Masteroppgave

NTNU
Norges teknisk-naturvitenskapelige universitet
Fakultet for ingeniørvitenskap
Institutt for energi- og prosessteknikk

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Economic performance of heating systems for energy renovation of wooden dwellings in Norway

Masteroppgave i Energi og miljø
Veileder: Laurent Georges
Medveileder: Vegard Heide
Juni 2022

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Abstract

By committing to the Paris agreement in 2015, Norway set a goal of reducing the country's greenhouse gas emissions by 50% to 55% compared to the emission levels in 1990 by 2030 [1]. Therefore, the motion of reducing the annual energy consumption of the existing building stock by 10 TWh by 2030 was carried in 2016 [2]. Energy retrofitting of existing residential buildings can therefore play a part in Norway's efforts to reach the goals in the Paris agreement.

This thesis is a part of OPPTRE, which is a research project supported by the Research Council of Norway [3]. OPPTRE aims to propose a cost effective Nearly Zero Energy level of retrofit for small wooden dwellings in Norway with high architectural quality and low environmental impact. The basis of the research project is six existing dwellings built in the period 1950-1990. Proposed energy upgrades for the six dwellings have been made in an architecture competition. The winning proposals of the competition have formed the basis for the rest of the OPPTRE-project.

The work conducted in this thesis is a continuation of the previous work carried out in Johansen and Kjellberg's master's thesis [4]. Johansen and Kjellberg investigated the economic, energy and environmental performance of different heating supply combinations with three different renovation levels for two of the houses from the architecture competition. The energy performances were evaluated through simulation models in IDA ICE, while the methods described in NS-EN 15459-1 are used for the evaluation of economic performance.

During the work with this master's thesis, the simulation models from the previous work have been revised and validated. In order to validate the models, the SPF of the simulated models have been compared with the SPF of similar systems found in a literature review. The evaluation of the energy and economic performance of the heating supply combinations with the three renovation levels have been refined from the previous work. Additionally, two new combinations have been investigated. Furthermore, the effects on the economic performance of different grid tariff models, which are supposed to be induced during 2022, are looked into. Finally, optimal heating supply combinations for each renovation level of the two dwellings have been proposed. These propositions are based on predefined key performance indicators related to energy and economic performance, and thermal comfort.

The results show that upgrading the heating systems is more profitable at lower insulation levels. The investment costs is an important factor for the economic performance, and the cheaper combinations induce lower life cycle costs in most cases. With increasing renovation levels, upgrades related to the ventilation system and the heating of DHW is the most cost efficient due to the low space heating demand.

Grid tariffs with fixed fees based on monthly power peaks yield marginal differences in terms of economic performance. However, a sensitivity analysis show that increasing the rates of the power based fixed fee can make the more expensive and efficient heating systems more cost effective compared to cheaper combinations.

Based on the performance indicators related to energy performance, cost effectiveness, and thermal comfort, combinations with low investment costs outperform more expensive and efficient combinations. This becomes more evident at higher insulation levels, where the energy saving potential of the efficient heating supply combinations is reduced.

Sammendrag

Etter at Norge sluttet seg til i Parisavtalen i 2015, ble det satt som mål å redusere landets klimagassutslipp med 50 til 55 %, sammenlignet med 1990-nivået, innen 2030 [1]. Det ble derfor i 2016 vedtatt at energibruken knyttet til den eksisterende bygningsmassen skal reduseres med 10 TWh innen 2030 [2]. Energioppgradering av eksisterende boliger kan dermed være et viktig bidrag for å nå målene i Parisavtalen.

Denne masteroppgaven er en del av OPPTRE, som er et forskningsprosjekt finansiert av Forskningsrådet [3]. Målet er å foreslå kostnadseffektive energirenoveringer for boliger som tilsvarer nesten nullenergibygg. Forslagene skal ha høy arkitektonisk kvalitet og lavt klimafotavtrykk. Seks eksisterende boliger bygd i perioden 1950 til 1990 utgjør grunnlaget til forskningsprosjektet. Det har blitt foreslått energioppgraderinger til disse gjennom en arktitektkonkurranse, hvor vinnerforslagene har formet grunnlaget for det videre arbeidet i OPPTRE-prosjektet.

Arbeidet utført i denne masteroppgaven er en fortsettelse på arbeidet utført i Johansen og Kjellberg sin masteroppgave [4]. Johansen og Kjellberg har undersøkt kostnads- og energieffektiviteten, og miljøpåvirkningen til to av husene fra arkitektkonkurransen med ulike varme- og ventilasjonsløsninger, samt tre ulike oppgraderingsnivå av bygningskroppen. For å undersøke energieffektiviteten ble simuleringsprogrammet IDA ICE benyttet, mens kostnadseffektiviteten ble evaluert metodene beskrevet i NS-EN 15459-1.

I arbeidet med masteroppgaven, har simuleringsmodellene fra det tidligere arbeidet blitt revidert og validert. For å validere simuleringsmodellene, har årsvarmefaktoren til de simulerte varmepumpesystemene blitt sammenlignet opp mot årsvarmefaktoren til lignende systemer i faglitteratur. Videre har evalueringen av energi- og kostnadseffektiviteten til de ulike kombinasjonene med energiforsyning sammen med de tre renoveringsnivåene blitt raffinert. I tillegg har to nye oppvarmingsløsninger blitt tatt med i vurderingen. De økonomiske virkningene av nye effektbaserte tariffer for nettleie, som er planlagt å innføres iløpet av 2022, blitt undersøkt. Til slutt har optimale oppvarmingsløsninger blitt foreslått for de tre renoveringsnivåene for de to boligene. Disse forslagene tar utarbeidet etter nøkkeltallsindikatorer innen energi og kostnadseffektivitet, samt termisk komfort.

Resultatene viser at oppgradering av oppvarmingsløsningen er mer gunstig ved lavere renovasjonsnivå. Investeringskostnaden spiller en stor rolle for kostnadseffektiviteten, og de billigere kombinasjonene fører i de fleste tilfellene til lavere livsløpskostnader. Ved høyere renoveringsnivå, er oppgraderinger knyttet til ventilasjon og varmtvannsoppvarming mest kostnadseffektivt på grunn av lavere romoppvarmingsbehov.

Tariffer for nettleie med effektbasert fastledd påvirker kostnadseffektiviteten til de ulike kombinasjonene i liten grad. Likevel viser en følsomhetsanalyse utført i oppgaven at de dyrere og mer effektive kombinasjonene oppnår høyere kostnadseffektivitet dersom satsene på det effektbaserte fastleddet økes.

Basert på nøkkeltallsindikatorene relatert til energi- og kostnadseffektivitet, samt termisk komfort, gjør rimeligere kombinasjoner det bedre enn dyrere og mer effektive kombinasjoner. Dette blir tydeligere ved høyere renoveringsnivå, hvor energisparepotensialet til de mest effektive kombinasjonene reduseres.

Preface

This master's thesis is a continuation of the previous master's thesis *Economic Performance of Heating and Ventilation Systems in Energy Retrofit of Detached Houses* conducted by Bianca Kjellberg and Sondre Valstad Johansen. The work with this thesis has been performed during the spring of 2022 at the Norwegian University of Science and Technology (NTNU).

I would like to thank my supervisors Laurent Georges and Vegard Heide for the great guidance during my work. I would also like to thank Mathea Antonsen for showing great support, and my dad Dag Thingbø for the help provided with proofreading the thesis.

Content

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List of abbreviations

CHP	Compact heat pump
COP	Coefficient of performance
DHW	Domestic hot water
DOT	Dimensioning outdoor temperature
EAHP	Exhaust air heat pump
GHG	Green house gas
GSHP	Ground source heat pump
HVAC	Heating, ventilation and air conditioning
KPI	Key performance indicator
SCOP	Seasonal coefficient of performance
SFP	Specific fan power
SPF	Seasonal performance factor

1 Introduction

1.1 Background

By committing to the Paris agreement in 2015, Norway set a goal of reducing the country's greenhouse gas emissions by 50% to 55% by 2030 compared to the emission levels in 1990 [1]. Therefore, the motion of reducing the annual energy consumption of the existing building stock by 10 TWh by 2030 was carried in 2016 [2]. Energy retrofitting of existing residential buildings can therefore play a part in Norway's efforts to reach the goals in the Paris agreement. Furthermore, in IEA's Sustainable recovery plan published in July 2020, 30 measures that could be implemented in the period 2021-2023 and secure sustainable growth after the COVID-19 shock are presented [5]. Among these, energy retrofit of existing buildings is the only measure that fulfills all objectives: improving the energy sustainability and resilience, boosting the economy, and creating jobs.

This project work is a part of OPPTRE, which is a research project supported by the Research Council of Norway [3]. OPPTRE aims to propose a cost effective Nearly Zero Energy level of retrofit for small wooden dwellings in Norway with high architectural quality and low environmental impact. An architecture competition has been the core activity of OPPTRE, where proposals of energy upgrades for six characteristic Norwegian dwellings built in the period 1950-1990 were made [6]. The results of the competition have formed the basis for the rest of the research activities in the project.

This project work investigates the previously proposed heating combinations and different levels of retrofit for two of the participating houses of the OPPTRE architecture competition. The following tasks have thus been considered: The first task has been revising and verifying the simulation models of the two houses made in previous works. The models have been validated by comparing the SPF to the SPF of studied buildings with comparable heating systems found in literature. Secondly, the energy performance and cost effectiveness of the heating supply solutions have been evaluated using methods described in NS-EN 15459. The effects on economic performance of the grid tariff models that are supposed to be induced in 2022 are also looked into. Lastly, optimal heating supply combinations have been proposed for each level of retrofit for the two houses based on defined key performance indicators.

1.2 Research questions and objectives

This project aims at comparing the energy and cost performance of heating and ventilation systems for deep-energy retrofit of detached houses. The project is a follow-up of a previous masters thesis done in spring 2021 and the specialization project I conducted during the autumn 2021. The following research question has been formulated:

Which heating combinations are most effective in terms of energy and economic performance for renovated dwellings?

In order to investigate this problem, several objectives have been taken into consideration, which are presented as follows:

- Revise, refine and validate the simulation models from previous work.
- Evaluate the energy and economic performance of the dwellings with different renovation levels and heating supply solutions.
- Make a description of the new grid tariffs to be induced in Norway, and evaluate the impact of these on the economic performance of the dwellings.
- Refine the modeling of exhaust air and compact heat pumps in IDA ICE.
- Propose an heating supply combination for each renovation level of the two case houses based on key performance indicators defined in the thesis.

1.3 Previous work

This thesis is a continuation of the work carried out in Kjellberg and Johansen's master's thesis *Economic Performance of Heating and Ventilation Systems in Energy Retrofit of Detached Houses* [4]. Kjellberg and Johansen evaluated the cost and energy performance of different HVAC-technologies that can potentially be implemented in renovated dwellings in Norway. In their study, two of the dwellings from the OPPTRE architecture competition were evaluated. The dwellings are located in Kristiansand and Malvik respectively. Eight different heating solutions were defined and investigated in combination with the three renovation levels. Thus, a total of 24 scenarios combining different levels of energy retrofit and heating systems were investigated for each house.

Models of all scenarios were implemented and simulated using the building simulation software IDA ICE. The simulation results were used to evaluate which heating combinations are optimal for the different levels of retrofit based on the criteria global costs, payback time, energy consumption and environmental impact. Furthermore, the effects of prebound and rebound effects on energy consumption and cost effectiveness were investigated.

During my specialization project in the autumn of 2021, I refined the work, revised the simulations and simulation models, and implemented a new reference scenario for evaluation of payback times.

1.4 Scope

The scope of this thesis is the energy and economic performance of deep energy retrofit of wooden dwellings in Norway. Wooden dwellings are responsible for more than half of the total energy use of the Norwegian building stock. Two renovated case houses, which where originally constructed in the 1950's and 1970's respectively, have been evaluated. Before renovation, these houses could be considered characteristic for the time period in which they were built.

Three different insulation levels of the building envelopes have been defined and investigated for each building. The performance of the three insulation levels have been investigated in combination with 10 different heating supply systems, in addition to a direct electric heating system which is the reference heating solution. In terms of heating supply combinations, the scope is mainly limited to different heat pump systems.

The building performance simulation have been used to estimate the energy performance of the dwellings. The simulations are performed using the software IDA ICE. Occupant behavior may have a heavy influence on the energy consumption, as the number of persons in different households may vary. Thus, the electricity the use of electrical equipment and DHW can fluctuate heavily between different households. Preferences regarding the thermal environment can also be differing. The simulations are therefore based on standardized behaviour, rather than actual behavior.

This thesis is a continuation of the work conducted in Johansen and Kjellberg's masters thesis [4]. They put a lot of work in collecting a great amount of market data regarding the heating supply solutions. This data consist of product market prices, installation prices and costs of maintenance for different HVAC installations and equipment. For the sake of simplicity, this data have been utilized in this thesis as well. Furthermore, the conditions set in their thesis for the evaluation of the economic performance, have also been used when possible

The economic performance of the dwellings have been evaluated with the grid tariffs structure that was supposed to be induced the 1st of January 2022. This thesis evaluates the new tariff models of Glitre Energi, Elvia and Nettselskapet have been used. These grid companies operate in different parts of the country, both in urban and rural areas. The tariff of Elvia and Nettselskapet have been used because the structure of their tariff models can be considered similar to the new tariff models of most grid companies in the country. Furthermore, the tariff model of Glitre is also included in the evaluation, as the structure of their tariff model differs from the two others. Glitre's tariff model was also induced before the new year, and has been an option for their customers along with their standard tariff model.

1.5 Outline

The work in this thesis can be divided into two parts; in the first part the energy and economic performance of the different renovation levels and heat supply combinations is evaluated for the two dwellings. For this evaluation, a fixed energy price is used. This part is a continuation of the work conducted by Johansen and Kjellberg in the spring semester of 2021, and my specialization project from the autumn of 2021. The second part investigates how different grid tariffs influence the economic performance. In this part, different operating measures to reduce the costs of the grid tariffs are also proposed and investigated.

The theory section presents different boundary conditions when evaluating the performance of heat pump systems.

Literature reviews on the performance of heat pump systems similar to the ones investigated in this work, and on the energy and economic performance of building renovation, are also presented. The literature reviews are followed by descriptions of the case houses, the heat supply combinations and the state of grid tariffs in Norway. The method for evaluating the economic performance of the two dwellings are also presented. In the methodology, the implementation of the simulation models are presented. This includes both modeling of the case houses and the heating supply solutions. Furthermore, the conditions for the economic performance evaluation are described. These include financial parameters, as well as costs of the different renovation levels, heating solution, and energy and grid tariffs. Operating measures to reduce the costs of the grid tariffs are also described. Finally, methods and system boundary conditions for evaluating the performance of the heat pump systems are presented.

The results are presented and discussed in section 4. Results of the system performance of the heat pump systems are presented, and validated by comparing with the performance of similar systems found in the literature review. Furthermore, results of the energy and economic performance of the dwellings are presented, both with fixed energy prices and with different energy and grid prices. Results with different operating measures to reduce the grid fee are also presented. Furthermore, sensitivity analysis on parameters such as discount rate, governmental grants and fee rates of the grid tariff are presented and discussed. The section is rounded off by presenting a method for choosing an optimal heating supply combination for all three renovation levels of both dwellings. Based on the results and discussion, a conclusion is made. Finally, suggestions for further work is presented.

2 Theory and groundwork

2.1 Evaluating the performance of heat pump systems

2.1.1 Seasonal performance factor

In general, the SPF of a heating system is defined as the ratio of the annual heating and cooling delivered to the building by the system, Q_{sys}, and the annual electricity consumed by the system, E_{sys}. The (SPF) of a heat pump system is a common way to evaluate the system's heating and cooling performance. However, in order to compare the performances of different systems, common boundary conditions for the systems have to be defined. The IEE project SEPEMO-build have proposed four different boundary conditions, H1 - H4, and calculation models for the SPF of heat pump systems [7]. These are illustrated in Figure 2.1, and explained in this section.

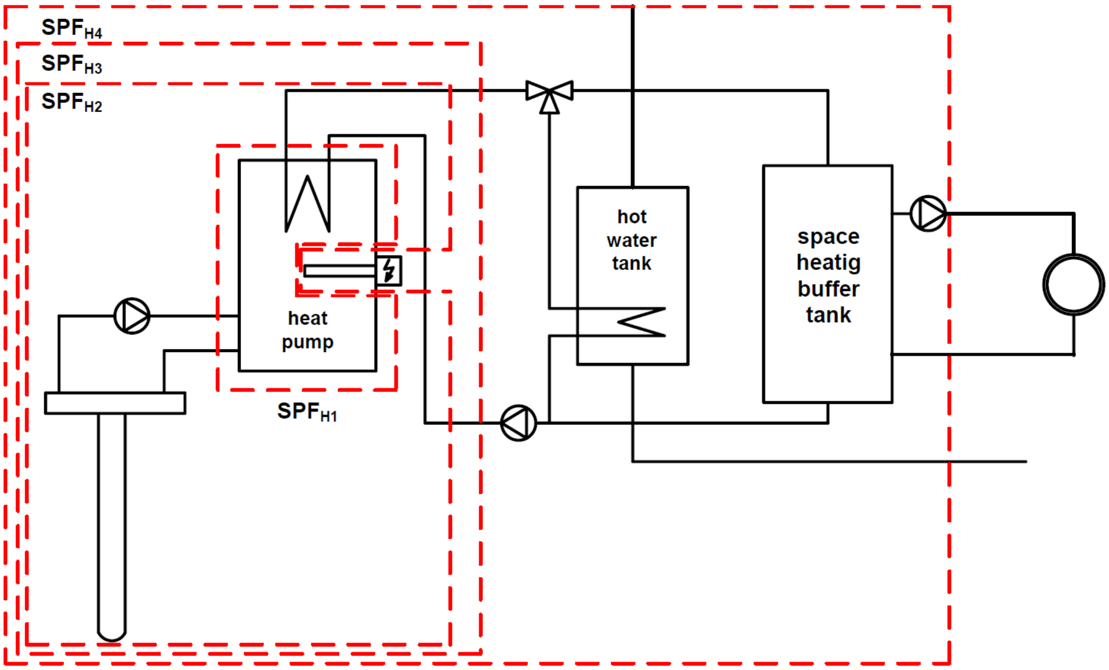


Figure 2.1: *Proposed boundary conditions in the SEPEMO-build project [7].*

SPF_{H1} is only considering the efficiency of the refrigerant cycle of the heat pump. Thus only the electricity consumed by the compressor is taken into account, along with the heat delivered by the condenser. The SPF_{H1} is thus calculated using Equation 2.1:

$$SPF_{H1} = \frac{Q_{H,hp} + Q_{W,hp}}{E_{comp}}, \tag{2.1}$$

where $Q_{H,hp}$ is the heat delivered by the heat pump for space heating, $Q_{W,hp}$ is the heat delivered by the heat pump for heating of domestic hot water, and E_{comp} is the electricity consumed by the compressor.

