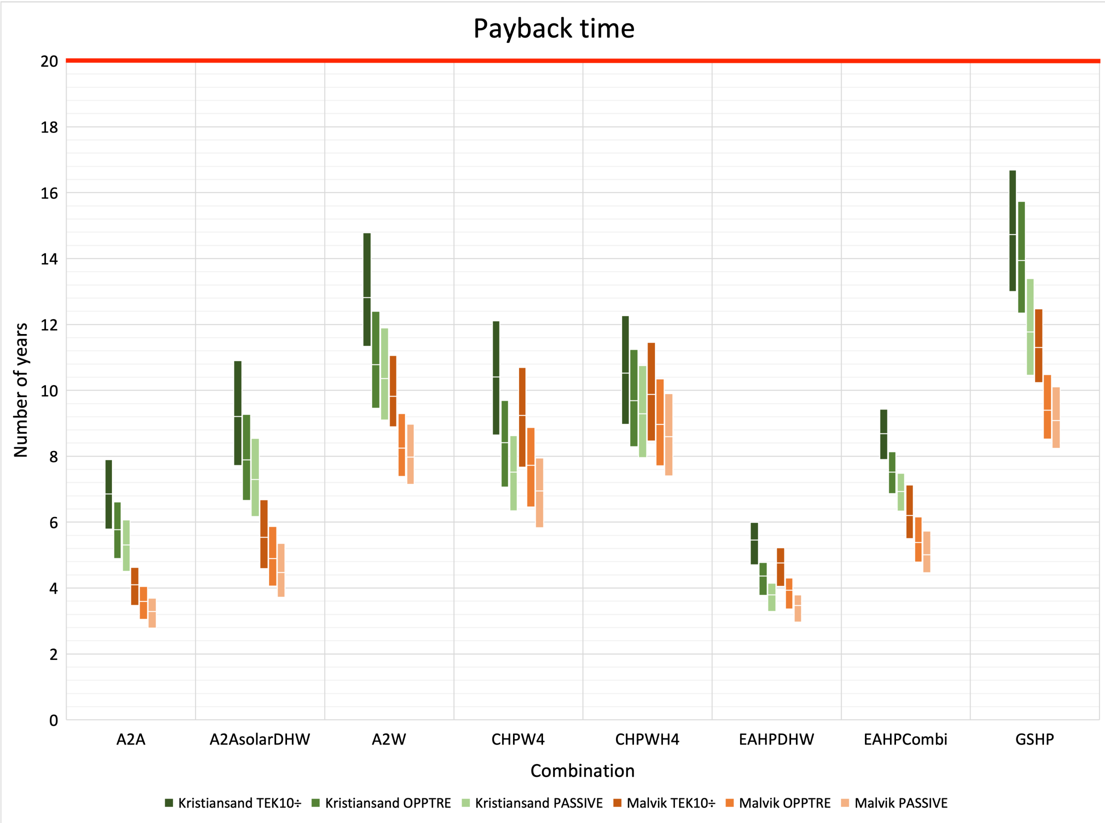

Figure 6.6: *Payback time for both case houses when increasing the discount rate from 3% to 6%*

The payback time solely depends on the investment costs, the energy costs of scenario EXISTING and the energy costs of the retrofitted scenarios. Of these costs, only energy costs are future cash flows which will be affected by the increase of discount rate. As one can see in Figure 6.6, the payback time is overall larger compared to the original results shown in Figure 5.4. This is a result of the future energy costs being decreased by the new discount rate. Scenario EXISTING has the largest energy costs and will therefore be affected more than the retrofitted scenarios. This leads to fewer savings in the energy costs difference after retrofitting the case houses, which means the payback time increases.

The effects of decreasing the discount rate to 0.5%

If Equation (4.7) is to be considered with an interest of 3% on a house loan, the resulting discount rate will be 0.5% (Section 6.5.2). Doing the cost performance assessment with the decreased discount rate will result in the overall global costs becoming larger than the original results. This is shown in Figure 6.7 and 6.8.