SPF_{H2} also takes into account the electricity consumed by the equipment needed to utilize the heat source, $E_{fan/pump}$. This is for instance fans or pumps that circulates air or brine water through the evaporator, allowing the refrigerant to absorb heat from the heat source. Thus, the SPF_{H2} can be calculated as presented in Equation 2.2:

$$SPF_{H2} = \frac{Q_{H,hp} + Q_{W,hp}}{E_{fan/pump} + E_{comp}}. \tag{2.2}$$

SPF_{H3} also includes the heat distributed and electricity consumed by the backup heater, usually an electric boiler. Thus, the SPF_{H3} can be calculated by Equation 2.3:

$$SPF_{H3} = \frac{Q_{H,hp} + Q_{W,hp} + Q_{backup}}{E_{fan/pump} + E_{comp} + E_{backup}}, \tag{2.3}$$

where Q_{backup} and E_{backup} are the heat produced and electricity consumed by the backup heater respectively.

The SPF_{H4} of the heat pump system can be calculated using Equation 2.4:

$$SPF_{H4} = \frac{Q_{H,hp} + Q_{W,hp} + Q_{backup}}{E_{fan/pump} + E_{comp} + E_{backup} + E_{distr}}. \tag{2.4}$$

Compared to the SPF_{H3}, the SPF_{H4} also takes into account the electricity consumed by the pumps distributing the heat in the building, E_{distr}.

2.1.2 Energy coverage factor

The energy coverage factor of a heating source, α, is defined as the ratio between the annual production of heat for spaces, ventilation air and domestic hot water by the heat source, and the total annual net energy need for heating. This is shown in equation Equation 2.5:

$$\alpha = \frac{Q_{SH,source}}{Q_{tot}} + \frac{Q_{vent,source}}{Q_{tot}} + \frac{Q_{DHW,source}}{Q_{tot}}, \tag{2.5}$$

where $Q_{SH,source}$, $Q_{vent,source}$ and $Q_{DHW,source}$ are the annual productions of heat by the heat source for spaces, ventilation air and domestic hot water respectively.

The energy need for space heating depend on the insulation level of the building, while for heating of domestic hot water it does not. Therefore, heating sources covering space heating only tend to have a low energy coverage factor for well-insulated buildings, while the opposite is true for heat sources covering domestic hot water only.

2.2 Literature review

2.2.1 Heat pump system performance

The validity of the modeled heat pumps in this project work can be evaluated by comparing the performances of the simulated heat pump systems in this thesis with the performances of heat pump systems in other studies. In order to do so, common boundary conditions of the heat pump systems being compared have to be defined. As the heating systems in this project work contains an electric boiler, and direct electric space heating in some scenarios, in addition to the heat pump, the boundary conditions for the SPF_{H3} described in Figure 2.1 and Equation 2.3 have been considered the most adequate.

As it is hard to continuously measure the heat production of non-ducted air-to-air heat pumps with sufficient accuracy, few studies have been found addressing the SPF of air-to-air heat pump systems. However from March 2008 to February 2009 SP Technical Research Institute of Sweden made field measurements of five air-to-air heat pumps [8]. The field measurements are described in Nordman et al. [9]. In the study, the electricity consumption and temperatures were logged continually, while the heat produced by the heat pumps were measured at five different temperature levels. The COP is then calculated at the five temperature levels. The COP can then be expressed as a function of temperature, and the average monthly COP can be calculated using average monthly temperatures. Thus, the SPF_{H2} and SPF_{H3}, when the electricity consumption of the elecatric backup heaters included, can be calculated. The study presents a SPF_{H3} for space heating only of 2.1. However, these might be overestimated as the heat pumps did not run any defrosting cycles during the measurements of the heating. Stignor and Walfridson state that very few field measurements of air-to-air heat pumps are found in open literature [10]. However, they present field measurements of air-to-air heat pumps from other studies with SPF_{H2}-values in the range of 2.2 to 2.6. The SPF_{H2} is approximately similar to the SCOP of the heat pump.

Nordman et al. evaluated the economic, environmental and energy saving potential of air-to-water and ground source heat pumps [11]. In order to do so, the SPF of several heat pump systems in different countries have been measured. In total, six air-to-water heat pumps and six ground source heat pumps were investigated. Three were located in Sweden, five in Switzerland and four in Scotland. The heat pumps located in Sweden, one air source and two ground source, are utilizing the sun or exhaust air as an additional heat sources. Furthermore, three of the remaining air-source heat pumps are covering space heating only. The boundary conditions used for the measured SPFs in the study are equal to the boundary conditions for the SPF_{H3} defined in the SEPEMO-build project. For the air-source heat pumps, the measured SPF range between 2.6 to 3.7. The SPF of the ground source heat pumps range from 3.3 to 4.7.

Miara et al. present the results of monitoring nearly 250 air-to-water and brine-to-water heat pumps in Germany, installed both in older and newer buildings [12]. The SPF from the measurements were calculated based on the heat produced from the heat pumps and back up heaters, and the electricity consumption for the heat pumps, backup heaters and fans/pumps for circulation of the heat source. The range of measured SPFs were between 2.1 and 4.2, and 2.2 and 5.4 for air-to-water and ground source heat pumps.

Kelly and Cockroft assessed the performance of an 8 kW air-to-water heat pump in a retrofitted house in Westfield, Scotland [13]. The performance of the heat pump was investigated through simulation and verified by comparing to field measurements of 8 similar buildings retrofitted with air-to-water heat pumps in the area. The simulations yielded an SCOP of 2.77.

Kazjonovs et al. investigated the performance of two air-to-water heat pump systems in two Latvian residential houses over two separate heating seasons [14]. The heat pumps covered both space heating and DHW, and the heating capacities were 12 and 6 kW respectively. Hydronic floor heating was utilized for both houses. The measured SPF of the heat pumps were 3.2 and 2.9 respectively.

Abdel-Salam, Zaidi and Cable investigated the performance of three ground source heat pumps installed in single-family houses in Canada [15]. The heat pumps, located approximately 80 km north of Toronto, were monitored over a heating season. The heat pumps were able to cover the entire heating demand without activating the electric backup heater. The SCOP of the heat pump system, equivalent to the SPF with H3 boundary conditions, ranged from 2.7 to 3.8.

O'Sullivan et al. investigated the performances of two identical integrated units combining exhaust air heat pump and heat recovery of ventilation air [16]. The exhaust air heat pump systems were installed in two PassivHaus certified buildings located in Ireland, one in a rural area and the other in an urban area. The exhaust air heat pump and heat recovery unit covered space heating, heating of ventilation air, and heating of domestic hot water. The system was monitored for approximately 12 months. With H3 boundary conditions, the measured SPF values were 1.7 and 2.4 for the rural and urban buildings respectively.

Shirani et al. evaluated the energy performance of an exhaust air heat pump in combination with ventilation heat recovery [17]. The peformance is evaluated through simulation using a Matlab Simulink model based on data from long term field monitoring of a physical heat pump model. The heat pump in the study is part of a hybrid heating system, where it serves as a centralized heating unit. The heat from the heat pump is distributed in the building through ventilation heaters. The remaining heat demand is covered by several de-centralized electrical heaters. The electrical heaters are only activated if the heat pump is operating at full load. The simulated heat pump system is applied in three different building types with annual heating demands of 34, 23 and 16 kWh/m^2 respectively. The effects of five different operating strategies are also investigated. The results show the operating strategies have a significant effect on the performance. The SPF_{H3} for the space heating system range from more than 3 to less than 1.5 depending on building type and operating strategy. Higher insulation levels yielded higher SPF, and the most efficient operating strategy is reducing the temperature set point of the electrical heaters by 1 K. The SCOP of the heat pump ranged from approximately 3.5 to 4.1. Furthermore, it was concluded the heating capacity was limited by the ventilation air flows.

Dermentzis et al. monitored a system consisting of an exhaust air heat pump and ventilation heat recovery in a renovated residential house in Germany over a heating season [18]. Similarly to the system in the study by Shirani et al., the heat pump covered space heating through ventilation heaters. In addition, the system contained direct electric backup heaters. The achieved SPF_{H3} for space heating throughout the heating season was 1.7. The SPF of the heat pump alone was 2.5.

Saini et al. present a techno-economic analysis of a heating system in a Swedish residential cluster [19]. The heating system consist of a exhaust air heat pump, solar collectors and an electric boiler for backup heating. The building cluster is modeled and simulated in TRNSYS, and the effects of adjusting the solar collector area are investigated. For the reference case, where the solar collectors are not included, the measured SPF is 1.43. The electricity consumption of the pumps for heat distribution through the building cluster is taken into account, so the boundary conditions are comparable to the H4 boundary conditions presented in Figure 2.1. The electricity consumption of the pumps amounted to 1.9% of the total electricity consumption of the heating system.

Thalfeldt, Kurnitski and Latõšov simulated an apartment building located in Estonia equipped with an exhaust air ventilation heat pump and connection to the district heating grid [20]. The energy need for space heating and domestic hot water were 77.6 kWh/m^2 and 30.2 kWh/m^2 respectively, which in total is 107.8 kWh/m^2. Three different connection schemes for the exhaust air heat pump were simulated. The total delivered energy to the heat pump and from district heating were 51.6, 56,4 and 55,9 kWh/m^2 for the three connection schemes. Thus, the SPFs were 2.09, 1.91 and 1.93 respectively.

Pylsy and Kurnitski studied the performance of the exhaust ventilation systems of two case houses, A and B [21]. Case A consists of one appartment building while case B consists of two. Both cases are connected to the district heating grid. Measurements of the buildings were made over a two year period. The SCOP of the two cases were both measured to 3.7, while the energy coverage factors were measured to 54% and 40% for case A and case B respectively.

The literature study on heat pump system performances are summarized in Table 2.1.

Table 2.1: *Summary of the literature review on performance of heat pump systems. Continuation on next page.*

Study	Heat pump system	Country	Method	Main findings
Nordman et al. [9].	Air to air heat pump.	Sweden.	Measurements of the heat pump performance at five different outdoor temperature levels. The heat pump performance at other temperatures are then estimated through interpolation.	SPF_{H3} for space heating is estimated to 2.1.
Stignor and Walfridson [10].	Air to air heat pumps.	Nordic countries.	The study presents field measurements from other studies.	SPF_{H2} ranging from 2.2 to 2.6.
Nordman et al. [11].	Six air-to-water and six ground source heat pump systems.	Scotland, Sweden and Switzerland.	The study presents the results of field measurements of six air-to-water and six ground source heat pump systems.	The study presents values of SPF_{H3} ranging from 2.6 to 3.7 for the air-to-water systems. For the ground source heat pumps, SPF_{H3} values range from 3.3 to 4.7.
Miara et al. [12].	88 air-to-water heat pump systems, and 137 ground source heat pump systems.	Germany	The study evaluates the heat pump performance of three different monitoring projects.	The study presents values of SPF_{H3} ranging from 2.1 to 4.2 for the air source heat pumps. The mean SPF_{H3} of the three projects are 2.6, 2.9 and 3.1 respectively. For the ground source heat pump systems, values of SPF_{H3} are ranging between 2.2 to 5.4, with averages of 3.3, 3.9 and 4.0 for the three projects.
Abdel-Salam, Zaidi and Cable [15].	Three ground source heat pump systems	Canada	The heat pumps were monitored over a heating season.	Achieved SPF_{H3} ranging from 2.7 to 3.8 for the three systems.
Kelly and Cockroft [13].	Air-to-water heat pump system.	Scotland	The performance of an air-to-water heat pump system is evaluated through simulation. The results are validated by comparing with field measurements of 8 similar systems.	A SCOP of 2.77 was achieved.

Study	**Heat pump system**	**Country**	**Method**	**Main findings**
Kazjonovs et al. [14].	Two air-to-water heat pump systems.	Latvia	Two air-to-water heat pump systems were monitored over two separate heating systems.	The heat pumps achieved SPFs of 3.2 and 2.9 respectively.
O'Sullivan et al. [16].	Two exhaust air heat pumps combined with ventilation heat recovery.	Ireland	The heat pumps were monitored for a 12 month period.	SPF_{H3} values of 1.7 and 2.4 were achieved for the two heat pump systems.
Shirani et al. [17].	Exhaust air heat pump combined with ventilation heat recovery.	Germany	Performance estimated through simulation. The simulation model is based on measurement data of a physical model.	SPF_{H3} values ranging from approximately 1.5 to more than 3 for different insulation levels and operating strategies. Heat pump SCOPs ranging from 3.5 to 4.1 were achieved.
Dermentzis et al. [18].	Exhaust air heat pump combined with ventilation heat recovery.	Germany	Field measurements over a heating season.	The heat pump system achieved a SPF_{H3} of 1.7. The heat pump alone achieved a SPF of 2.5.
Saini et al. [19].	Exhaust air heat pump.	Sweden	The heat pump performance is estimated through simulation.	The heat pump system achieved an SPF_{H4} value of 1.43.
Thalfeldt, Kurnitski and Latõšov [20].	Exhaust air heat pump.	Estonia	The heat pump performance is estimated through simulation.	The heat pump system achieved SPF_{H3} values ranging from 1.91 to 2.09 depending on connection schemes for the heating system.
Pylsy and Kurnitski [21].	Two exhaust air heat pump systems.	Finland	Field measurements over two years.	The SCOP of both heat pump systems were estimated to 3.7, while the energy coverage factor were estimated to 54 % and 40 % respectively.

2.2.2 Energy and economic performance of building renovation

Langdal evaluated the economic feasibility of energy renovation of two Norwegian detached houses constructed in 1957 and 1987 [22]. Three renovation levels equivalent to the TEK10, TEK17 and passive house standard were investigated. The simulation software SIMIEN has been utilized to estimate the energy performance of the buildings before and after renovation. The energy saving measures applied to the buildings include upgrades on the envelope, heating system and ventilation system. The TEK10 level is the recommended renovation level in terms of economic performance. However, the economic feasibility is highly dependent on the governmental grants through Enova.

Ekstrøm, Bernardo and Blomsterberg evaluated the cost effectiveness of renovating Swedish single-family houses to the passive house level, compared with upgrading the houses to the building regulation level and performing no renovation at all [23]. The energy performance was estimated using the building performance simulation software IDA ICE. In addition to upgrading the building envelope, different upgrades of the heating and ventilation system were evaluated. The ventilation system was upgraded to a mechanical ventilation system with either heat recovery or exhaust air heat pump. The exhaust heat pump supplied both space heating and DHW, and therefore acted as an upgrade of the heating system as well. Ground source heat pump, pellet boiler and district heating were the other heating systems being considered. The results show a reduction in energy consumption of up to 90 % when upgrading to passive house level, depending on the heating system. Both the ground-source heat pump and exhaust air heat pumps are cost effective at both passive house and building regulation level. The exhaust air heat pump proved to be the most cost efficient heating combination. Upgrading of windows were considered to be the least cost efficient measure.

Asaee, Ugursal and Beausoleil-Morrison assessed the techno-economic feasibility of converting the Canadian housing stock into net/near zero energy buildings [24]. The energy retrofit include air-to-water heat pump, auxiliary boiler, thermal storage tank, and hydronic heat delivery and DHW heating. The energy savings, GHG emission changes and economic feasibility were evaluated. The building energy simulation program ESP-r was utilized to predict the energy consumption. For the economic performance, a reverse payback analysis was conducted, where the capital costs needed to achieve acceptable payback times for the residential customers were determined. The capital costs were calculated with three different loan interest rates and fuel price escalation rates. The results showed the energy consumption and GHG emissions can be reduced by up to 36 % and 23 % respectively. The economic performance is harder to evaluate, as the feasibility is highly dependent on the energy prices and interest rates.

Hirvonen et al. evaluated the cost effectiveness of energy measures on the Finnish building stock [25]. In the study, the Finnish building stock is divided into four different age groups based on characteristics; those constructed before 1976, between 1976 and 2002, 2002 and 2009, and from 2010 and onward. Five different heating solutions (district heating, wood/oil boiler, direct electric heating and ground-source heat pump) were evaluated in combination with different renovation measures. Multi-objective optimization was used to find the combination of renovation measures with lowest life cycle costs and GHG emissions for each heating solution and building. The energy performance of four houses, each representative for one of the defined construction periods, was estimated through simulations using IDA ICE. Results showed replacing oil boilers with the other heating solution in combination with renovation measures had potential to be both cost effective and yield reductions in GHG emissions. The ground source heat pump yielded the highes reductions in GHG emissions, ranging from 79 to 92 % reduction depending on construction year and renovation measures. Air-to-air heat pump for auxiliary heating and improving the insulation levels of external walls proved to be the most cost effective renovation measures.

Gustafsson et al. compared the energy performance of three innovative HVAC systems through dynamic simulation [26]. System A is based on a mechanical ventilation with a micro heat pump (compact heat pump) for heating of ventilation air, system B consists of exhaust ventilation with exhaust air-to-water heat pump and ventilation radiators, and system C consists of exhaust ventilation with air-to-water heat pump and ventilation radiators. These systems were compared to a reference system D; exhaust ventilation with air-to-water heat pump and panel radiators. The systems were simulated using Matlab Simulink and TRNSYS, and were tested with two different renovation levels with heating demands of 15 and 25 kWh/m^2 respectively. Several locations across Europe were simulated. The results showed system A and B were favorable in colder climate. System A was best suited for the highly insulated envelope, while system B was best suited for the envelope with higher heating demand.

Jermyn and Richman developed and analyzed retrofit packages for three housing archetypes in Toronto [27]. The retrofit packages included upgrading of the building envelope and ventilation system, and improving efficiency of the heating system. Two separate energy intensity goals for heating and cooling were defined: 75 kWh/m^2 per year, and 25 kWh/m^2 per year, which is equivalent to the Passive House EnerPHit certificate. The reduction in energy consumption for the two goals were 64 to 67 %, and 88 to 89 % compared with the baseline. In two of the houses, the energy intensity goal of 75 kWh/m^2 yielded the lowest costs over a 25-year period. For the third house, the baseline yielded lower costs than the 75 kWh/m^2 and EnerPHit goals over the same period. Upgrading the exterior walls and slab yielded the highest energy savings, while upgrading the heating system yielded the highest cost/benefit. Upgrading the windows proved to be the least beneficial measure. Overall, with capital costs of the upgrade packages ranging from $30 000 to $80 000, it is concluded the packages may be considered unattractive for homeowners.