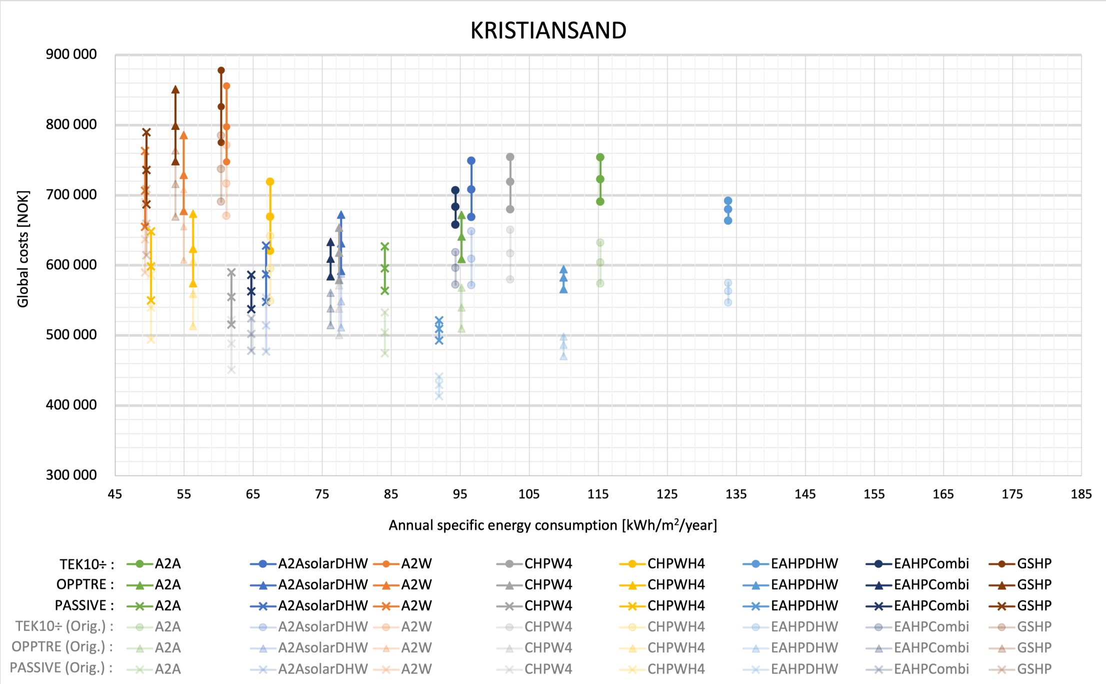

Figure 6.7: *Global costs for the Kristiansand house when decreasing the discount rate from 3% to 0.5%*

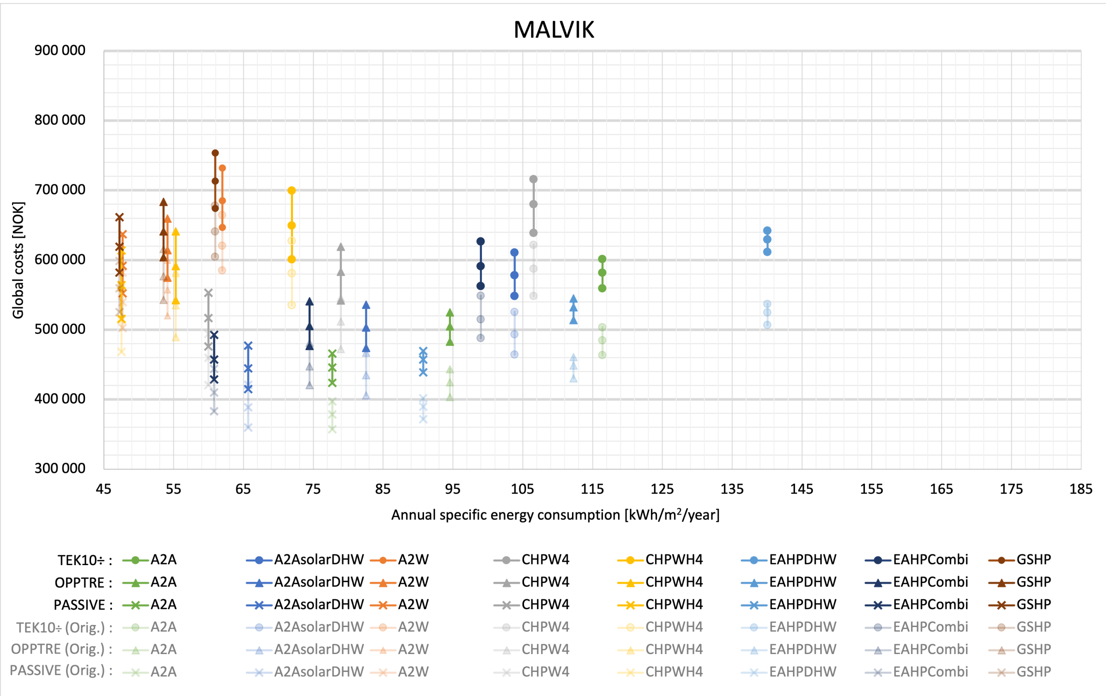

Figure 6.8: *Global costs for the Malvik house when decreasing the discount rate from 3% to 0.5%*

The global costs are now increasing due to greater values of future cash flows. The energy costs, maintenance costs and replacement costs are all increased, resulting in greater global costs. On the other hand, the residual value will reduce the global costs as it increases with decreasing discount rate. Nevertheless, the residual value does not affect the global costs that much as it is insignificant compared to the total global costs.

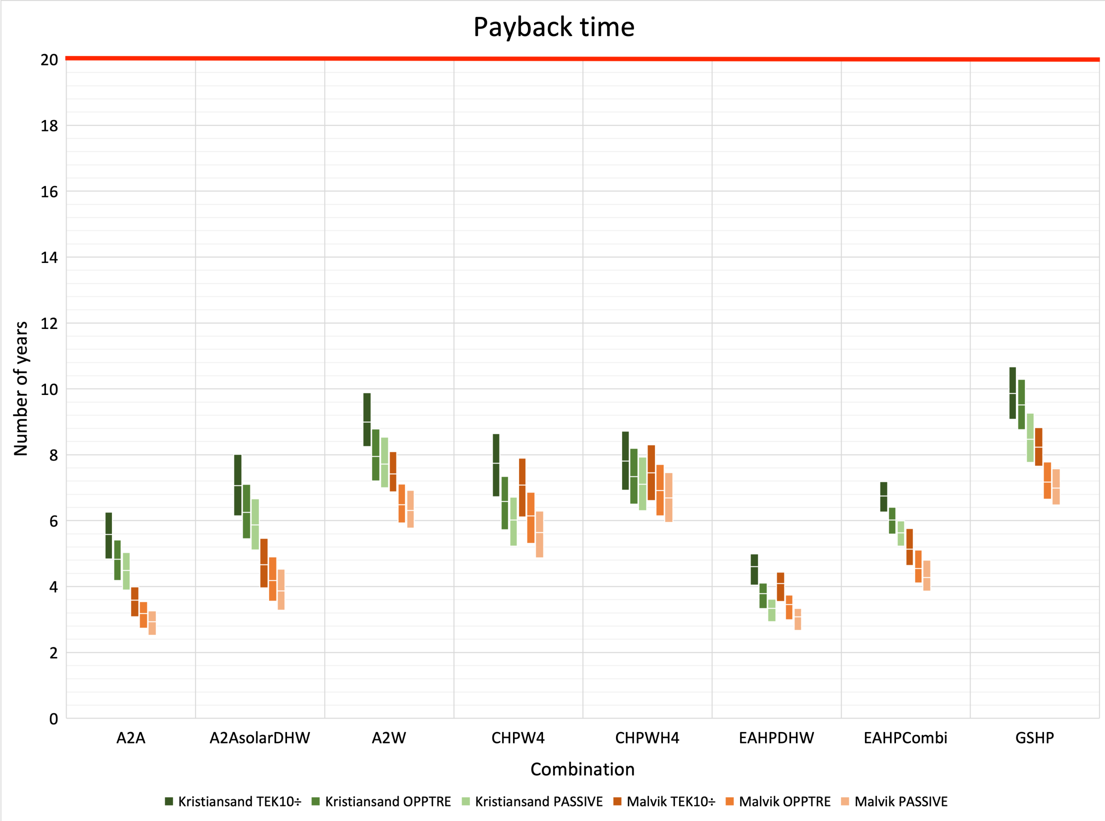

Figure 6.9: *Payback for both case houses when decreasing the discount rate from 3% to 0.5%*

Looking at the new spans of payback time, shown in Figure 6.9, they are affected by the decrease in discount rate in the same way as when increasing the electricity price. This has to do with the fact that the energy costs of scenario EXISTING are more reduced than the energy costs of the retrofitted scenarios, leading to larger savings when retrofitting the case houses. Combinations with low energy savings relative to a high investment cost have some of the longest initial payback times, such as A2W and GSHP. The larger the initial payback time of a combination, the more affected it will be when varying the discount rate. That is why A2W and GSHP have amongst the largest reductions of payback time when decreasing the discount rate.

6.6 Future development of investment costs and efficiency

The investment cost spans and efficiencies determined for each HVAC-technology considered in this thesis are subject to change in the future. Some technologies might get reinvented and get more expensive. The reinvention might also introduce better efficiencies. Other technologies may develop less expensive production strategies, leading to lower investment costs. The alteration in the investment cost span would affect both global costs and the payback time of a combination. The same applies to the increase in efficiencies, which would cause lower energy consumption resulting in lower global costs. Increased efficiencies would also decrease the energy costs of the retrofitted scenarios, meaning larger energy savings resulting in shorter payback time.

An air to air heat pump used to be more expensive when it was introduced to the market, but over the years it seems as if it has stabilized around 10 000 to 20 000 NOK. On the other hand, a compact heat pump is relatively new on the market implying that the price might be reduced in the future, as it gets more popular and further developed. Based on the data collection, it does not seem as if compact heat pumps are common HVAC-technologies for private households as of now. Maybe this will change drastically within only 5 years. This would mean the benefits of choosing a compact heat pump might outmatch the traditional air to air heat pump for some households. The global cost results are very sensitive to larger changes in the investment cost span as it is the largest cost considered in the calculations. The same applies to the payback time.

Even though photovoltaic (PV) panels were not considered in this master's thesis, it is an important technology when it comes to reducing the energy costs. PV panels have used to be an expensive investment for private households, but all projections point to a decrease in investment costs as the technology improves. This has already happened during the last decade and more and more private dwellings are installing PV panels on their roofs. The investment cost is still expected to decrease alongside an increase in efficiency in the coming decades [71].

Balanced ventilation is also subject to being improved and developed for residential buildings. If there is a drop in the investment costs of balanced ventilation, a drop in the global costs will be introduced for A2A, A2AsolarDHW, A2W and GSHP. These are the only combinations that include balanced ventilation separately. However, if there is a reasonable drop in the investment costs for balanced ventilation this might affect the investment costs of compact heat pumps as well. These complex heat pumps will most likely introduce the same new technology on the balanced ventilation part of the indoor climate central, resulting in lower total investment costs.

6.7 Validation of research

The optimal HVAC-combinations considering cost-, energy- and environmental performance have been discussed and explained. Nevertheless, it is also important to highlight some of the limitations of the findings in this master's thesis and discuss the validity of the research.

6.7.1 Data collection

In the online research of technology performance, it was discovered that there were minor differences in the COP and capacities of some specific heat pump models, depending on which source was used. The product sheets were most often possible to retrieve, but depending on the supplier, there could also be differences. This applies to air to air heat pumps in particular, whose data collection consists of over 100 different models. It is difficult to verify which performance parameters are the most correct and could lead to uncertainties in the simulations. In this thesis, the COPs and capacities found in product sheets are only assumed and not proven realistic.

The market conversion factor used on the Swedish and Danish prices is found solely from the collected investment costs. This does not necessarily represent the actual market differences. There are not enough models of air to water heat pumps, exhaust air heat pumps and ground source heat pumps with investment costs to create a realistic base for finding the market conversion factor. However, in the data collection of this thesis, the conversion factor seemed to be the same for all the three mentioned types of heat pumps. This could indicate that a 25% difference might not be too far from reality.