2.3 Electric grid tariffs in Norway

2.3.1 Current situation

In Norway, the electricity bill is split into two parts. The first part covers the electricity bought by the consumer from the electricity supplier. The second part is called the electric grid tariff, and is paid to the local grid owner. The grid tariff covers operation, maintenance and improvements of the electricity grid, as well as taxes and fees to the authorities. The grid tariffs are usually consisting of two fees; one fixed, annual or monthly fee and one variable fee based on electricity consumption. In contrast to the electricity suppliers, the grid owners have monopoly within their supply areas. The Norwegian Regulatory Authority (NVE-RME) have therefore placed an individual limit on each grid owner's revenue by regulating the tariffs [28]. As all costs for operation, maintenance and improvements of the electricity grid is covered by the consumers alone, the revenue limits set by NVE-RME are based on these costs.

2.3.2 Proposed new grid tariffs

The total annual costs of the electricity grid amount to approximately 27 billion NOK [29]. Around 90% of these costs are fixed, and not affected by the consumers' behaviour. These fixed costs are related to existing investments in the grid, in addition to necessary costs for making the grid available for its users. The remaining 10 % of the total costs are related to losses when transferring electricity from the producers to the consumers. These losses increase with increased simultaneous electricity consumption, i.e. during power peaks, and is therefore affected by the consumers' behaviour.

Over the last decade, electricity has to a great extent started to replace fossil fuels in the Norwegian society through transitioning from fossil fueled vehicles on both land and water to electric ones, banning of oil-fired heating of residential and commercial buildings, and electrification of Norwegian industry [30]. While the electrification enables better utilization of renewable energy, the current grid capacity requires expansion to be able to deliver the future power need if the user behaviour is not changed [31]. Thus, in order to avoid or reduce the high costs related to future grid expansions, the electric power peaks have to be reduced.

Most grid companies offer a grid tariff where the variable energy fee amount to approximately 70 % of the total fee consumers pay annually. This does not reflect the actual costs related to the electricity grid, where the costs of consumer behavior are related to the power peaks, and not energy consumption. Therefore, in 2020 NVE-RME proposed a new grid tariff model where the consumers are incentivised to reduce their power peaks [29]. In order to do so, the variable energy fee is reduced, while the fixed fee is changed to depend on the consumer's power peaks. Other incentives could be reduced energy fees during hours when the electricity consumption is low, e.g. during the night.

The transition from the existing grid tariff model to the new tariffs was supposed to take place the 1st of January 2022, however the authorities agreed to delay the induction of the new tariffs on the 17th of December 2021. This resulted in grid companies delaying the induction of their new grid tariffs, even though most grid owners already had announced new price information.

The 6th of May 2022, during the work on this thesis, it was announced that the tariff models being investigated in this dissertation were withdrawn [32]. Instead, new regulation for grid tariffs were announced, which will be induced the 1st of July 2022. The tariff that are supposed to be induced differs slightly from the ones being investigated in this thesis. The main difference is that the fixed fee will be based on several power peaks during the month, instead of just one [33]. This is mainly due to reducing the impact of isolated incidents that cause abnormal power peaks. As the energy performance in this thesis is estimated through simulation, such incidents will occur to a less extent. Therefore, evaluating the grid tariffs that were supposed to be induced by 1st of January is still considered useful.

2.4 Economic performance

The procedures described in NS-EN 15459-1:2017 are used to evaluate the economic performance of the heating solutions in combination with the three different renovation levels [34]. Two evaluation methods have been performed; the calculation of global costs and payback time. These methods are described further in sections 2.4.1 and 2.4.2.

2.4.1 Global costs

The global costs of an heating combination are the present value of initial investment costs, annual maintenance costs, and energy costs over a defined calculation period. If equipment has a shorter lifetime than the calculation period, the replacement costs of equipment are also added. Finally, the present residual value of the equipment is subtracted from the global costs. Inflation is taken into account for future cash flows. The global costs are calculated using Equation 2.6.

$$GC = CO_{INIT} + \sum_{j} \left[\sum_{i=1}^{TC} \left(CO_{a(i)}(J) \cdot \left(1 + RAT_{XX(i)}(j) \right) \right) \cdot D\_f(i) - VAL_{fin(t_{TC})}(j) \right], \tag{2.6}$$

where:

GC	are the global costs,
CO_{INIT}	are the initial investment costs,
$CO_{a(i}(j)$	are the annual costs of system j in year i,
$RAT_{xx}(j)$	is the price development or inflation rate for year i,
$VAL_{fin(t_{TC})}(j)$	is the present residual value of system j at the end of the calculation period TC,
$D\_f(i)$	is the discount factor for year i.

The discount factor is used to calculate the present value of future cash flows, and is calculated using Equation 2.7:

$$D\_f(i) = \left(\frac{1}{1 + RAT_{disc}} \right)^{i}, \tag{2.7}$$

where:

i	is the number of years from the starting year,
RAT_{disc}	is the discount rate.

If the investments made are financed externally, for instance by loan financing, the discount rate is decided by factors such as inflation, relative energy price change compared to the price index, and taxes. For loan financed investments, the discount rate is set according to Equation 2.8 [35]:

$$RAT_{disc} = \frac{1}{1+e} \left[\frac{RAT_{loan}(1-s) - RAT_{xx}}{1 + RATxx} \right], \tag{2.8}$$

where:

s	is the tax deduction on loan interest,
e	is the relative change of energy price compared to price index,
RAT_{loan}	is the interest on the loan,
RAT_{xx}	is the general inflation rate.

The residual value of the system at the end of the calculation period is determined by linearly depreciating the investment cost of the system. Then, the present residual value is calculated by multiplying with the discount factor. If the system has been replaced during the calculation period one or several times, the investment cost of the final replacement is employed for the calculation. Finally, the residual value is calculated using Equation 2.9:

$$VAL_{fin(t_{TC})} = V_0 \cdot (1 + RAT_{pr})^{n \cdot LS} \cdot \left[\frac{TC - n \cdot LS}{LS}\right] \cdot D\_f_{TC}, \tag{2.9}$$

where:

V_0	is the initial investment cost,
RAT_{pr}	is the inflation rate of the product,
$\frac{TC-n \cdot LS}{LS}$	is the linear depreciation of the system,
n	is the number of replacements,
LS	is the expected lifetime of the system.

The future investment costs of possible replacements are determined by the inflation rate. Then the replacement costs are discounted to present value and added to CO_{INIT} in Equation 2.6.

2.4.2 Payback time

The payback time is the number of years it takes before the costs of an investment is recouped. In order for an investment to be profitable, the payback time has to be shorter than the expected lifetime of the equipment. The investments are compared to a reference scenario, which in many cases is not investing in any improvements. The payback time is calculated using Equation 2.10.

$$PB = ln\left[\frac{1}{1 - \frac{CO_{INIT} - CO_{INIT,ref}}{CF} \cdot RAT_{disc}}\right] \cdot \frac{1}{ln(1 + RAT_{disc})}, \tag{2.10}$$

where:

RAT_{disc}	is the discount rate,
CO_{INIT}	is the initial investment cost of the system,
$CO_{INIT,ref}$	initial investment cost of the reference, which is set to 0 if it is doing nothing,
CF	difference between running costs of the new investment and the reference.

2.5 The two case houses

The two case houses are participants in OPPTRE's architecture competition; *En pluss en... er tre (One plus one... equals three)* and *Hus i hage (House in a garden)*. In this thesis, three renovation levels for each house have been investigated. The first renovation level aim to nearly fulfill the requirements of the TEK10 regulations, the second level is the proposed level by the architectures in the competition, while the third renovation level aims to fulfill the requirements in the Norwegian passive house standard [36]. Pre renovation, the case houses can be considered characteristic for the Norwegian residential building stock. The layouts of the case houses before and after renovation are briefly described in sections 2.5.1 and 2.5.2.

2.5.1 Before renovation

Kristiansand The existing house in Kristiansand was built in 1972, and is characteristic for the period of time it was built. It has two floors; a main level and a basement with a combined floor area of 162 m^2, in addition to an unheated attic. The dwelling has two bedrooms on the main floor, one bedroom in the basement, and one bathroom in each floor.

Malvik Originally, the Malvik house is based on drawings of a prefabricated house from 1957. It contains two floors above ground level with a combined floor area of approximately 100 m^2, and an unheated basement with floor area of approximately 50 m^2. It is a family dwelling which has three bedrooms and one bathroom.

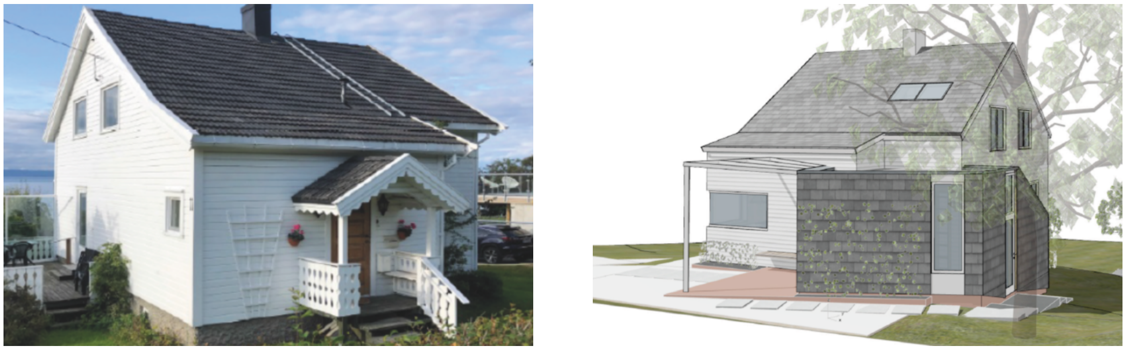
2.5.2 After renovation

Kristiansand In the renovated case house, hall areas are reemployed to rooms with more desired functions, such as additional bedrooms and bathrooms. Furthermore, the floor area is increased to 214 m^2 by utilizing cut-outs in the building body where the main entrance and terrace were located before renovation. In addition, a part of the basement have been transformed into a second living unit for rental consisting of a kitchen, living room, bedroom, bathroom, storage room and entrance. In total, the house has three bathrooms and bedrooms after renovation. The appearance of the dwelling before renovation and its proposed appearance after renovation are displayed in Figure 2.2.

(a) *The house in Kristiansand before renovation.* **(b)** *The house in Kristiansand after renovation.*

Figure 2.2: *The house in Kristiansand before and after renovation [37].*

Malvik The current owners of the house are a married couple in their 60's. The number of bedrooms have therefore been reduced from three to one in the renovated dwelling. Furthermore, the ground floor has been extended with an annex, which contains a door to the backyard and new stairs leading to the basement. The roof has been elevated, making it possible to increase the floor area of the top floor. The basement and annex are partly heated, and supposed to keep a minimum temperature of 15 °C. With the extensions of the dwelling in the renovated case, the total floor area is approximately 184.1 m^2. The appearance of the Malvik house before renovation and its proposed appearence after renovation are shown in Figure 2.3.



(a) *The house in Malvik before renovation.* **(b)** *The house in Malvik after renovation.*

Figure 2.3: *The house in Malvik before and after renovation [38].*

2.5.3 Energy characteristics

The specific heating demand of both space heating and DHW of the three renovation levels for both dwellings, both with and without balanced ventilation, are presented in Table 2.2.

Table 2.2: *Specific heating demand (kWh/m^2) of the three renovation levels both with and without balanced ventilation.*

	Kristiansand			**Malvik**		
	TEK10÷	**OPPTRE**	**PASSIVE**	**TEK10÷**	**OPPTRE**	**PASSIVE**
With balanced ventilation	68.3	53.1	40.0	91.1	71.3	50.6
Without balanced ventilation	93.1	82.3	70.3	108.7	95.1	76.2

The impact of the balanced ventilation system is significant, and increases as the renovation levels increase.

2.6 Heating solutions

The three renovation levels for the two case house are investigated in combination with 11 different heating solutions. The combinations mainly consist of different heat pumps, which are presented in Table 2.3. The different heating supply combination are presented in Table 2.4. These combinations, with the exception og ElRad, BalVent and CHPVentHeat, were also investigated in the work conducted by Kjelberg and Johansen [4]. The combination *ElRad* is considered to be the heating solution in the case houses before renovation, where minimal investments have been made after renovation. This combination, along with BalVent and CHPVentHeat have been All other combinations are considered as upgrades compared to this. Note that balanced ventilation is implemented in all upgraded heating solutions, with the exception of *EAHPDHW* and *EAHPCombi*.

Table 2.3: *Descriptions of the heat pumps employed in the studied combinations in previous work [4].*

Heat pump	**Description**
Air-to-air heat pump	Utilizes the heat from outdoor air, and blows it into the house through an indoor unit using fans.
Air-to-water heat pump	Utilizes the heat from outdoor air the same way as an air-to-air heat pump. However it is used to heat the water for hydronic radiators and floor heating, and domestic hot water.
Ground source heat pump	Extracts heat from the ground to heat water used in a hydronic heating system, and domestic hot water, similarly to the air-to-water heat pump.
Exhaust air heat pump	Extracts the heat from the exhaust ventilation air to heat the the domestic hot water, or both domestic hot water and the water in a hydronic heating system. The heating capacity is limited by the ventilation air flow rate.
Compact heat pump	A unit combining both exhaust air heat pump and balanced ventilation with heat recovery. The exhaust air heats the supply air through the heat recovery unit, before the remaining heat is extracted by the heat pump. Similarly to the exhaust air heat pump, the heating capacity is limited by the ventilation air flow rate.

Table 2.4: *Description of the investigated heating solutions.*

Combination	**Description**
ElRad	Exhaust ventilation with electric heating of spaces and DHW.
BalVent	Balanced ventilation combined with electric radiators and electric floor heating.
A2A	Air-to-air heat pump combined with electric radiators and electric floor heating.
A2AsolarDHW	Air-to-air heat pump combined with electric radiators and electric floor heating. Solar collectors for heating of DHW.
A2W	Air-to-water heat pump for both space heating and heating of domestic hot water. Hydronic distribution system. Electric backup heater.
CHPW4	Compact heat pump for heating of ventilation air and DHW. Electric radiators and electric floor heating for space heating. Electric backup heater for DHW.
CHPVentHeat	Compact heat pump for heating of ventilation air and DHW. Electric radiators and electric floor heating for space heating. Electric backup heater for DHW.
CHPWH4	Compact heat pump combined with an additional outdoor air unit for both space heating and heating of domestic hot water. Hydronic distribution system. Electric backup heater.
EAHPDHW	Exhaust air heat pump for heating of domestic hot water. Electric radiators and electric floor heating for space heating. Electric backup heater for DHW.
EAHPCombi	Exhaust heat pump for both space heating and heating of domestic hot water. Hydronic distribution system. Electric backup heater.
GSHP	Ground source heat pump for both space heating and heating of domestic hot water. Hydronic distribution system. Electric backup heater.

2.7 Governmental grants through Enova and external financing

2.7.1 Enova grants

Enova is owned by the Ministry of Climate and Environment and its task is to promote environmentally friendly energy consumption and production, and development of energy and climate technology [39]. New, innovative and environmentally friendly technologies are often both risky and costly for the consumer. Enova helps private individuals and enterprises implement such technologies in their projects by providing economic support and counselling [40]. This helps new technology getting established in the market and compete with well-established and cheaper solutions. The economic support provided by Enova for different HVAC-technologies and measures is presented in Table 2.5. Note that the hydronic heating system bonus is awarded if a brine-to-water heat pump, hydronic heating system *and* an accumulator tank for hydronic heating are all installed.

Table 2.5: *Economic support provided by Enova for different HVAC-measures [41–46]. *Up to 25 m^2.*

Measure	Economic support
Balanced ventilation	10 000 NOK
Brine-to-water heat pump	10 000 NOK
Hydronic heating	10 000 NOK
Accumulator tank for hydronic heating	5 000 NOK
Solar thermal collectors	5 000 NOK + 200 NOK per m^2 of panels*
Bonus: Complete hydronic heating system	15 000 NOK

Upgrading the building envelope might also yield economic grants from 100 000 NOK up to 150 000 NOK, depending on the renovation level. 100 000 NOK can be achieved if the building is upgraded to approximately TEK10-level. 125 000 NOK can be granted if the the building is upgraded to approximately low energy level, while upgrading to approximately passive house level grants 150 000 NOK. It is therefore assumed the TEK10÷, OPPTRE and PASSIVE renovation levels are eligible for economic grants of 100 000, 125 000 and 150 000 NOK respectively.

2.7.2 EU taxonomy

The EU taxonomy is a classification system which has established a list of activities that are considered environmentally sustainable [47]. The taxonomy aims to create unified definitions of sustainable activities, which in turn may help companies, investors and policymakers identify which activities that can be considered environmentally friendly. The taxonomy acts as a list of requirements that activities must fulfill in order to be considered sustainable. The EU taxonomy will be implemented in Norway through the EEA Agreement, and might give benefits such as green funding for the activities that fulfill the sustainability requirements [48]. Both renovation of existing buildings and installing and operation of heat pumps are among the activities considered sustainable [49]. Thus, the measures investigated in this thesis might the fulfill requirements for green loans.

3 Method

The work in this thesis can be divided into two main parts. Simulation models of two case houses located in Kristiansand and Malvik form the basis of both parts. The first part is a continuation of the work done in a specialization project from the autumn of 2021 and Johansen and Kjellberg's masters thesis from the spring of 2021 [4]. In this part, the economic performance of 10 different upgrades of the heating solution in combination with three renovation are investigated. In the second part, the effects different electric grid tariffs on the economic performance are looked into. Furthermore, the saving potential of different operational measures to reduce power peaks and energy consumption are evaluated.

3.1 Simulation models

The chosen simulation tool for this project is IDA Indoor Climate and Energy (IDA ICE), which is developed by the Swedish company EQUA Simulation AB [50]. IDA ICE is a dynamic multi-zone simulation tool for study of thermal indoor climate and energy consumtion of buildings. The simulation tool is accessed through a educational license provided by Department of Energy and Process Engineering at NTNU.

The basis of the IDA ICE-models are from the models which are utilized in the Johansen and Kjellberg's work [4]. The models were revised and refined in a specialization project during the autumn of 2021. The models have been further revised and refined in the work with this thesis. In this section, the implementations and simulation inputs of the revised IDA ICE-models are presented.

3.1.1 Renovation levels

The parameters which define the three renovation levels, such as U-values of walls, roofs, floors, windows and doors, standardized thermal bridge values, and the air tightness of the envelope, are presented in Table 3.1.

3.1.2 Standardized inputs

Due to the different layout of the two dwellings, several of the simulation inputs have been standardized for comparative reasons. Most standardized inputs are set and scheduled according to SN-NSPEK 3031:2021 [51]. These inputs include internal gains such as lighting, technical equipment, persons and DHW, set points for heating and ventilation air flows. Furthermore, the location is set to Oslo for both dwellings.

The annual amount of energy consumed and heat emitted from internal gains are presented in Table 3.2, while the daily operational schedules are displayed in figures 3.1, 3.2, 3.3 and 3.4.

In IDA ICE, the heat emitted from persons is adjusted through the number of persons present and their activity level. In these models, an activity level of 1.2 MET has been set for all persons. According to NS-EN ISO 7730:2005, a heat emission of 1.2 MET is equal to approximately 70 W/(m^2 body surface), where the body surface of an average person is 1.8 m^2. Thus, an average person emits 126 W of heat at an activity level of 1.2 MET. During a year, this is corresponds to approximately 1100 kWh. For the two case houses with floor area of 214 m^2 and 184.1 m^2, this is equal to 5.16 kWh/m^2 and 6.00 kWh/m^2 respectively. In order to fulfill the NSPEK 3031 standard, the number of persons present are therefore set to 2.54 and 2.18 in the two dwellings.

Table 3.1: *Simulation inputs for both case houses. *Betwen basement and floor 1. **Between floor 1 and attic/floor 2.*

		Kristiansand			**Malvik**		
Parameter	**Unit**	**TEK10÷**	**OPPTRE**	**PASSIVE**	**TEK10÷**	**OPPTRE**	**PASSIVE**
U-value external wall		0.22	0.18	0.11	0.22	0.17	0.11
U-value basement wall		0.33	0.20	0.11	0.33	0.20	0.11
U-value roof		0.18	0.14	0.085	0.18	0.14	0.085
U-value external floor	W/(m^2·K)	0.30	0.18	0.11	4.37	4.37	0.11
U-value internal walls		0.47	0.47	0.47	0.47	0.47	0.47
U-value internal floor		0.47* 0.09**	0.47* 0.09**	0.47* 0.09**	0.47* 0.09**	0.47* 0.09**	0.47* 0.09**
U-value glazing and door		1.20	1.00	0.80	1.20	1.00	0.80
Normalized thermal bridge value	W/(m^2·K)	0.07	0.05	0.03	0.07	0.05	0.03
Air tightness	h^{-1}	3.0	1.5	0.6	3.0	1.5	0.6

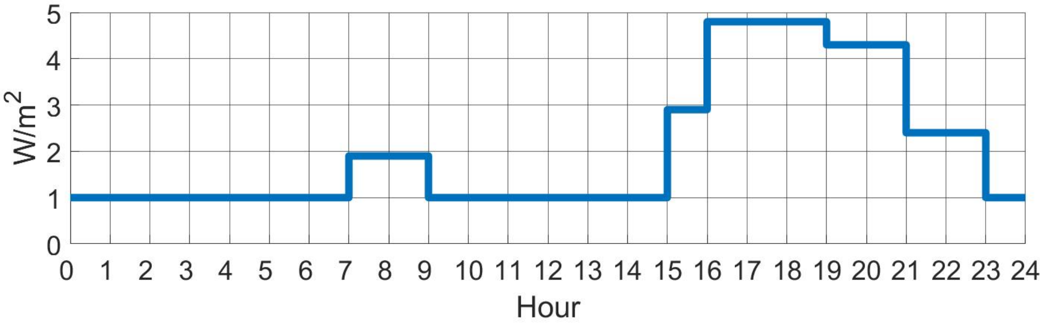


Figure 3.1: *Schedule for technical equipment according to NSPEK 3031 [51].*

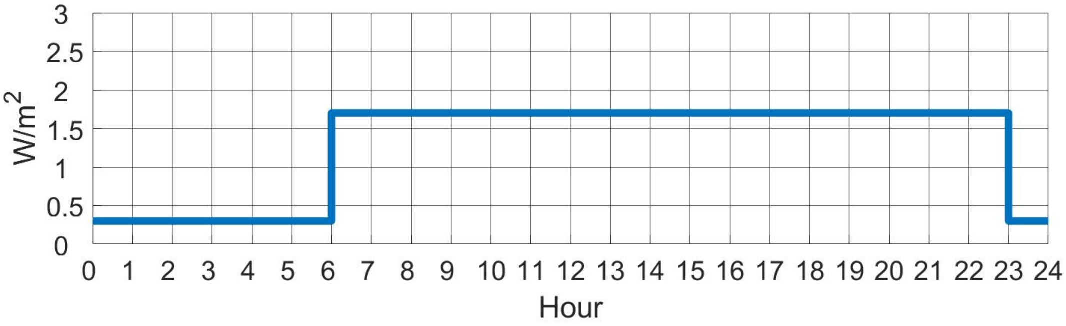


Figure 3.2: *Lighting schedule according to NSPEK 3031 [51].*

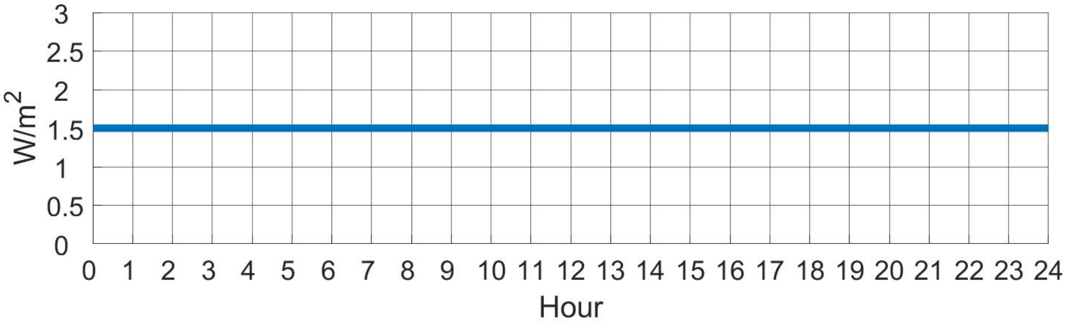


Figure 3.3: *Schedule for persons according to NSPEK 3031 [51].*

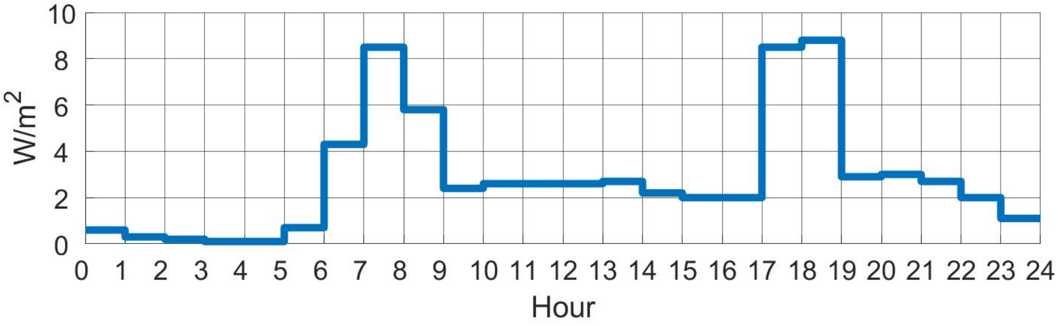


Figure 3.4: *DHW schedule according to NSPEK 3031 [52].*

Table 3.2: *The energy need per heated floor area and the heat emitted to zones for all internal gains [51].*

Internal gain	Energy per year	Amount of heat emitted to zones
Technical equipment	17.5 kWh/m^2	60 %
Lighting	11.4 kWh/m^2	100 %
Persons	13.1 kWh/m^2	100 %
DHW	25.0 kWh/m^2	0 %

The ventilation air flow rates are also set according to the minimum requirements in NSPEK 3031, which is 1.2 m^3/(h·m^2). In Malvik, some rooms in the basement are considered to be not intended for continuous occupancy. The ventilation flow rates in these rooms are set to 0.7 m^3/(h·m^2), which is in accordance to TEK17 [53]. Thus, the total air flow rates are 256.3 m^3/h and 202.7 m^3/h for the Kristiansand and Malvik house respectively. Exhaust air terminals are mainly installed in rooms such as bathrooms and toilets, kitchen, storage rooms and laundry. For the heating combinations where balanced ventilation is installed, the supply air is mainly distributed to rooms where occupancy is continuous, such as living room, kitchen and bedrooms.

The set point for heating is set to 22 °C, which is according to NSPEK 3031 [51]. However, a temperature setback is implemented between 00:00 and 08:00. During the setback, the temperature is reduced to 20 °C.

3.1.3 Modeling of heating combinations

The implementations of the heating combinations are presented in this section. In the previous simulation models, the heat pumps of the CHPW4, CHPWH4, EAHPDHW and EAHPCombi were modeled in a decoupled approach using Excel. As a part of the work with this thesis, these heat pumps have been modeled in IDA ICE instead. Furthermore, the CHPVentHeat combination have not been investigated in the previous works, and is a new addition in this thesis. More detailed implementation of these combinations are therefore presented in this section.

Heat distribution and heat emitters Depending on heating combination, heat is emitted to zones through either a direct electric or hydronic heating system. For the direct electric heating system, heat is emitted to zones through electric panel heaters. For the hydronic system, fan convectors have been utilized. Floor heating has been installed in zones like bathrooms, entrance and lavatories for both heating systems. The supply water temperature in the hydronic heating system is adjusted according to the weather compensating curve presented in Figure 3.5. The return water temperature is set to 20 °C. The sizes of the heat emitters are adjusted according to the heating demand at DOT, with internal and solar heat gains not taken into account.

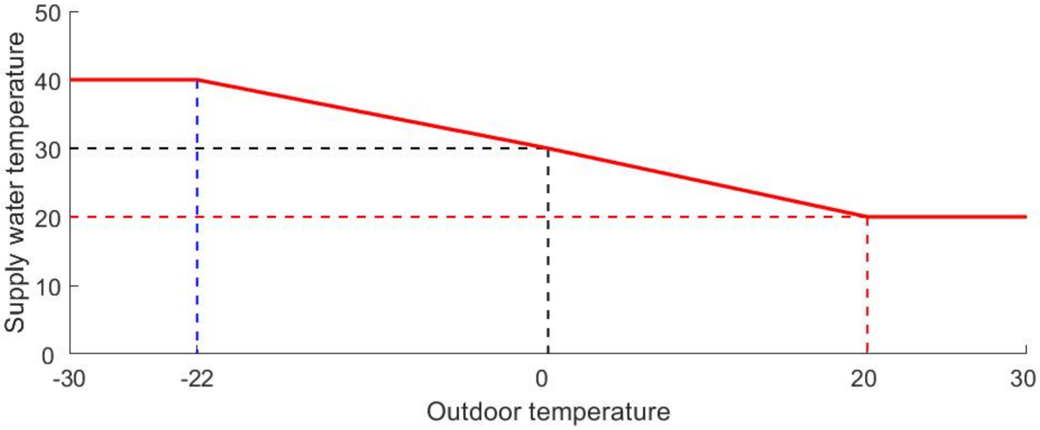


Figure 3.5: *Weather compensating curve for the supply water in the hydronic heating system.*

Domestic hot water The temperature of the DHW is set to 55 °C. Furthermore, a hot water tank has been installed in all combinations. With the exception of the A2ASolar combination, the size of the tank is 300 L. In order to increase the energy storage for the solar thermal collectors, the tank size is set to 600 L for the A2ASolar combination. The solar thermal collectors in the A2ASolar scenario are dimensioned to cover approximately 50 % of the DHW demand. Thus, the size of the solar thermal collector are set to 10 m^2 and 6 m^2 for the Kristiansand and Malvik house respectively.

Mechanical ventilation Depending on the heating combination, balanced or exhaust ventilation systems have been implemented. For both ventilation systems, the SFP is set to 1.5 $kW/(m^3/s)$, which is the minimum requirement of the TEK10 regulations [54]. In the balanced ventilation system, a heat recovery with 80 % efficiency is implemented. The set point temperature for the supply air after the heat recovery is 18 °C. An electric heating coil is activated if the supply air temperature is lower than 16 °C after the heat recovery.

Heat pump parameters All heat pump parameters, and the temperature conditions at which the parameters are set, are presented in tables 3.3 and 3.4 for the Kristiansand and Malvik house respectively. The reasoning behind the heat pump parameters is described in the following paragraphs.

Table 3.3: *Heat pump parameters for the Kristiansand house, and the temperature conditions at which the parameters are set. The presented conditions are the temperature of the air/brine at the evaporator inlet and the air/water temperature at the condenser outlet.*

	COP [-]			**Size [kW]**			**Rating conditions [°C]**	
Combination	TEK10÷	OPPTRE	PASSIVE	TEK10÷	OPPTRE	PASSIVE	t_{ev}	t_{co}
A2A	3.0	3.0	3.0	4.5	4.5	4.5	7	21
A2W	3.5	3.5	3.5	9.0	7.3	7.3	7	45
CHPW4	3.5	3.5	3.5	1.5	1.5	1.5	0	35
CHPWH4	3.5	3.5	3.5	6.0	6.0	6.0	0	35
CHPVentHeat	3.5	3.5	3.5	1.5	1.5	1.5	0	35
EAHPDHW	3.93	3.93	3.93	1.9	1.9	1.9	0	35
EAHPCombi	3.93	3.93	3.93	1.9	1.9	1.9	0	35
GSHP	4.5	4.5	4.4	8.2	8.2	4.5	0	35

Table 3.4: *Heat pump parameters for the Malvik house, and the temperature conditions at which the parameters are set. The presented conditions are the temperature of the air/brine at the evaporator inlet and the air/water temperature at the condenser outlet.*

	COP [-]			**Size [kW]**			**Rating conditions [°C]**	
Combination	TEK10÷	OPPTRE	PASSIVE	TEK10÷	OPPTRE	PASSIVE	t_{ev}	t_{co}
A2A	3.0	3.0	3.0	4.5	4.5	4.5	7	21
A2W	3.5	3.5	3.5	9.0	7.3	7.3	7	45
CHPW4	3.5	3.5	3.5	1.5	1.5	1.5	0	35
CHPWH4	3.5	3.5	3.5	6.0	6.0	6.0	0	35
CHPVentHeat	3.5	3.5	3.5	1.5	1.5	1.5	0	35
EAHPDHW	3.93	3.93	3.93	1.9	1.9	1.9	0	35
EAHPCombi	3.93	3.93	3.93	1.9	1.9	1.9	0	35
GSHP	4.5	4.4	4.4	8.2	4.5	4.5	0	35

EAHPDHW and EAHPCombi The implementation of the heating systems for both the EAHPDHW and EAHPCombi scenarios are similar. These heating combination do not have a balanced ventilation system installed, only exhaust air. The heat pump extracts heat from the exhaust ventilation air through a liquid heat recovery coil. The modeled AHU with liquid heat recovery coil is displayed in Figure 3.6.

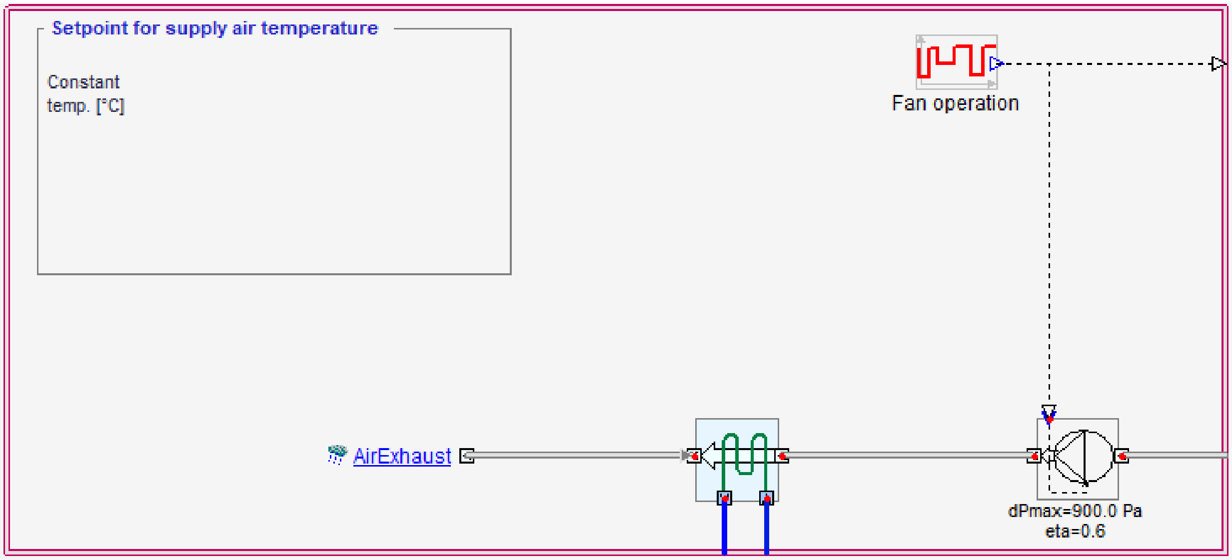


Figure 3.6: *AHU for the EAHPDHW and EAHPCombi scenarios.*

The liquid heat recovery coil is dimensioned to lower the exhaust air temperature from 22 °C to 1 °C, and a brine temperature change in the heat recovery coil of 5 K; from -2.5 °C to 2.5 °C. With ventilation air flow rates of 256.3 and 202.7 m^3/m in the Kristiansand and Malvik house, the heat extracted from the exhaust air is approximately 2.3 kW and 1.9 kW. This yields a brine mass flow in the heat recovery coils of 0.1371 kg/s and 0.1084 kg/s respectively.

The liquid heat recovery coil is connected to a liquid circuit for AHU heat recovery in the ESBO plant in IDA ICE. The massflow rate and temperature change of the liquid circuit are set to be equal to the heat recovery coil. The standard IDA ICE heat pump model has been used, and is extracting heat from the liquid circuit in the ESBO plant. The size of the heat pump has therefore been dimensioned corresponding to the heat extracted by the liquid coil. The COP is set according to the product sheet of a real exhaust air heat pump [55].