6.7.2 Simulation

There are limitations related to the fact that both modeling and calculations are standardized. As mentioned in Section 4.1.2, the correlation with reality is not easy to affirm. In fact, there may be no correlation at all between real and standardized behavior. According to Heide (2019), the assumed occupant preferences and occupant behavior seem to be important for the final choice of system [7]. Therefore, the consequence will be that an optimal combination in one dwelling may not be optimal for instance in a dwelling with different occupancy behavior. However, as shown in the results, the measured energy use of the existing Kristiansand house and the calculated energy use in scenario EXISTING correlated quite well when prebound and rebound effects were considered. Therefore, taking these two effects into account is hopefully improving the correlation with reality.

There is a weakness in how the compact heat pumps Econordic W4 and Econordic WH4 were modeled in the decoupled approach. Since the compact heat pumps were modeled in the same way as an exhaust air heat pump, they were also limited to only retrieving heat from the extract air. Consequently, the capacities of the heat pumps were limited, and direct electricity was considered to cover the peak heating. However, in reality, Econordic W4 and Econordic WH4 are also able to supplement with heat retrieved from the outdoor air. If these two HVAC-technologies were modeled correctly, the energy consumption of combinations CHPW4 and CHPWH4 would most likely be lower, especially for scenario TEK10÷.

In the OPPTRE-project, the specific energy consumption for all six detached wooden dwellings was calculated by the different architect- and engineering teams. It is possible to use the calculated energy demands for the existing houses to compare with the results of scenario EXISTING. The specific energy consumption for the Kristiansand house and Malvik house was calculated by using TEK-sjekk and IDA ICE, respectively. The results from these calculations are shown in Table 6.2. Compared to the calculations done in this thesis, it is possible to notice that the calculations coincide relatively well for the Kristiansand house.

In this thesis, the calculated specific energy consumption for the Malvik house deviates significantly from the calculated value in the architect competition. The reason for this is due to different framework conditions for the simulations as regards the existing HVAC-combination. As mentioned in Section 4.1.2, Rambøll was kind enough to provide us with their IDA ICE model. In their IDA ICE model, the HVAC-combination solely consists of one ideal heater in the living room, leading to low temperatures in many of the rooms in the house. In this thesis, it was decided to have electric panel heaters in every heated zone. Furthermore, it was chosen to implement a standard air handling unit to simulate the heat losses from natural ventilation as described in Section 4.1.2. This air handling unit was on the other hand not implemented in Rambøll's IDA ICE model. Because of the different framework conditions, it is difficult to compare their calculated energy consumption with the results of this thesis.

Table 6.2: *Specific energy consumption [kWh/m^2] calculated for each of the existing dwellings*

Case house	Kristiansand	Malvik
Calculated (architect competition) [kWh/m^2]	261	189.7
Calculated (in this thesis) [kWh/m^2]	246	292

6.7.3 The prebound and rebound effects

Using the trendline of Sandberg et al. (2017), it is possible to retrieve a specific rebound factor for each combination in each scenario, depending on the simulated energy consumption. However, to simplify the analysis a common rebound factor was used, based on the average specific energy consumption of all simulations. This means that scenario PASSIVE may have a larger degree of rebound compared to OPPTRE, and scenario TEK10÷ may have a lower degree of rebound. The same simplification was done for prebound as well, where the average specific energy consumption of the two case houses was inserted in Equation (2.1), describing the trendline.

6.7.4 Cost performance assessment

In the cost performance assessment, standardized maintenance costs are used. However, they could in reality be larger or smaller. This depends on the awareness of the end users and their willingness to maintain the HVAC-combination. Depending on usage and original quality, the maintenance will in turn affect the lifetime expectancy of the technology. The technology might be more or less durable than the considered lifetime expectancy. Such aspects would affect the profitability and cost effectiveness of the considered HVAC-combinations.

The validity of the cost performance assessment is improved by considering an investment cost span. Even though these spans might have some inaccuracies, the results are representative of a large variety of investment costs. This means the market is well represented for most of the HVAC-combinations considered. In addition, redoing the cost performance assessment with different values of the electricity price and discount rate will bring a sense of how these values impact the results. In addition, dimensioning the heat pumps and utilizing investment cost spans for a certain capacity group will give a more realistic relationship between cost effectiveness and energy efficiency.

In the payback time calculations, replacement costs are not considered. This is because of the standardized approach given in Section 4.3.5, which does not include possible replacement costs, only initial investment costs. Ultimately, one could say that only combinations with a payback time shorter than the lifetime expectancy of the technologies included, have a realistic payback time. The lowest lifetime expectancy constraint in this thesis is 15 years, and all combinations considered have a payback time within 15 years in the original results, before accounting for prebound and rebound effects. In the analysis of the prebound and rebound effects, the constraint mostly applies to scenario TEK10÷ of both case houses, and especially the Kristiansand house.

This thesis is only focusing on the cost effectiveness of different HVAC-combinations when doing a deep energy retrofit. The different retrofitted scenarios considered have different investment costs in terms of upgrading the building envelope etc. If these investment costs were included, this thesis would be very different. Upgrading to scenario PASSIVE would induce larger investment costs than upgrading to scenario TEK10÷, possibly changing the optimal combination in terms of cost effectiveness.

Obyn and Moeseke stated that the optimal solution for existing houses is found when the entire existing system is conserved, in preference to a replacement of the heating system during the retrofit [6]. In this master's thesis, the existing HVAC-combination of scenario EXISTING was not considered nor simulated for the retrofitted scenarios. This means that the optimal solution found in Obyn and Moeseke's study could possibly be applicable to the retrofitted scenarios being described in this master's thesis.