CHPW4 and CHPWH4 The liquid exhaust air heat recovery coil has been installed in the AHU of CHPW4 and CHPWH4 scenarios as well. However, these heating combinations also include balanced ventilation systems with heat recovery. The liquid heat recovery coil extracts the remaining heat of the exhaust air after the heat recovery unit. The heat recovery unit will heat the supply air temperature up to 18 °C. An electric heating coil is turned on if the heat recovery is unable to heat the supply air to 16 °C. A schematic of the AHU is presented in Figure 3.7.

During the heating season, most of the useful heat in the exhaust air is recovered to the supply air through the heat recovery unit. This means less heat is available for the heat recovery coil. The heat recovery coil has therefore been dimensioned differently compared to the heat recovery coil in the combinations with exhaust air heat pumps. Due to great variations in the exhaust temperature after the first heat recovery, the dimensioning the heat recovery coil correctly is challenging. The heat pump in the study of Shirani et al. has therefore been used as reference [17]. In this

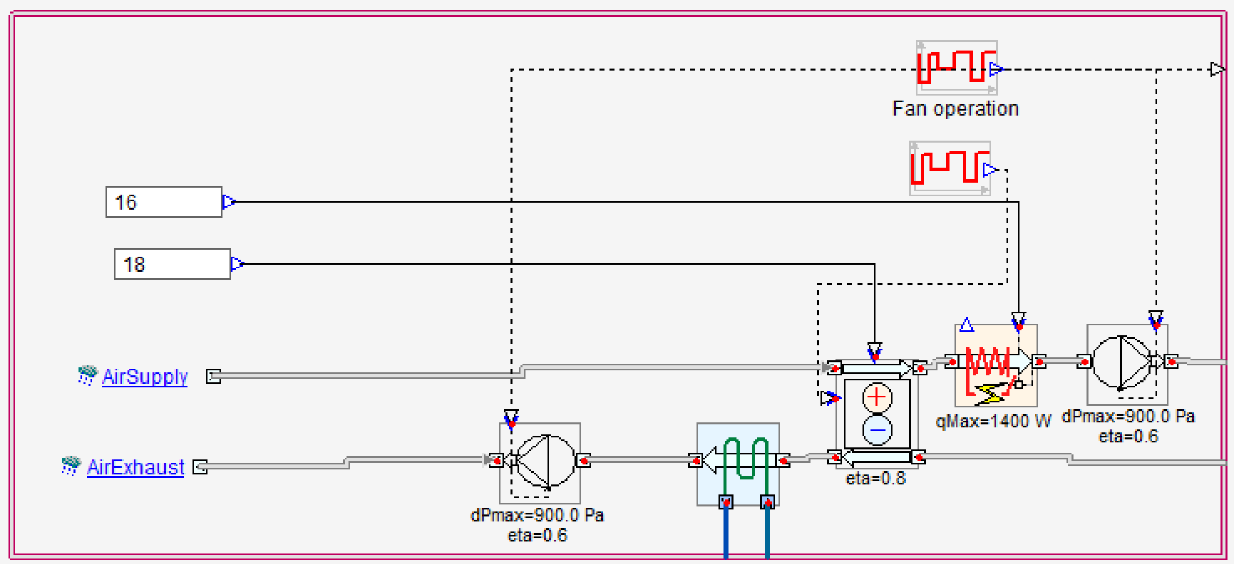


Figure 3.7: *Schematic of the AHU for the CHPW4 and CHPWH4 scenarios.*

study, the exhaust air temperature reaches temperatures just below -10 °C after passing through both heat recoveries. Thus, the size of the heat recovery coil was adjusted until exhaust air temperatures after both heat recoveries were similar to the reference during periods with low outdoor temperatures. The obtained exhaust air temperature for the CHPWH4 scenario in the Kristiansand house throughout the year is displayed in Figure 3.8.

The heat pumps in the CHPW4 and CHPWH4 combinations are connected to the exhaust air heat coil in the same way as the exhaust air heat pumps through a liquid circuit. As the CHPWH4 heat pump covers both space heating and DHW, it is also connected to an outdoor heat exchanger, which increases its heating capacity. The heating capacities of the CHPW4 and the CHPWH4 heat pumps are set to 1.5 kW and 6 kW respectively, with a COP of 3.5 for both.

CHPVentHeat In the CHPVentHeat scenario, the electric heating coil in the AHU is replaced with a hydronic heating coil. Thus, the heat pump is able to provide heat to the supply ventilation air in addition to heating the DHW. The COP and heating capacity of the heat pump, as well as the rest of the AHU and ESBO plant, are similar to the CHPW4 combination

A2A, A2ASolar and A2W Air source heat pumps tend to underperform compared to their product rated performance [56]. Therefore, the goal has been emulating the performance of heat pumps from field studies when adjusting the parameters of these in IDA ICE.

Both A2A and A2ASolar combinations include the same air-to-air heat pump for space heating. In both Kristansand and Malvik, the air-to-air heat pump has replaced the electric radiators in the zones with the highest heating demand. In both houses, the zone with the highest heating demand is the living room. The COP is adjusted to emulate the SCOP of the heat pump in Stignor and Walfridson's study [10].

The air-to-water heat pumps are modeled using the ESBO plant. For the A2W combination, the heating capacity of the air-to-water heat pumps are set to 9.0 kW in the TEK10÷ scenarios, and 7.3 kW in the OPPTRE and PASSIVE

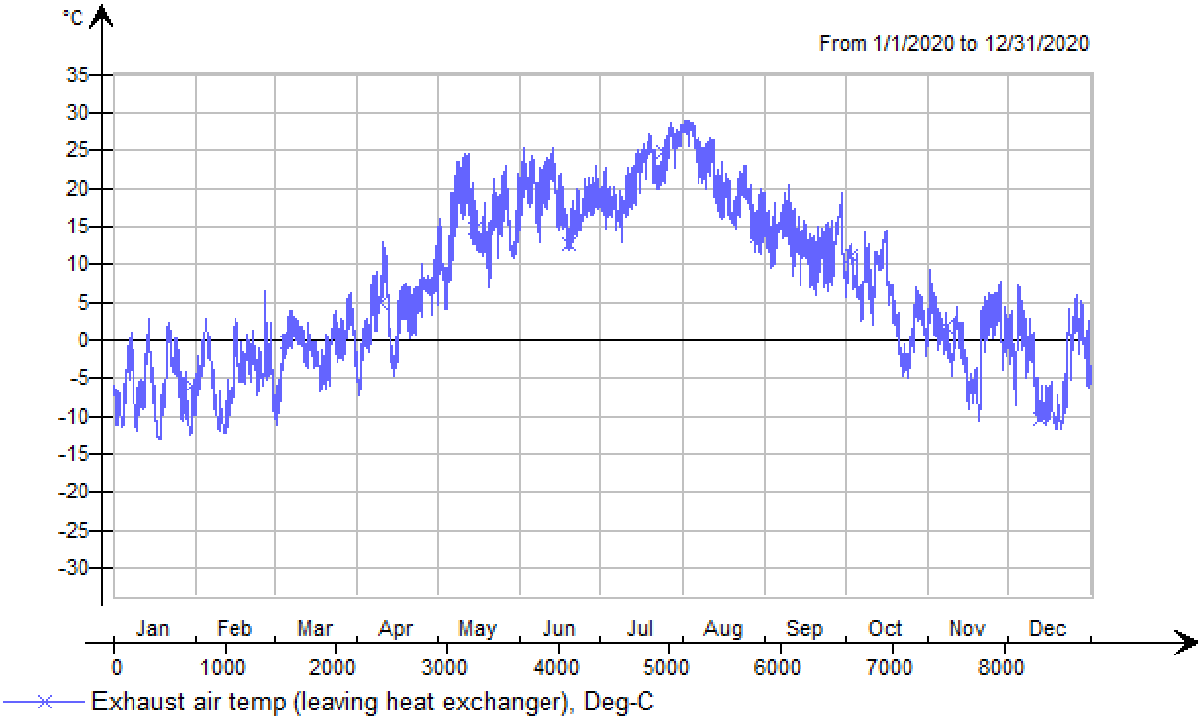


Figure 3.8: *Exhaust air temperature throughout a year for the CHPW4, CHPWH4 and CHPVentheat scenarios.*

scenarios for both houses. The COP is adjusted to emulate the performance of the heat pump in Kelly and Cockroft's study, where a SCOP of 2.77 is recorded [13]. By setting the COP presented in tables 3.3 and 3.4, a similar SCOP is achieved.

GSHP The ground source heat pumps are also modeled in the ESBO plant. The heat capacity and COP of the ground source heat pumps remain unchanged compared to the parameters used in the previous work by Johansen and Kjellberg [4]. Thus, a heating capacity of 8.3 kW and COP of 4.5 have been set for the heat pumps in the TEK10÷ and OPPTRE scenarios in the Kristansand house, as well as in the TEK10÷ scenario in Malvik. For the remaining scenarios, a heat pump with heating capacity of 5.5 kW and COP of 4.4 have been used.

3.2 Initial conditions for the economic performance evaluation

3.2.1 Parameters for the economic performance evaluation

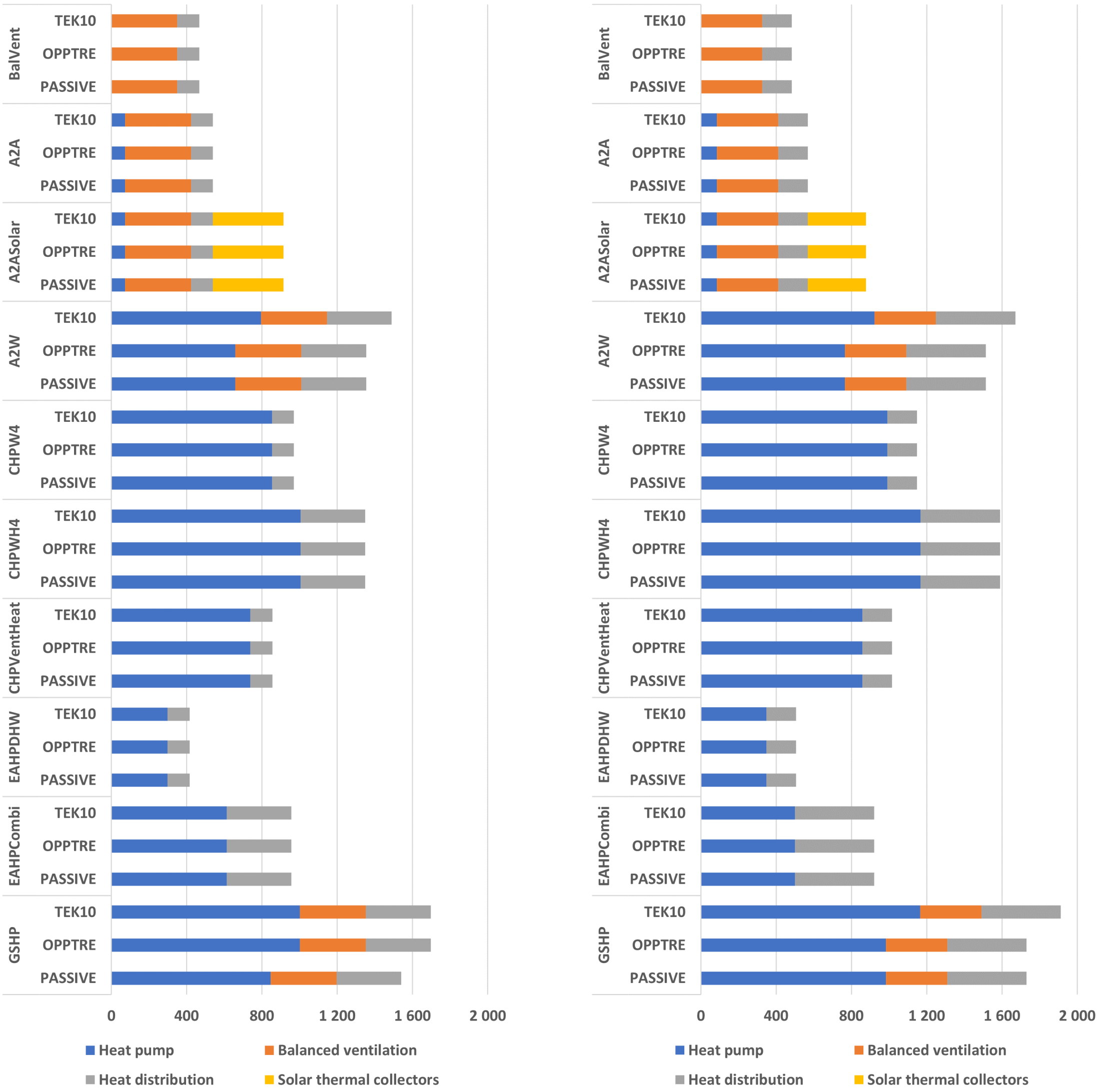
The parameters for the economic performance evaluation have been derived from Johansen and Kjellberg's thesis [4]. These are presented in Table 3.5.

Table 3.5: *Parameters for the calculation of economic performance.*

Parameter		**Value**
Calculation period (TC)		20 years
Inflation rate		2 %
Real discount rate		3 %
Discount factor at the end of TC		0.55
Lifetime	Building envelope	60 years
	Air-to-air, air-to-water and exhaust air heat pump	15 years
	Ground source and compact heat pump	20 years
	Electric panel heaters	25 years
	Fan convectors	15 years
	Floor heating	50 years
	Solar thermal collectors	25 years
	Balanced ventilation	20 years

3.2.2 Costs assessment of HVAC-technologies and building renovation

In order to investigate the economic performance of the different heating combinations, the costs of investment, maintenance and installation have been estimated. These costs are to a large extent derived from Johansen and Kjellberg's thesis [4]. The costs are collected by contacting suppliers directly, from their web pages, or from reports and statistics. For some combinations that are less common in Norway, the prices have been collected from the Danish and Swedish market. Due to lower prices in these countries, a conversion factor of 1.25 was used. Each combination has a certain price range due to several suppliers and brands that produce products of different qualities and sizes. These price ranges have been included, making it possible to take high end, low end and average prices into consideration. For most heating combinations, the investment costs are similar for all renovation levels. However, for the A2W and GSHP combinations, the heat pump capacities are reduced at higher building renovation levels, leading to lower investment costs. An overview of the mean specific investment costs including installation for all combinations are displayed in Figure 3.9.



(a) *Specific investment costs (NOK/m^2) of heating combinations for the Kristiansand house.*

(b) *Specific investment costs (NOK/m^2) of heating combinations for the Malvik house.*

Figure 3.9: *Specific investment costs (NOK/m^2) of heating combinations. Balanced ventilation is included in the heat pump costs for the CHPW4, CHPWH4 and CHPVentHeat combinations. Costs for heat emitters such as radiators, convectors and floor heating are included in the heat distribution category.*

The maintenance costs for each component have been estimated to constitute a fixed percentage of its investment costs. The maintenance costs of each component in the heating combinations are presented in Table 3.6.

Table 3.6: *Maintenance costs for each component in the heating combinations as a percentage of its investment costs.*

Component	Maintenance cost
Heat pump	2.0 %
Floor heating (electric or hydronic)	2.0 %
Electric radiators	1.0 %
Fan convectors	4.0 %
Balanced ventilation	5.0 %

The specific investment costs for renovation of the building envelopes are also included. The costs have been estimated by Jan Erik Åsen from Mestergruppen Arkitekter, and are presented in Figure 3.10. Maintenance costs of the building envelope have not been taken into account.

(a) *Specific renovation costs for the Kristiansand house.*

(b) *Specific renovation costs for the Malvik house.*

Figure 3.10: *Mean specific investment costs (NOK/m^2) for renovation of the building envelope.*

Only the costs of *energy* upgrades have been considered in this thesis. In Norway, floor heating is regarded as a comfort measure rather than energy measure in many cases. It is used for drying of shoes and snow melting in entrances, and in bathrooms where people often are barefoot. Parts of the investment costs for floor heating have been considered as comfort upgrade costs, and 20 000 NOK have therefore been deducted from the energy upgrade costs.

The initial investment costs are reduced by the grants provided by Enova. The total economic support granted by Enova for each heating combination is presented in Figure 3.11.

In addition to those grants presented in Figure 3.11, the grants provided for upgrading the building envelope have also been included.

3.2.3 Energy prices

The price trend of electricity is unpredictable, and setting a reasonable price when evaluating the economic performance of the scenarios in this thesis is hard. Different energy price models have been used in this thesis. In the first part, a default price model has been used where the price is fixed for the entire calculation period. In the second part, energy prices have been modeled focusing on the current grid tariffs and grid tariffs that are planned to be implemented in the future. In these models, the energy prices fluctuate based on grid tariff and the time of the year.

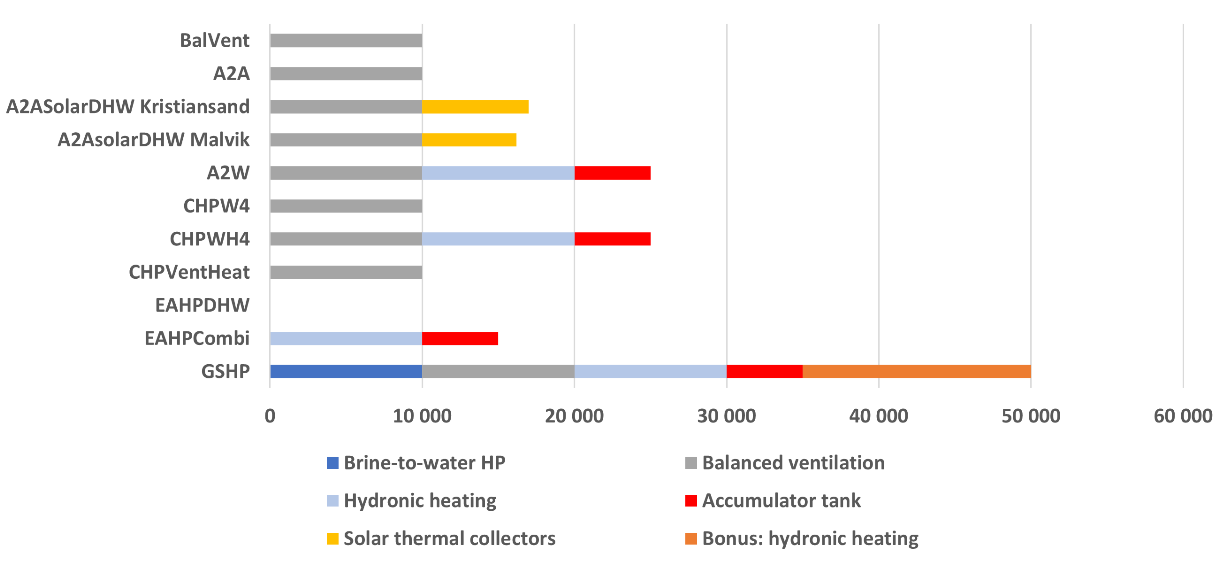


Figure 3.11: *Economic grants from Enova for each heating combination.*

Default energy prices Hydro power constitutes a high share of the power production in Norway, which traditionally has yielded lower electricity prices compared to the rest of Europe [57]. However, during 2021 Norway faced a drastic increase in electricity prices, especially in the southern parts of country. Abnormally low water reservoir levels is one of the reasons for the price increase. Furthermore, Norway is a part of the European power market, where low wind power production and high fossil fuel prices have resulted in a further increase of the electricity prices [58]. Therefore, a fixed price of 1.50 NOK/kWH has been set in the economic performance evaluation in the first part of this thesis. This price includes the electricity price, grid tariff and fees to the government. The price is higher than the average price from 2012 to 2021, but still significantly lower than the average price for the last and first quarter of 2021 and 2022 respectively [59, 60].