6.7.5 Optimal combination

As regards finding an optimal combination, it is important to stress that it is solely based on the analysis and weighing of cost effectiveness, energy efficiency and carbon footprint done for this thesis. Some of the global cost spans are fairly similar in the scenarios of the two case houses. All in all, the end users' preferences play an important role when selecting the optimal combination. If a certain combination is more preferable to the end user it becomes more competitive, even though it may not be the most cost-effective or energy-efficient presented in this master's thesis. These personal preferences are hard to account for when suggesting an optimal combination for each scenario.

Conclusion

The aim of this thesis was to answer the research question by evaluating the cost-, energy- and environmental performance of different HVAC-combinations, as presented in Section 1.2. This was done for the purpose of enlightening end users and possibly contributing to reaching the national climate target.

Through the energy analysis, the simulated energy consumption of each retrofitted scenario was discussed. In general, A2W, CHPWH4 and GSHP had the lowest specific energy consumption of all the HVAC-combinations considered in this thesis. The common factor of these combinations is centralized hydronic space heating. The low energy consumption also led to these combinations having the lowest CO_2-emissions. On the other hand, EAHPDHW had the overall largest energy consumption and CO_2-emissions in all retrofitted scenarios.

From a cost performance perspective, the combination that stands out as the most cost-effective is EAHPDHW in the Kristiansand house. This combination consists of an exhaust air heat pump covering the domestic hot water demand. In addition, electric panel heaters and electric floor heating cover the demand for space heating. This combination has low initial investment costs resulting in low global costs. However, in scenario TEK10÷ of the Kristiansand house, the energy costs of EAHPDHW are substantial enough to make other combinations, such as CHPWH4, more competitive. All combinations are deemed profitable as regards payback time in the Kristiansand house.

The cost performance assessment of the Malvik house was different, due to lower investment cost spans of some of the HVAC-technologies. As such, combinations A2A, A2AsolarDHW, EAHPCombi and EAHPDHW all stand out as cost-effective solutions in all scenarios of the Malvik house. These combinations have either an air to air heat pump or an exhaust air heat pump, which both have low investment costs compared to other types of heat pumps. All combinations are deemed profitable as regards payback time in the Malvik house.

The hardest decision when determining an optimal combination is how to weigh the different aspects. In this thesis, cost effectiveness is regarded as the most important aspect. To conclude the discussion of optimal combination, each retrofitted scenario of each case house is presented with its respective optimal combination in Table 7.1. It is important to stress that these suggestions are based on the methodology and assumptions of this thesis.

Table 7.1: *Optimal combinations derived in this thesis*

Case house	Kristiansand	Malvik
TEK10÷	CHPWH4	CHPWH4
OPPTRE	CHPWH4	EAHPCombi
PASSIVE	CHPW4	EAHPCombi/A2AsolarDHW

In Table 7.1, combinations with an exhaust air heat pump or a compact heat pump are well represented. However, personal preferences may play a role in determining an optimal combination for the case houses. Combinations CHPW4 and CHPWH4 do not include a separate ventilation aggregate for the studio apartment in the Kristiansand house, limiting the ability of independent control. As regards combinations EAHPDHW and EAHPCombi, the exhaust air heat pump may cause an uncomfortable draft in both case houses, as cold air is directly supplied through cracks and vents. These disadvantages and other personal preferences are not considered in the determination of optimal combinations in this thesis.

When taking the prebound and rebound effects into account, all global costs increased due to larger energy costs. This led to some combinations being deemed unprofitable, especially in scenario TEK10÷ of the Kristiansand house. For instance, investing in combinations such as EAHPDHW and CHPW4 in this scenario resulted in a payback time above 20 years due to large energy costs. The energy consumption of the retrofitted scenarios is significantly affected by the prebound and rebound effects, meaning the optimal combinations found in the original results may not be optimal in reality.

In the sensitivity analysis, the effects of an increased electricity price and altered discount rates were discussed. The increased electricity price and decreased discount rate both led to larger global costs, whereas increasing the discount rate led to reduced global costs. As regards the effects on payback time, only the increase of the discount rate increased the payback time compared to the original results. Still, with the increase of discount rate, all combinations were profitable. In the other cases of increasing the electricity price and decreasing the discount rate, the payback time was reduced. It is important to stress that the calculation of payback time is very sensitive to the discount rate, the investment cost of a combination and the difference in energy cost.

All in all, through the analysis of different HVAC-combinations and scenarios, we have discovered that the energy consumption is decreased and several of the considered combinations are profitable when doing a deep energy retrofit. To answer the research question, this thesis shows that deep energy retrofitting detached wooden dwellings can contribute to reducing the energy use in the Norwegian building stock through cost-effective and energy-efficient measures with low environmental impact. In conclusion, these measures could include several of the considered HVAC-combinations in this master's thesis, depending on the energy efficiency of the building envelope and type of detached wooden dwelling.

Further work

There are several HVAC-technologies not considered in the scope of this master's thesis due to the time limit. It could be interesting to add more combinations to the cost performance assessment in order to explore the energy efficiency and cost effectiveness of even more technologies. For instance, PV panels, wood stove water jacket and single room ventilation have not been evaluated in this master's thesis. The implementation of PV panels is especially interesting as it might substantially reduce the energy costs of an HVAC-combination, to better meet the nZEB-requirements.

An HVAC-technology that could be analyzed in further work is hydronic radiators. In this thesis, it was decided to only consider fan convectors in combination with hydronic floor heating. Instead of fan convectors, hydronic radiators could be installed. Doing so will introduce more complex simulations, as the radiators require a higher water temperature than floor heating. However, it may be more cost-effective to invest in hydronic radiators than fan convectors. Therefore, this could be interesting to analyze further in order to determine which combination is more cost-effective.