Energy prices with different grid tariffs In order to evaluate the economic effects of new grid on the scenarios, economic performance evaluations are made with energy prices that include the grid tariff of three different grid companies operating in Norway. These grid companies are Glitre, Elvia and Nettselskapet. Glitre is the owner of the regional grid of the former Buskerud county, and the distribution grids in the municipals of Drammen, Lier, Kongsberg, Gran, Jevnaker, Lunner and Finse [61]. Elvia is the owner of the grid in the former counties of Hedmark, Oppland, Østfold and Akershus, as well as Oslo [62]. Nettselskapet is the owner, and is responsible for operation and maintenance of the electric grid in the municipals of Orkland, Ørland, Indre Fosen, Heim and Hitra [63].

There are price differences among the three grid companies as they are operating in different areas of the country. However, their current grid tariffs are structured in the same way; one fixed fee, and one variable fee based on electricity consumption. The current tariffs of the grid companies will from now on be referred to as standard tariffs. Price information of their standard grid tariffs are collected from their home pages, and presented in Table 3.7. The prices include governmental fees.

The economic performance of the heating combinations with the standard grid tariffs have been compared to the grid

Table 3.7: *Price information for the standard grid tariffs of Glitre, Elvia and Nettselskapet [64–66]*

Fee	Glitre	Elvia	Nettselskapet	
Variable	47.39	48.20	33.51	øre/kWh
Fixed	1920	1380	4375	NOK/year

tariffs that were supposed to be induced in January 2022. The new tariffs are referred to as pilot tariffs from now on. The pilot grid tariffs are structured slightly different among the three grid companies. For all grid companies, the variable energy fee is reduced during nights and weekends. Furthermore, for Elvia the variable fee is reduced during summer months. For all companies, the size of the fixed fee now depends on the monthly power peaks. For Elvia and Nettselskapet, the fixed fee is paid monthly, and the size of the fee is decided by the highest power peak during the previous month. For Glitre, this fixed fee is also paid monthly, and is decided by the running average of the five highest monthly power peaks over the last 12 months. The price information of the pilot tariffs are presented in Table 3.8. For Glitre and Elvia, the price information have been collected from their homepage [67, 68]. For Nettselskapet, the price information has been collected by directly contacting the company.

Table 3.8: *Price information for the pilot grid tariffs [67, 68]. The hours between 22:00 - 08:00 are considered night, and the months April - September are considered summer. All governmental fees and taxes are included.*

Fee		Glitre	Elvia	Nettselskapet	
Variable, winter	Day	47.39	41.70	40.28	øre/kWh
	Night and weekend	35.39	29.20	28.32	øre/kWh
Variable, summer	Day	47.39	37.35	40.28	øre/kWh
	Night and weekend	35.49	31.10	28.32	øre/kWh
Fixed	0 - 2 kW	160	130	62.50	NOK/month
	2 - 5 kW	160	190	187.50	NOK/month
	5 - 10 kW	220	280	345	NOK/month
	> 10 kW	320	375	540	NOK/month

In addition to the grid tariffs, both old and new, the cost of electricity has to be considered as well. The average spot price for the Oslo area the past year, from May 2021 to April 2022, has been used. According to Nordpool, the average spot price for the period is approximately 112 øre/kWh excluding taxes, which is approximately 140 øre/kWh including taxes[69].

In order to calculate the energy costs with the new grid tariffs, the output resolution of the simulation results had to be set to 1 hour. Two Matlab scripts were used to extract the relevant information from the results files. One script was used to extract the highest power peaks for each month. The other script was used to summarize the electricity consumption during different times of the day, week and year. This had to be done in order to apply the correct variable grid price throughout the entire year. Furthermore, as the power peaks during the previous year is needed to calculate the fixed fee for the new Glitre tariff, it is assumed that the energy performance of the simulated year and the year prior are equal.

3.3 Measures to reduce power peaks

As the new grid tariffs should be rewarding for those who manage to reduce their electric power peaks, all scenarios have been simulated with different measures to reduce power peaks. These measures include removal of the night setback, temperature zoning, heat recovery of DHW, and a combination of all these measures. In addition to these measures, the electric backup heater have been dimensioned properly as the unlimited heating capacity set in the initial simulations would lead to unrealistically high power peaks. As trade-offs by dimensioning the back up heaters, the total heating capacity of the different scenarios are differing and the DHW is not maintained at a constant 55 °C. This leads to differing heating needs for the different scenarios, and a slightly reduced comparability. The heating capacity of the backup heaters have been set slightly lower than their highest power peaks logged during an energy simulation with unlimited heating power. The dimensions of the electric backup heaters in all scenarios are presented in Table 3.9.

Table 3.9: *Heating capacity of the electric backup heaters in all scenarios.*

	Kristiansand			**Malvik**		
Scenario	**TEK10÷**	**OPPTRE**	**PASSIVE**	**TEK10÷**	**OPPTRE**	**PASSIVE**
ElRad	3 kW	3 kW	3 kW	3 kW	3 kW	3 kW
BalVent	3 kW	3 kW	3 kW	3 kW	3 kW	3 kW
A2A	3 kW	3 kW	3 kW	3 kW	3 kW	3 kW
A2ASolar	3 kW	3 kW	3 kW	3 kW	3 kW	3 kW
A2W	6 kW	3 kW	3 kW	6 kW	3 kW	3 kW
GSHP	3 kW	3 kW	3 kW	3 kW	3 kW	3 kW
CHPW4	3 kW	3 kW	3 kW	1.5 kW	1.5 kW	1.5 kW
CHPWH4	6 kW	6 kW	6 kW	6 kW	6 kW	6 kW
CHPVentHeat	3 kW	3 kW	3 kW	1.5 kW	1.5 kW	1.5 kW
EAHP	1.5 kW	1.5 kW	1.5 kW	1.5 kW	1.5 kW	1.5 kW
EAHPCombi	6 kW	6 kW	6 kW	6 kW	6 kW	6 kW

3.3.1 No night setback

Initially, a temperature setback between 00:00 and 08:00 have been implemented to the models. During the setback, the heating setpoint is reduced from 22 °C to 20 °C. With night setback, the heating system have to increase the output in order to increase the temperature from 20 °C to 22 °C during the mornings. This coincides with the hours with a peak consumption of DHW and electricity for technical equipment due to showering and cooking of breakfast. This results results in a high electricity power peak, which might get expensive with the new grid tariffs. By setting the heating setpoint to a constant 22 °C during both day and night, the required heating output in the morning is reduced. However, as this measure might yield higher energy consumption, the profitability is uncertain.

3.3.2 Temperature zoning

Initially, the heating setpoint is equal for all zones, with the exception for the unheated attic and unheated basement in Kristiansand and Malvik respectively. With this heating strategy, a lot of energy goes wasted as zones such as storage rooms, technical rooms, laundry rooms, entrances and guest rooms are occupied for only limited amounts of time. Having a heating set point of 22 °C can therefore be considered excessive in such rooms. Models with reduced heating set points for zones with limited occupancy have therefore been simulated. The heating setpoints with temperature zoning implemented are presented in Table 3.10.

Table 3.10: *Heating setpoints with temperature zoning implemented. Night setback is still implemented in zones with a temperature setpoint of 22 °C.*

Setpoint	Kristiansand	Malvik
22 °C	Kitchens, living rooms and bathrooms on both floors	Bathroom, kitchen, living room and hallway
18 °C	Guest room, lavatory, laundry room	Loft, dressing room, stairways, lavatory and porch
15 °C	Entrance, storage rooms and technical rooms	Basement
No setpoint	Attic and bedrooms	Bedroom

3.3.3 Heat recovery of DHW

As a third measure, a simplified heat recovery of DHW has been implemented in the simulation models. With heat recovery of DHW, it is assumed that the energy consumption for DHW is reduced by 25 %. Furthermore, there is assumed no investment costs related to the heat recovery. As DHW make up a bigger share of the total energy consumption with higher insulation of the building envelope, the effects of the DHW heat recovery is expected to be greater in these scenarios.

3.4 Calculation of seasonal performance factor and energy coverage factor

To evaluate the system performance of the heat pump systems, the energy coverage factor and SPF has been calculated. The boundary conditions for the SPF include both the heat pump, the electric boiler, and any direct electric space heating system. The boundary conditions are thus similar to the H3 boundary described by Equation 2.3 in section 2.1.1 [7].

3.4.1 Energy coverage factor

To calculate the energy coverage factor of the heat pumps, the annual heat produced by the boiler has been logged along with the annual heat emitted by the condenser of the heat pump. Thus, for hydronic heating systems, the total heat emitted by the whole heating system is calculated using Equation 3.1:

$$Q_{tot} = Q_c + Q_{eb}, \tag{3.1}$$

where:

Q_{tot} is the total heat emitted by the heating system,

Q_c is the heat emitted by the heat pump,

Q_{eb} is the heat emitted by the electric boiler.

For the scenarios with direct electric heating of zones, the heat emitted by electric panel heaters and floor heating has to be taken into account as well. Then, with an direct electric space heating system, the total heat emitted by the heating system is calculated using Equation 3.2:

$$Q_{tot} = Q_c + Q_{eb} + Q_{el}, \tag{3.2}$$

where:

Q_{el} is the heat emitted by the direct electric heating system.

With the total heat emitted by the heating systems, the energy coverage factor of the heat pump can be calculated for hydronic heating systems and direct electric heating systems using Equation 3.3 and Equation 3.4 respectively:

$$\alpha_{hp} = \frac{Q_c}{Q_c + Q_{boiler}}, \tag{3.3}$$

$$\alpha_{hp} = \frac{Q_c}{Q_c + Q_{eb} + Q_{el}}, \tag{3.4}$$

where:

α_{hp} is the energy coverage factor of the heat pump.

3.4.2 Seasonal performance factor

To calculate the SPF, the annual heat emitted by the condenser of the heat pumps and the electric boiler, and the annual consumption of electricity by the heat pump and electric boiler were logged in IDA ICE. The electricity use of the heat pumps includes the electricity used by the compressor, as well as the electricity used by the fans or pumps to allow the heat source flow through the evaporator. Thus, the SPF is calculated using Equation 3.5:

$$SPF = \frac{Q_c + Q_{boiler} + Q_{el}}{E_{hp} + E_{boiler} + E_{el}}. \tag{3.5}$$

where:

E_{hp} is the electricity consumption of the heat pump,

E_{eb} is the electricity consumption of the electric boiler,

E_{el} is the electricity consumption of the direct electric space heating system.

For combinations with hydronic heating system, E_{el} and Q_{el} equal zero.

4 Results and discussion

4.1 System performance

4.1.1 Seasonal performance factor and energy coverage factor

The SPF and energy coverage factor for the heat pumps in all scenarios with the initial simulation parameters are presented in Figure 4.1 and Figure 4.2. As displayed in the two figures, the SPF and energy coverage factor correlate to a high degree. The scenarios with the highest SPF are A2W, CHPWH4, EAHPCombi and GSHP. All of these, with the exception of EAHPCombi also have an energy coverage factor of more than 80 %. This is due to EAHPCombi the only scenario among these where balanced ventilation is not installed, resulting in a higher net energy need. However, the favorable operating conditions for the exhaust air heat pump leads to a higher SPF than the energy coverage factor would indicate.

A drop in the SPF can be noticed at higher insulation levels for the GSHP combination. As the heating demand for ventilation air is constant for all insulation levels, the ratio of the *ventilation air heating need* to the *total heating need* increases as the insulation levels increase. The heat pump in this combination covers a high amount of the space heating and DHW for all insulation levels, meanwhile the heating of ventilation air is covered by an electric heating coil. Thus, the heating need covered by the direct electric coil increases as the renovation levels increase, leading to a decreasing SPF. This is the case for the CHPWH4 scenario in Malvik as well, although to a less degree. Furthermore, the size of the ground source heat pump is reduced in the Kristiansand PASSIVE scenarios, and the OPPTRE and PASSIVE scenarios of Malvik, compared to the scenarios with lower insulation levels. This also leads to a slight drop in SPF and energy coverage factor for the higher insulation scenarios. The same effect can be seen in the A2W scenario to a less degree, where the heat pump size is reduced for the OPPTRE and PASSIVE scenarios in both houses.

For the CHPW4, CHPVentHeat, EAHPDHW and A2ASolar scenarios, the SPFs and energy coverage factors are increasing along with increased insulation levels. The reason for this, is the heating need for DHW constitutes a higher share of the total heating demand at higher insulation levels. These combinations are mainly covering the DHW, with some heat delivered to ventilation air and spaces in the CHPVentHeat and A2ASolarDHW combinations respectively.

The SPF and energy coverage factor of the A2A scenario decreases as the renovation level of the building envelopes increase. With higher insulation levels, the space heating need decreases and amounts to a smaller share of the total heating demand. Thus, the air-to-air heat pump covers a smaller share of the total heating demand as well.

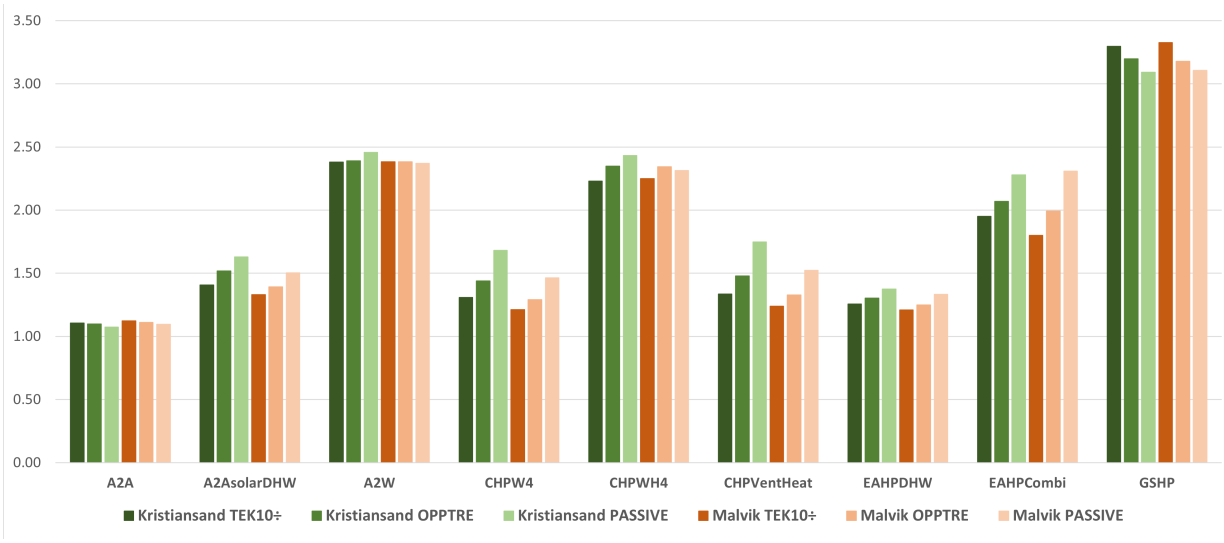


Figure 4.1: *SPF for all scenarios with initial simulation conditions.*

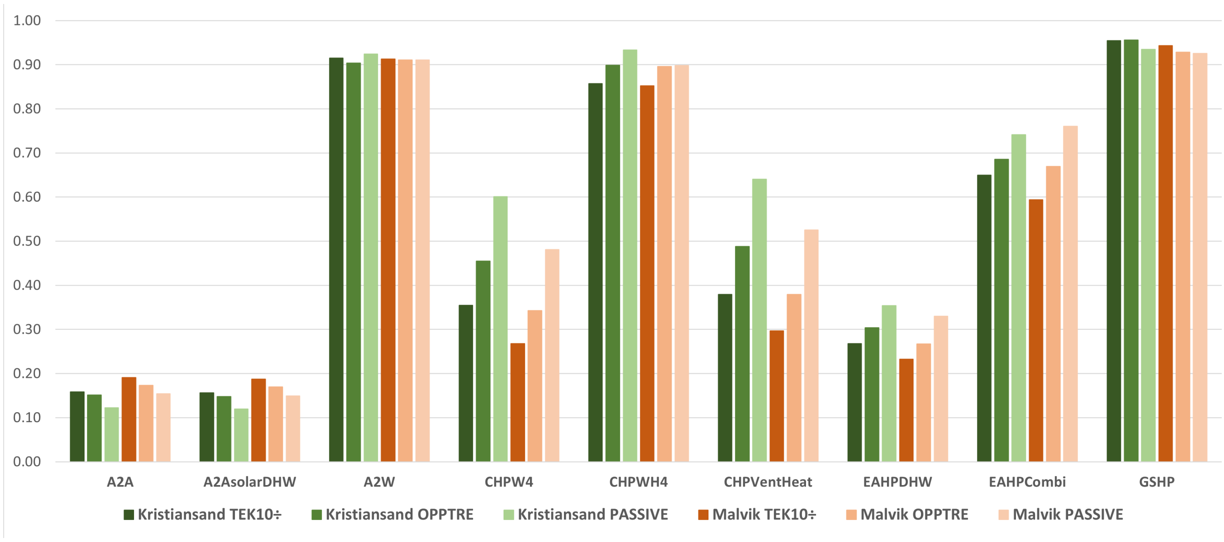


Figure 4.2: *Energy coverage factor for all scenarios with initial simulation conditions.*

4.1.2 Validation of the simulation models

In order to validate the simulation models and the results, the performance of the heat pump systems in this thesis have been compared with the performance of similar systems in literature. The literature used for validation have been presented earlier in this thesis, and is summarized in Table 2.1.