In the simulation software IDA ICE, it could be interesting to consider load profiles throughout the year for the simulation models. This would clarify the exact times the energy demand is at its highest. Taking load profiles into account will give a better insight on when to run some of the HVAC-technologies in coordination with solar thermal collectors and PV panels.

As explained in Section 6.6, there are uncertainties related to the investment costs in the future. These costs could be further analyzed, taking future development into account. It would be possible to do a literature review to gain knowledge on the predicted technology investment costs of the future. In addition, the investment costs related to the upgrade of the building envelope can be done in order to get a holistic view of the total investment of a deep energy retrofit for the end user.

The actual rebound effects are not possible to obtain, as the houses are yet to be renovated. However, it would be interesting to analyze how accurate the estimated rebound effects actually are after the renovation of the case houses is complete. This would entail having one of the considered HVAC-combinations actually installed in the case houses, and the retrofit coinciding with one of the scenarios.

Since only CO_2-emission during operation was considered for this thesis, doing a full life cycle analysis could give more realistic results when considering the HVAC-combination with the lowest environmental impact. All in all, there are several interesting aspects to explore further to give a more elaborate answer to the research question introduced in this master's thesis.

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References of the data collection

The following references were used to determine the investment cost spans, maintenance costs, lifetime expectancies and efficiencies for each HVAC-technology used in the cost performance assessment. In addition, some references are used for general gathering of data such as ENOVA for the amount of support given with an investment. References used for simulation data are also listed below.

General references for HVAC-technology data

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- ENOVA [89][37][39]
- NOVAP - Norsk varmepumpeforening [90][28][26][33][91][92][60]
- NVE - Norges vassdrags- og energidirektorat [93][10]
- Standard NS-EN 15459 [12]

Air to air heat pump

- Elkjøp [94]
- Megaflis [95]
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- Panasonic [97]
- RoMy Clima AS [98]
- Samsung [99]
- Toshiba [100]
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Air to water heat pump

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- Energimyndigheten [105]
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- Offer on air to water heat pump provided by Øystein Strøm, K. Lund AS. Communication by email (May 2021)
- Oslo Vann og Varme AS [106]
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Exhaust air heat pump

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Ground source heat pump with energy wells

- Bergvärmepumpar.n.nu [117]
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Compact heat pump

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Hydronic floor heating

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Fan convectors

- Frico [130]
- GCMN Varmepumper [131]
- Jula [132]
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Electric floor heating

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- Smedegård et al. (2012)[129]

Electric panel ovens

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- Elkjøp [136]

Balanced ventilation

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Simulation Data

- Norgesvinduet [138]
- Standards: NS-EN ISO 7730 [15], NS 3700 [14], SN-NSPEK 3031 [13]
- Regulations: TEK10 [53], TEK17 [55]

A.1 Investment cost spans - Technology

Scenarios:			KRISTIANSAND											
			TEK10÷				OPPTRE				PASSIVE			
			UNIT	Investment cost			UNIT	Investment cost			UNIT	Investment cost		
Maintenance cost (%)	Lifetime	Technologies	[kW]	Min	Max	Mean	[kW]	Min	Max	Mean	[kW]	Min	Max	Mean
2 %	15	Air to air heat pump	4,5	13 000	20 000	15 600	4,5	13 000	20 000	15 600	4,5	13 000	20 000	15 600
2 %	15	Air to water heat pump	9	160 000	185 000	170 000	7,3	130 000	155 000	141 000	7,3	130 000	155 000	141 000
2 %	20	Compact heat pump Econordic W4		174 500	221 500	198 000		174 500	221 500	198 000		174 500	221 500	198 000
2 %	20	Compact heat pump Econordic WH4		192 500	243 500	218 000		192 500	243 500	218 000		192 500	243 500	218 000
2 %	20	Ground source heat pump	8,2	203 000	226 000	214 500	8,2	203 000	226 000	214 500	5,5	171 000	194 000	181 000
2 %	15	Exhaust air heat pump (Only DHW)	4,2	57 500	70 000	64 000	4,2	57 500	70 000	64 000	4,2	57 500	70 000	64 000
2 %	15	Exhaust air heat pump (SH & DHW)	4,2	123 000	137 000	131 000	4,2	123 000	137 000	131 000	4,2	123 000	137 000	131 000
			[#]				[#]				[#]			
1 %	25	Electric panel heaters	8	7 900	17 500	14 500	8	7 900	17 500	14 500	8	7 900	17 500	14 500
4 %	15	Fan convectors	3	27 000	42 000	34 200	3	27 000	42 000	34 200	3	27 000	42 000	34 200
			[m^2]				[m^2]				[m^2]			
2 %	50	Electric foor heating	25,6	30 440	30 440	30 440	25,6	30 440	30 440	30 440	25,6	30 440	30 440	30 440
2 %	50	Hydronic floor heating	25,6	59 573	59 573	59 573	25,6	59 573	59 573	59 573	25,6	59 573	59 573	59 573
			[m^2]				[m^2]				[m^2]			
0,5 %	25	Solar thermal collectors	12	67 000	86 000	75 000	12	67 000	86 000	75 000	12	67 000	86 000	75 000
			[m^3/h]				[m^3/h]				[m^3/h]			
5 %	20	Balanced ventilation	245,5	92 000	114 000	103 000	245,5	92 000	114 000	103 000	245,5	92 000	114 000	103 000

Scenarios:			MALVIK											
			TEK10÷				OPPTRE				PASSIVE			
			UNIT	Investment cost			UNIT	Investment cost			UNIT	Investment cost		
Maintenance cost (%)	Lifetime	Technologies	[kW]	Min	Max	Mean	[kW]	Min	Max	Mean	[kW]	Min	Max	Mean
2 %	15	Air to air heat pump	4,5	13 000	20 000	15 600	4,5	13 000	20 000	15 600	4,5	13 000	20 000	15 600
2 %	15	Air to water heat pump	9	160 000	185 000	170 000	7,3	130 000	155 000	141 000	7,3	130 000	155 000	141 000
2 %	20	Compact heat pump Econordic W4		174 500	221 500	198 000		174 500	221 500	198 000		174 500	221 500	198 000
2 %	20	Compact heat pump Econordic WH4		192 500	243 500	218 000		192 500	243 500	218 000		192 500	243 500	218 000
2 %	20	Ground source heat pump	8,2	203 000	226 000	214 500	5,5	171 000	194 000	181 000	5,5	171 000	194 000	181 000
2 %	15	Exhaust air heat pump (Only DHW)	3,1	57 500	70 000	64 000	3,1	57 500	70 000	64 000	3,1	57 500	70 000	64 000
2 %	15	Exhaust air heat pump (SH & DHW)	3,1	82 000	106 000	92 000	3,1	82 000	106 000	92 000	3,1	82 000	106 000	92 000
			[#]				[#]				[#]			
1 %	25	Electric panel heaters	10	9 400	21 300	17 800	10	9 400	21 300	17 800	10	9 400	21 300	17 800
4 %	15	Fan convectors	3	27 000	42 000	34 200	3	27 000	42 000	34 200	3	27 000	42 000	34 200
			[m^2]				[m^2]				[m^2]			
2 %	50	Electric foor heating	26,9	31 190	31 190	31 190	26,9	31 190	31 190	31 190	26,9	31 190	31 190	31 190
2 %	50	Hydronic floor heating	26,9	63 430	63 430	63 430	26,9	63 430	63 430	63 430	26,9	63 430	63 430	63 430
			[m^2]				[m^2]				[m^2]			
0,5 %	25	Solar thermal collectors	6	43 000	65 000	51 000	6	43 000	65 000	51 000	6	43 000	65 000	51 000
			[m^3/h]				[m^3/h]				[m^3/h]			
5 %	20	Balanced ventilation	182,2	55 000	65 000	60 000	182,2	55 000	65 000	60 000	182,2	55 000	65 000	60 000

Figure A.1: *Investment cost spans considered for each HVAC-technology in this thesis*

A.2 Investment cost spans - Combinations

Scenarios:	KRISTIANSAND												MALVIK											
	TEK10÷				OPPTRE				PASSIVE				TEK10÷				OPPTRE				PASSIVE			
	UNIT	Investment cost			UNIT	Investment cost			UNIT	Investment cost			UNIT	Investment cost			UNIT	Investment cost			UNIT	Investment cost		
Combinations	[kW]	Min	Max	Mean	[kW]	Min	Max	Mean	[kW]	Min	Max	Mean	[kW]	Min	Max	Mean	[kW]	Min	Max	Mean	[kW]	Min	Max	Mean
A2A	4,5	133 340	171 940	153 540	4,5	133 340	171 940	153 540	4,5	133 340	171 940	153 540	4,5	98 590	127 490	114 590	4,5	98 590	127 490	114 590	4,5	98 590	127 490	114 590
A2AsolarDHW	4,5	192 940	250 540	221 140	4,5	192 940	250 540	221 140	4,5	192 940	250 540	221 140	4,5	135 390	186 290	159 390	4,5	135 390	186 290	159 390	4,5	135 390	186 290	159 390
A2W	9	318 573	380 573	346 773	7,3	288 573	350 573	317 773	7,3	288 573	350 573	317 773	9	285 430	335 430	307 630	7,3	255 430	305 430	278 630	7,3	255 430	305 430	278 630
CHPW4		202 840	259 440	232 940		202 840	259 440	232 940		202 840	259 440	232 940		205 090	263 990	236 990		205 090	263 990	236 990		205 090	263 990	236 990
CHPWH4		259 073	325 073	291 773		259 073	325 073	291 773		259 073	325 073	291 773		262 930	328 930	295 630		262 930	328 930	295 630		262 930	328 930	295 630
EAHPDHW	4,2	95 840	117 940	108 940	4,2	95 840	117 940	108 940	4,2	95 840	117 940	108 940	3,1	98 090	122 490	112 990	3,1	98 090	122 490	112 990	3,1	98 090	122 490	112 990
EAHPCombi	4,2	199 573	228 573	214 773	4,2	199 573	228 573	214 773	4,2	199 573	228 573	214 773	3,1	162 430	201 430	179 630	3,1	162 430	201 430	179 630	3,1	162 430	201 430	179 630
GSHP	8,2	351 573	411 573	381 273	8,2	351 573	411 573	381 273	5,5	319 573	379 573	347 773	8,2	318 430	366 430	342 130	5,5	286 430	334 430	308 630	5,5	286 430	334 430	308 630

Figure A.2: *Investment cost spans considered for each HVAC-combination in this thesis*

IDA ICE specifications

B.1 Schedules - SN-NSPEK 3031 (2020)