Validating the A2A-models is hard due to several factors influencing the performance of air-to-air heat pumps. As with all air-source heat pumps, the climate heavily affects the performance. Thus, the performance of air-source heat pumps may be varying depending on the geographical location. Comparing the performance of two air-source heat pumps might therefore be challenging if the heat pumps are located in different locations. Furthermore, the heat distribution of the air-to.air heat pump is heavily affected by the floor plan and building layout. If the indoor unit of the heat pump is placed in a room where the heat is not distributed efficiently to other parts of the building, the heat pump output decreases. Two similar heat pumps placed in two different buildings might therefore perform different in terms SPF and energy coverage factor. Evaluating the air-to-air heat pump performance by SCOP might therefore better suited. The SCOP equivalent to the SPF_{H2} of the A2A heat pumps in this scenario range from 2.0 to 2.4. The literature presents SPF_{H2} values ranging from 2.2 to 2.6 in Nordic climate. The SCOP of the A2A heat pumps in this scenario are thus in the lower end of the findings in literature. However, it can be argued that an increase in efficiency of the heat pumps in this study would have little effect on the results. If the SCOP increased to 3.0, the energy savings compared with the present SCOP would only reduce the specific energy consumption by 1.5 kWh/m^2 and 1.7 kWh/m^2 for the TEK10÷ scenarios. The low influence of the SCOP is because of the low energy coverage factor of the air-to-air heat pump. This shows the importance of installing the heat pump properly in order to maximize the energy coverage factor.

The achieved SPF_{H3} of the air-to-water heat pumps range from approximately 2.4-2.5. The reported SPF_{H3} from the study by Miara et al. report SPF_{H3} values between 2.1 to 4.2 from three different monitoring projects in Germany, with average 2.6, 2.9 and 3.1 [12] respectively. Meanwhile, Nordman et al. report SPF_{H3} values between 2.6 and 3.7 from Scotland, Sweden and Switzerland. The SPF values achieved are among the lower end of the reported SPF values reported in the literature. However, this can be expected, as the performance of air source heat pumps are heavily dependent on the climate. The houses simulated in this thesis are located in a colder climate compared with many of the heat pumps in the literature, which may affect the performance in a negative way.

The ground source heat pump system in this study achieved the highest SPF_{H3} with values ranging from 3.1 to 3.3 for the two houses. The performance of ground source heat pump systems varies heavily, and the reported SPF values are ranging between 2.2 and 5.4. However, the SPF values achieved in this study are within reported SPF spans of all studies presented in this thesis, and performs similarly to the reported average of 3.3 in one of the three projects in the study of Miara et al. [12]. Despite the heavy spans of reported SPF values in literature, the achieved SPF's in this thesis can be considered reasonable.

Validating the compact and exhaust air heat pumps based on literature is harder, as there are fewer studies that cover the field performance of such heat pumps. Most literature cover the performance of these systems through simulation or laboratory testing. Such studies have therefore been included in the validation process.

In all studies presented in this thesis, the compact heat pumps have been installed in a house with very low heating demand. The reason for this is the heating capacity of the heat pump is heavily limited by the air flow rates. This can also be seen in this thesis, where the SPF of the CHPW4 and CHPVentHeat combinations increase with increasing insulation levels. In the studies by Shirani et al. and Dermentzis et al., the achieved values for SPF_{H3} were ranging between 1.5 and 3.0, and 1.7 respectively [17, 18]. Meanwhile, the monitored heat pumps in the study by O'Sullivan et al. yielded SPFs of 1.7 and 2.4 [16]. These values are not far from the achieved SPF_{H3} of the CHPW4 and CHPVentHeat PASSIVE scenarios in this thesis.

The CHPWH4 combination is more similar to the A2W combination. This combination has an additional outdoor unit, and its heating capacity is not limited by the air flow rated. This is also seen in this thesis, where its performance is very similar to the A2W combination. With the previous studies in mind, the performance of the compact heat pumps in this thesis can be considered reasonable.

The achieved SPF_{H3} of the EAHPCombi and EAHPDHW combinations range from 1.8 to 2.3 and 1.2 to 1.4 respectively. Thus SPFs of the EAHPCombi combination at PASSIVE level are higher than those reported in literature, where SPF_{H3} values between 1.91 and 2.09 are reported. Due to the low numbers of literature evaluating similar heat pump systems, it is hard to tell if this is a coincidence, however it can be argued that the COP parameter of the heat pump is slightly overestimated.

4.2 Energy performance

The specific energy consumption of all scenarios is presented in Figure 4.3. The energy consumption follows to a high degree the same trends as the SPF and energy coverage factor. GSHP is the scenario with overall lowest energy consumption, followed by A2W and CHPWH4. In all these scenarios, the heat pump covers both DHW and space heating, leading to a high energy coverage factor and SPF as presented earlier in Figure 4.1 and Figure 4.2. Furthermore, the CHPW4 and CHPVentHeat are better suited to highly insulated houses rather than lowly insulated ones. This is due to the DHW amount to a higher share of the total energy consumption at high renovation levels. This is displayed in Figure 4.3, where the difference in energy consumption between A2W, CHPWH4 and GSHP, and to CHPW4 and CHPVentHeat is a lot bigger at TEK10÷ level comnpared to PASSIVE level.

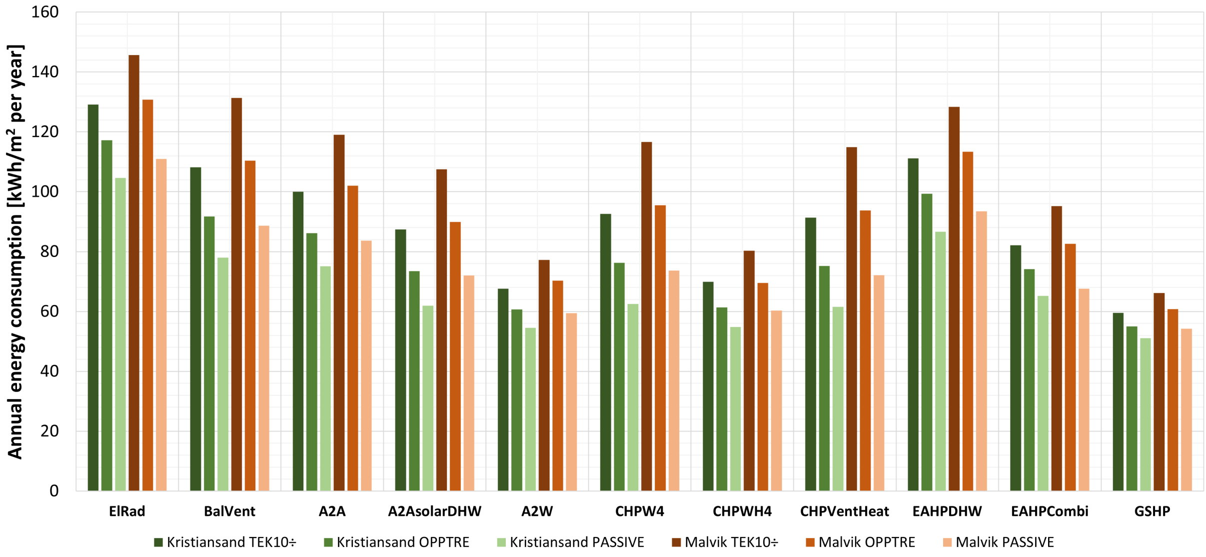


Figure 4.3: *Energy consumption of all simulated scenarios.*

Even though EAHPDHW also covers DHW only, this combination is not suited at high insulation levels. As this combination does not have balanced ventilation installed, it is less effective at higher insulation levels with the higher air tightness of the building envelope. This is clear at the Malvik house especially, where the energy consumption of the EAHPDHW combination is lower than BalVent at TEK÷ level. However, at PASSIVE level, the opposite becomes true. This is also displayed in Figure 4.4, where the energy savings of the BalVent scenario increase with higher renovation levels. The same is true for the EAHPCombi combination, which has a SPF not far off the A2W and CHPWH4 combinations. However, the increased heating need due to no heat recovery results in a much lower energy coverage factor and higher energy consumption.

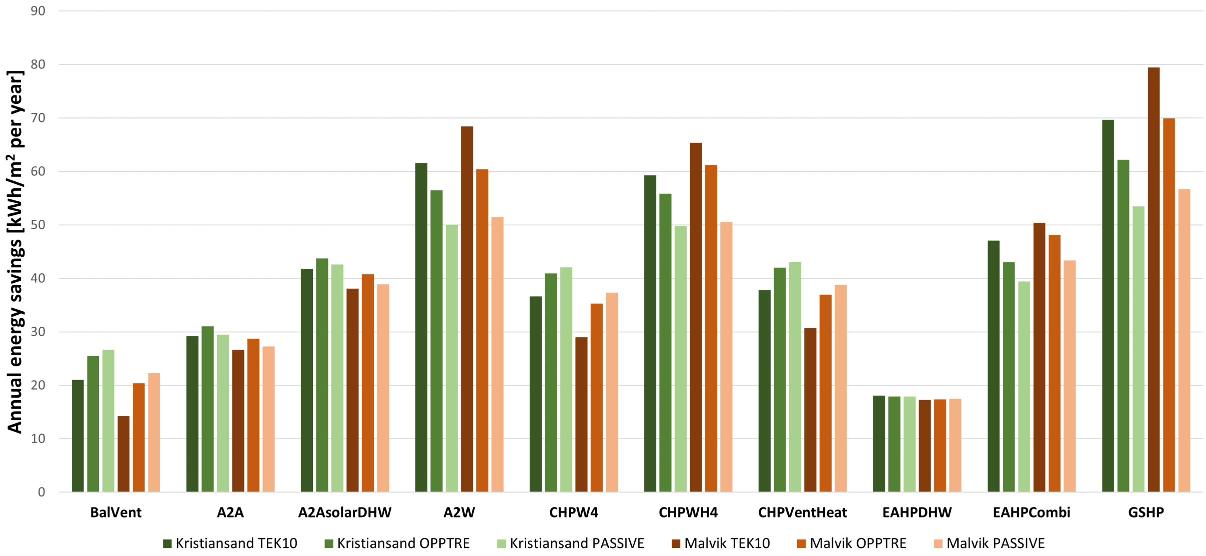


Figure 4.4: *Energy savings for all combinations compared to the ElRad combination.*

The A2A combination is a good choice at low insulation levels. At TEK÷, the air-to-air heat pump is able to reduce the energy consumption by a fair amount compared to the BalVent combination. However, at higher insulation levels the difference between these two combinations is reduced due to lower space heating needs. This is displayed in Figure 4.4, where the energy savings in the passive scenarios are lower than the OPPTRE scenario.

The addition of solar thermal panels in the A2ASolar combination is an equally good measure at all renovation levels as the consumption of DHW is the same for all levels. Thus, this combination proves to be more energy efficient than the heat pumps designed for covering DHW only.

As presented in Figure 4.4, the difference in energy savings between combinations covering both space heating and DHW, and combinations covering DHW decrease as the insulation levels increase. A premise for this to be true, is that balanced ventilation is a part of the combination. Ventilation heat recovery becomes a more efficient investment at higher renovation levels due to lower infiltration rates. Balanced ventilation is the only single measure that yields higher energy savings compared with the ElRad combination with higher insulation levels. This is emphasized by comparing the CHPW4 and CHPVentHeat combinations to EAHPCombi. Even though the CHPW4 and CHPVentHeat combinations have no upgrades to the space heating system, these combinations are almost achieving the same levels of energy savings compared to the reference as EAHPCombi at PASSIVE levels.

Overall, the energy savings from the balanced ventilation system are smaller for the Malvik house compared to the Kristiansand house. This is mainly because of lower air flow rates in the Malvik house. Additionally, some of the exhaust air terminals are placed in the basement in this house. In the basement, the heating set point is set to 15 °C. This leads to a lower exhaust air temperature, and a lower overall efficiency of the ventilation heat recovery.

4.3 Economic performance

4.3.1 Global costs

The ranges of global costs of each heating solution for the Kristiansand and Malvik house are presented in Figure 4.5 and Figure 4.6 respectively. With this perspective, the total costs of upgrading both the heating solution and building envelope are displayed.

As presented in Figure 4.5, the OPPTRE envelope yields the lowest global costs overall for the Kristiansand house. Meanwhile the PASSIVE envelope is the most expensive. This is because this envelope yields a lot higher investment costs compared to OPPTRE and TEK10÷. Meanwhile, the OPPTRE envelope is only slightly more expensive than the TEK10÷ envelope. The scenario yielding the lowest global costs is CHPVentHeat OPPTRE. The CHPVentHeat combination is among the best performer in terms of global costs across all renovation levels. On the other hand, GSHP, A2W and CHPWH4 are among the most expensive solutions for all renovation levels, despite being the most energy efficient ones by a large margin.

For the Malvik house as well, the OPPTRE envelope seems like the most cost effective. However, the TEK10÷ also performs very well. The combination that achieves the lowest global costs is EAHPCombi with the OPPTRE envelope. This combination performs well with the TEK10÷ envelope as well. This is in contrast to the Kristiansand house, where EAHPCombi did not perform as well compared to the other solutions. This combination appears more cost effective in the Malvik house mainly due to lower investment costs for this house. Just like for the Kristiansand house, the PASSIVE envelope seems like the most expensive solution. The three most energy efficient solutions also appear to be among the least cost effective ones for all renovation levels, just like in Kristiansand.

4.3.2 Payback time

The payback time of the heating combinations are presented in Figure 4.7. The ElRad combination is used as reference, which is the option of upgrading the building envelope, but not the heating system. In order for a combination to be profitable, the payback period needs to be shorter than the lifetime of the system. As each combination consist of several units with different lifetimes, the lifetime of the heat pumps have formed the basis of the evaluation. For the BalVent scenario, the lifetime of the balanced ventilation system has formed the basis. The lifetime of these units range from 15 to 20 years, and have been presented earlier in Table 3.5.

In general, the payback times tend to increase when the renovation level of the buildings increase. This is due to higher insulation levels reduces the energy consumption, which in turn reduces the energy saving potential by upgrading the heating system. The exception is for the balanced ventilation, which becomes more effective at higher insulation levels due to lower infiltration rates. The payback time is highly correlated with the ratio of energy savings provided by the heating supply combination and the investment costs. The ratio of energy savings per NOK invested for each combination is presented in Figure 4.8. Comparing Figure 4.7 and Figure 4.8 shows that higher energy savings per NOK invested yield a shorter payback time, and vice versa.

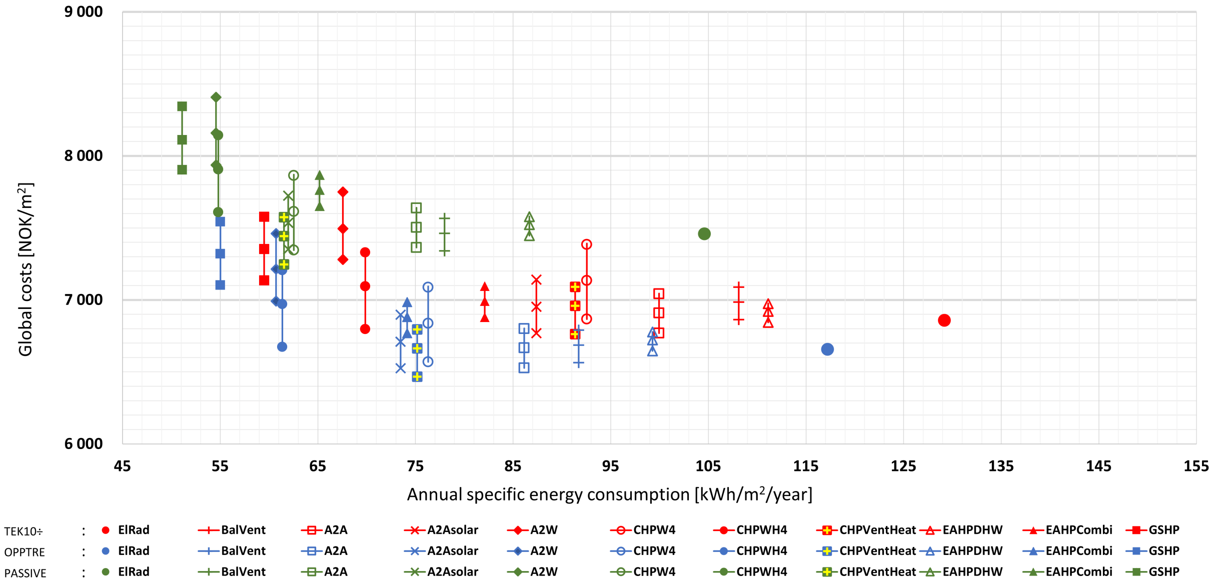


Figure 4.5: *Global costs for each heating solution in the Kristiansand house, including costs of upgrading the envelope*