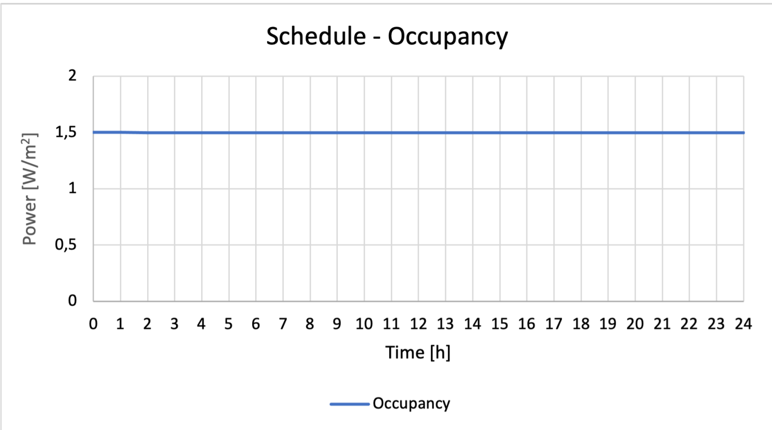

Figure B.1: *Schedule - Occupancy, SN-NSPEK 3031 (2020) [13]*

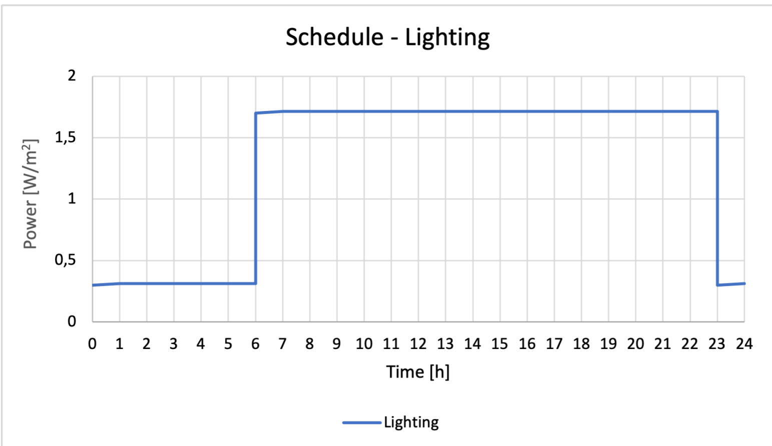

Figure B.2: *Schedule - Lighting, SN-NSPEK 3031 (2020) [13]*

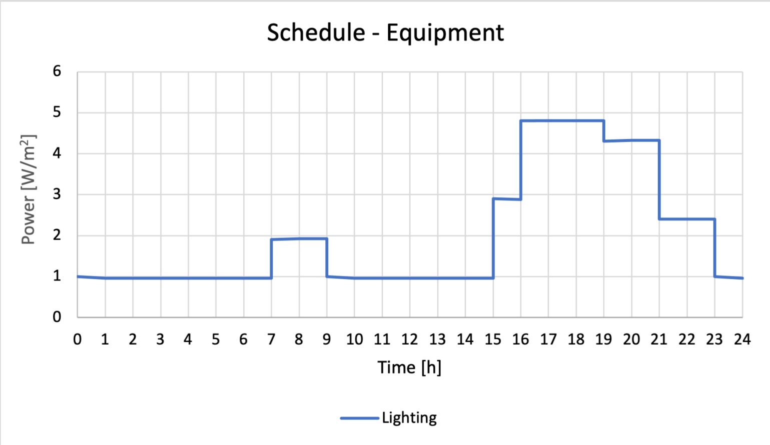

Figure B.3: *Schedule - Equipment, SN-NSPEK 3031 (2020) [13]*

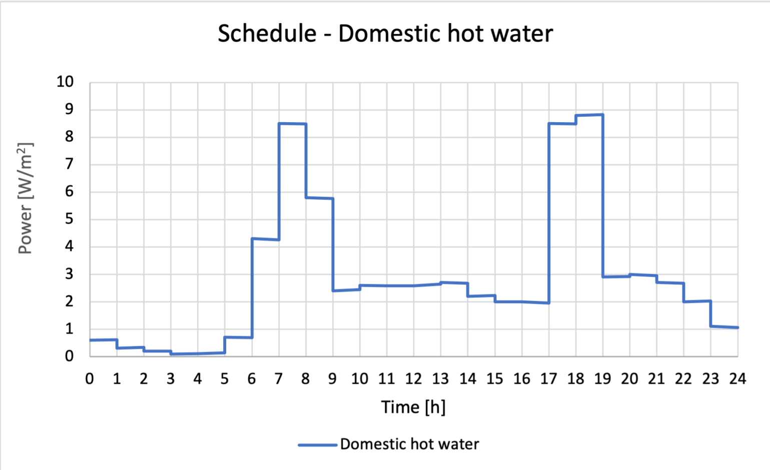

Figure B.4: *Schedule - Domestic hot water, SN-NSPEK 3031 (2020) [13]*

B.2 Areas used for floor heating

Kristiansand	m^2	Floor
Basement: Bathroom	11.5	Concrete
First floor: Bathroom	3.3	Concrete
First floor: WC	2.3	Concrete
First floor: Entrance	8.4	Concrete
Total floor heating area	25.6	

Table B.1: *Rooms and areas with floor heating in the Kristiansand case house*

Malvik	m^2	Floor
Basement: Laundry/WC	5.7	Concrete
First floor: WC	2.6	Concrete
First floor: Entrance	13.1	Concrete
Second floor: Bathroom	5.5	Timber studwork
Total floor heating area	26.9	

Table B.2: *Rooms and areas with floor heating in the Malvik case house*

Kjellberg, B. and Johansen, S. V.

Master's thesis

NTNU

Norwegian University of
Science and Technology