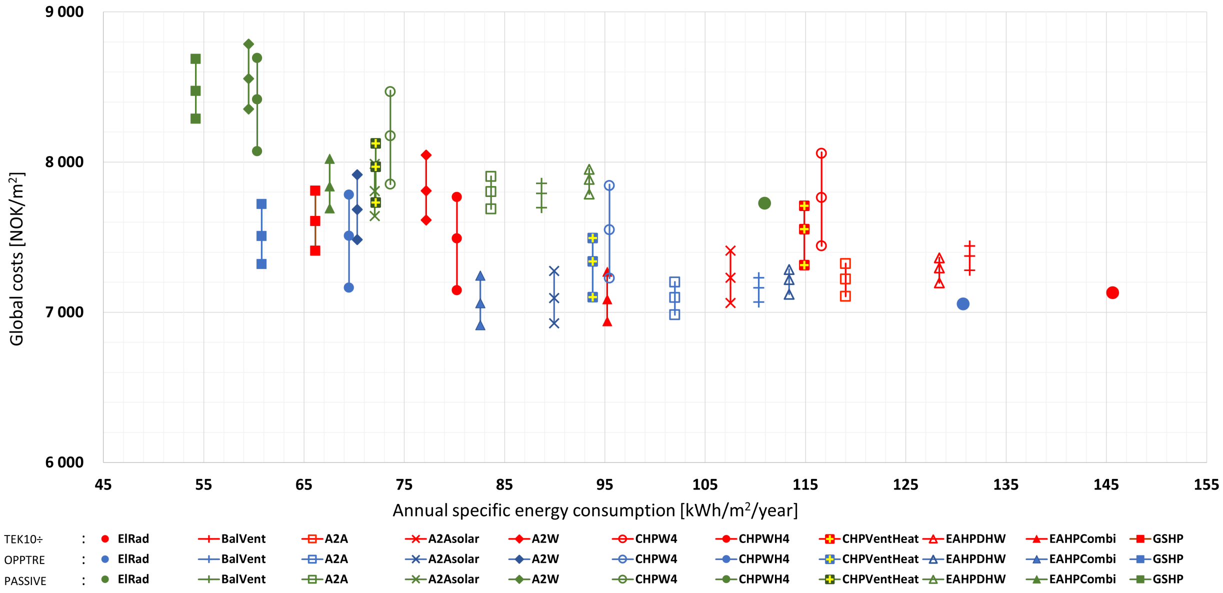


Figure 4.6: *Global costs for each heating solution in the Malvik house, including costs of upgrading the envelope*

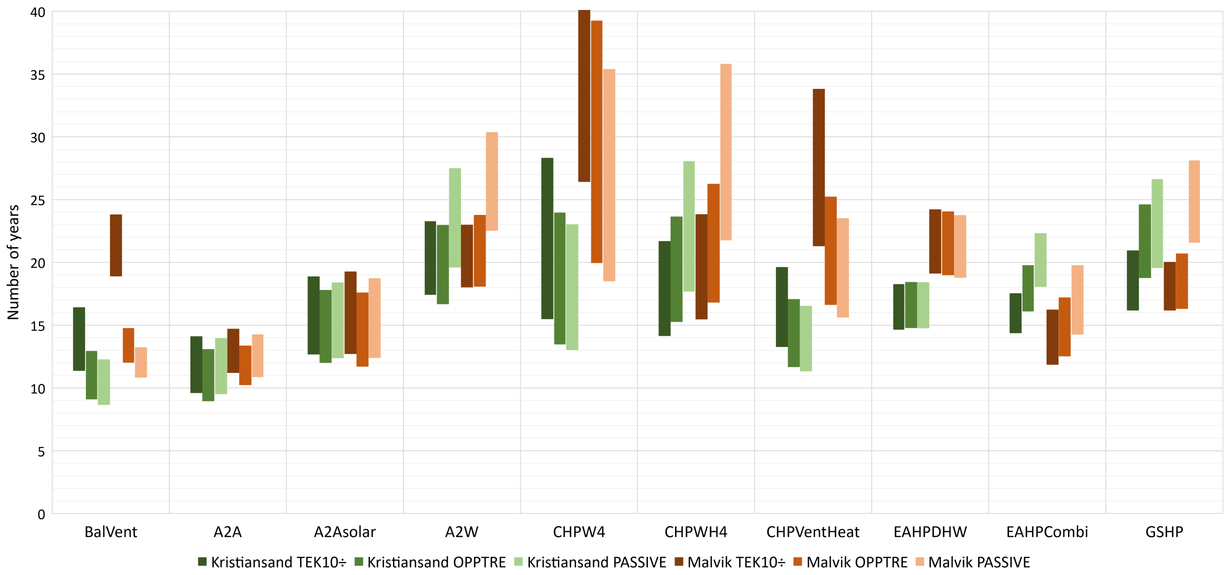


Figure 4.7: *Payback time of all heating combinations for both houses.*

For the BalVent scenario, the energy saving potential increases with higher levels of air tightness, as explained earlier. The combination is profitable for all renovation levels with a payback time shorter than its lifetime of 20 years, with the exception of TEK÷ level for the Malvik house. Depending on the investment costs in this scenario, the payback time might exceed the lifetime. However, near the low-end part of the investment cost span, the combination remains profitable.

For the A2A and A2ASolar combinations, the low investment cost of the air-to-air heat pump makes it a good investment at TEK10÷ level. At this renovation level, the heat pump has a good energy saving potential, which is seen by the reduced payback time compared to the BalVent combination. However, with increasing renovation levels and reduced energy saving potential for the heat pump, the payback time increases compared to the BalVent scenarios. The A2A combination is still profitable for all renovation levels as the payback times are lower than the lifetime of 15 years. The addition of solar thermal panels increases the payback time. However, the combination is still profitable near the low-end of the investment costs span for all renovation levels in both houses.

The payback trend of the A2W combination in the Kristiansand house does not follow the trend of increased payback time with lower energy savings. As displayed in Figure 4.7, the payback time of the combination with the OPPTRE envelope is shorter than the TEK÷ envelope. This is due to the smaller heat pump size in the OPPTRE level compared to TEK10÷ yields lower investment costs. This is also the case for the Malvik house, where the leap in payback time from TEK÷ to OPPTRE is significantly smaller than the leap from OPPTRE to PASSIVE. However, due to a fairly short lifetime of 15 years and high investment costs, the combination is not profitable in any scenario.

The energy saving potential for space heating of the CHPW4 and CHPVentHeat combinations are heavily correlated to the energy saving potential of the balanced ventilation system. The payback time of these combinations are therefore following the same trend as the payback time of the BalVent combination. However, the payback times and spans are longer and bigger due to higher investment costs with bigger spans between the low-end and high-

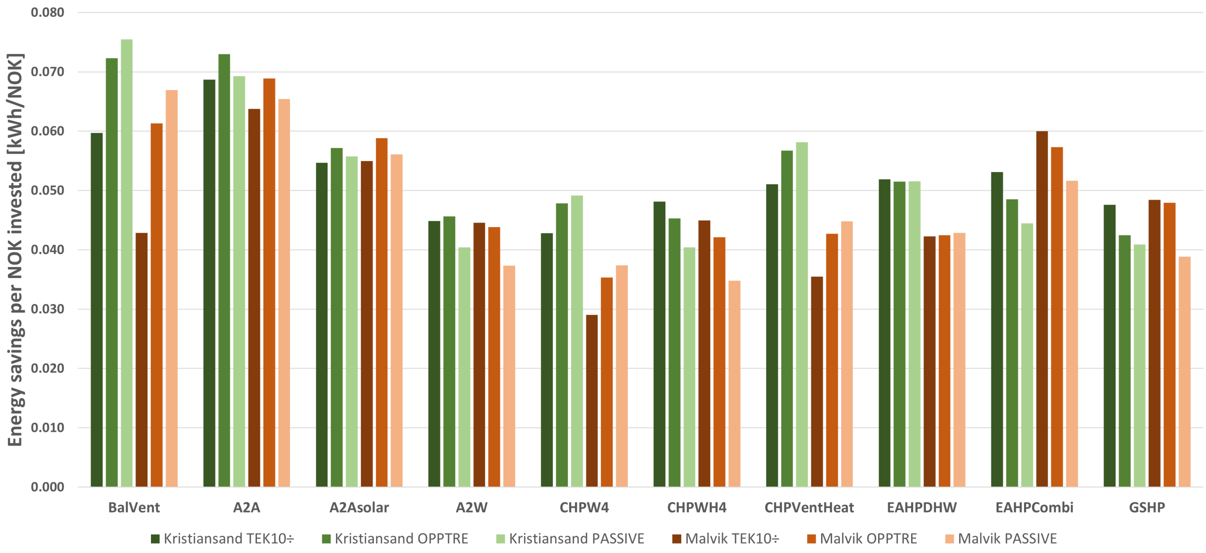


Figure 4.8: *Energy savings per NOK invested on average.*

end prices. When looking at the CHPVentHeat combination, the solution is profitable for all renovation levels in the Kristiansand house, with a payback time less than the lifetime of 20 years. This is not the case for the Malvik house however, which is due to balanced ventilation being less profitable in this house. Furthermore, the DHW consumption is lower in Malvik than in Kristiansand, which reduces the energy saving potential of the heat pump in these scenarios. The payback time of the CHPW4 combination is affected by the same factors as CHPVentHeat. However, the CHPW4 combination has a higher investment cost, which increases its payback time. This solution is therefore less profitable than the CHPVentHeat for both houses.

The energy saving potential of the CHPWH4 combination is comparable to the A2W combination. However, CHPWH4 has lower investment costs and a longer lifetime than the A2W combination. The combination is therefore able to achieve profitability in all scenarios in the lower end of the payback time spans.

As the energy saving potential for the DHW does not change with differing renovation levels, the payback periods of the EAHPDHW combination are close to constant for all renovation levels in both houses. The payback time deviates slightly due to small differences in the opperating conditions of the exhaust air heat pump for the different renovation levels. Overall, the combination is not profitable as the payback time exceeds the lifetime of 15 years.

EAHPCombi is the only combination where the payback time is shorter for the Malvik house than for the Kristiansand house. Although the mean specific investment cost for both combinations are approximately the same, the total investment cost of the combination is 40 000 NOK less for the Malvik house due to a cheaper heat pump. This is the main reason for the shorter payback period in this house. With a lifetime of 15 years, the combination is therefore profitable in the lower parts of the payback span for all renovation levels of the Malvik house. However, the combination is less profitable in the Kristiansand house, and is only profitable in the TEK10÷ scenario if the investment costs are low.

GSHP is the combination with the highest energy savings for all renovation levels in both houses. The combination also yields the highest grants from Enova. However, the high investment costs of the combination limits the profitability of the combination. Nonetheless, the combination is still profitable at the lower end of the investment costs span for TEK10÷ level in Kristiansand, and the TEK10÷ and OPPTRE levels in Malvik. At the higher renovation levels, the energy savings are too small to compensate for the high investment costs.

4.3.3 Dependency of the economic performance on governmental grants

As technologies get established on the market, and are able to compete with well-established technologies, the economic grants by Enova are reduced or removed completely. In order to evaluate the economic performance of the different heating combinations if the economic support by Enova is removed, the payback times have been calculated with the grants excluded. These are presented in Figure 4.9, while the mean increase of payback times when Enova grants are excluded are presented in Figure 4.10.

By excluding the Enova grants, Figure 4.10 shows that the low energy savings of the Malvik TEK10÷ BalVent scenario increases the payback time by more than 5 years due to the discounting of future cash flows. Otherwise, the BalVent scenario is a robust combination when removing the Enova grants, and the increase in payback times are less than 3 years. Thus, the BalVent scenario remains profitable for the Kristiansand house, and with the OPPTRE and PASSIVE envelopes for the Malvik house.

The CHPW4 combination proved to be an unprofitable combination in the Malvik house, and the removal of governmental grants further emphasize this. Also here the inefficient balanced ventilation system heavily affects the payback time of the combination with the TEK10÷ envelope when the grants are removed. The combination is more reobust in the Kristiansand house, where the mean payback time is increased by less than 2 years for all renovation levels. The combination therefore remains profitable in many cases.

CHPVentHeat follows the same trend as the CHPW4 when excluding the grants. The increase in payback time is low for the Kristiansand house, and higher for the Malvik house. Still, the combination can be profitable for both houses at all renovation levels, except Malvik TEK÷.

The CHPWH4 combination yields high Enova grants of 25 000 NOK, and the payback time increases heavily when these are excluded. However, the low end parts of the payback spans are lower than the lifetime of the combination, with the exception of Malvik TEK10÷.

The A2A combination yields low Enova grants, and is therefore a robust combination. Excluding the Enova grants increases the payback time by approximately 1.5 and 2 years for the Kristiansand and Malvik scenarios respectively. The combination is therefore still profitable overall.

The A2ASolar combination yields higher Enova grants than the A2A combination due to the solar thermal panels. This also results in a slightly higher increase in payback time when the grants are excluded. As the combination may or may not be profitable depending investment cost with the Enova grants included, the removal of these makes the combination overall unprofitable.

The profitability of the EAHPCombi combination is also depending on the investment costs when the Enova grants are included. Even though the increase in payback time is approximately 2 years and can be considered low, the combination is still highly dependant on the grants in order to be profitable.

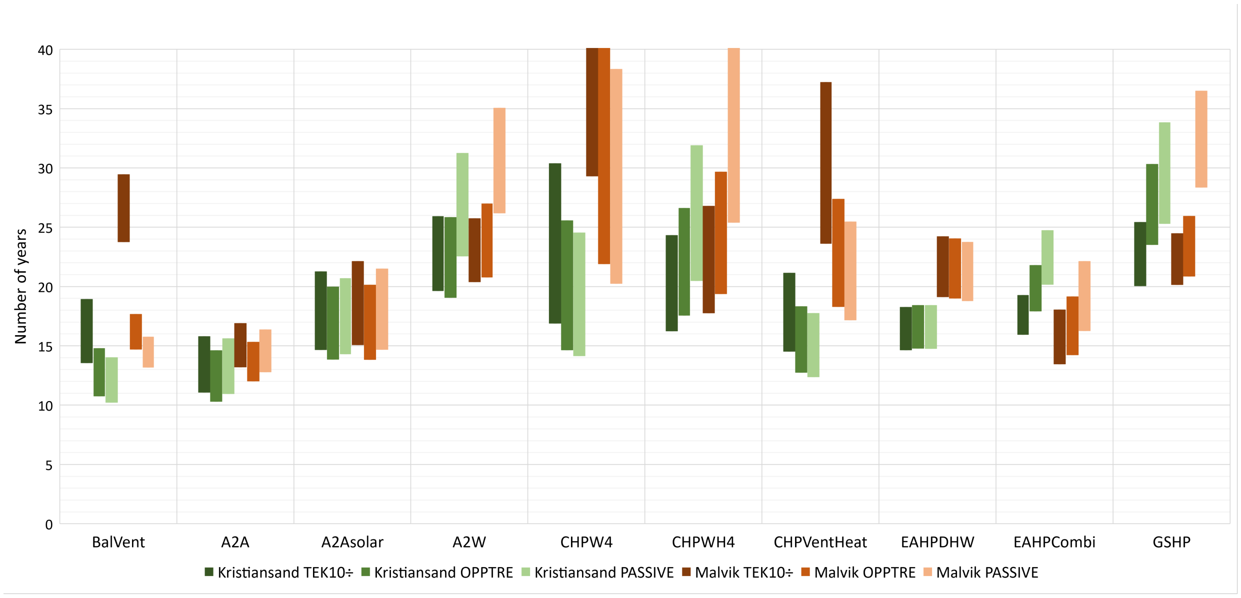


Figure 4.9: *Payback time of all heating combinations when the economic grants by Enova are excluded.*

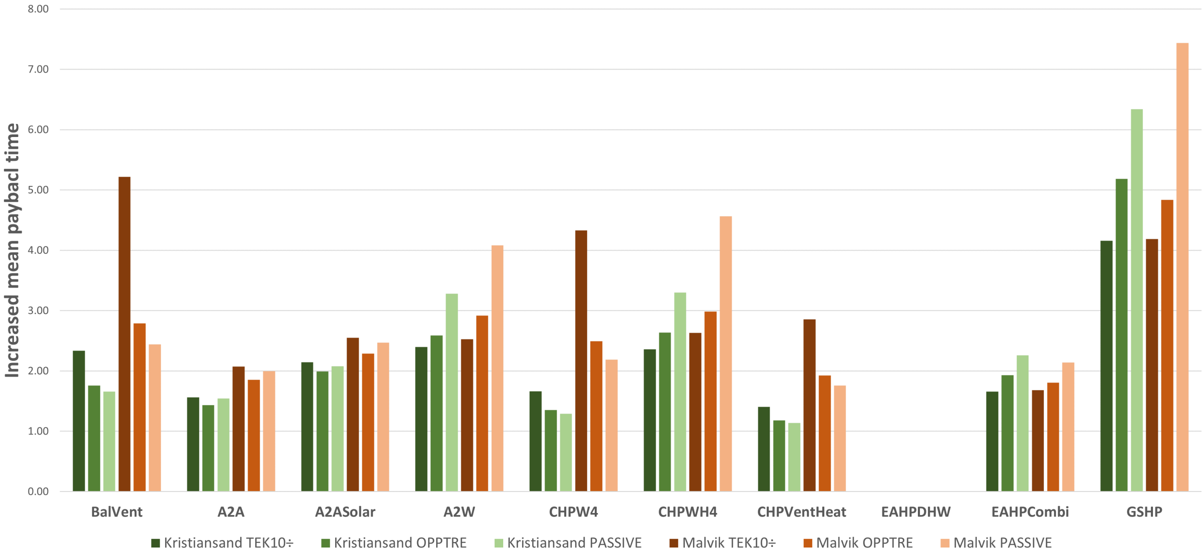


Figure 4.10: *The increase of mean payback times when Enova grants are excluded.*

A2W and GSHP both yield high Enova grants of 25 000 and 50 000 NOK respectively. The grants are therefore influencing the payback time of both combinations to a great extent. As the A2W combination is not profitable with the greants included, the outcome is not changing when these are excluded. However, the increased payback times of four to seven years changes the outcome for the GSHP combination. Thus, The payback time exceeds the life time of the combination in all scenarios when the grants are excluded. The profitability of the GSHP combination is therefore highly dependent on the governmental grants.

4.4 Global costs with external financing

As both renovation of existing buildings and installation and operation of heat pumps are part of the EU taxonomy compass, the global costs have been calculated when the envelope upgrades and heating combinations are financed by a loan with an interest of 10 %. In Norway, the tax deduction on loan interest is 22 %. Furthermore, the inflation rate is assumed to remain 2 %, and the relative change in energy price compared to the price index is zero. With these assumptions, the corresponding discount rate is 5.7 % according to Equation 2.8. Figure 4.11 and Figure 4.12 present comparisons of the global costs with discount rates of both 5.7 % and 3.0 % for the Kristiansand house and Malvik house respectively.

When the discount rates increase, the present value of future cash flows decrease. This reduces the value of future energy savings when investing in more energy efficient envelopes and heating combinations. Furthermore, the discounted residual values of the heating combinations and the building envelopes are also reduced. Thus, the scenarios with low investment costs have lower drops in residual value. The reduced value of future cash flows therefore make the scenarios with low investment costs more beneficial compared to those with high investment costs. This can especially be noticed with the different envelopes, as the global costs of the PASSIVE envelope increase more heavily than the TEK10÷ and OPPTRE envelopes.

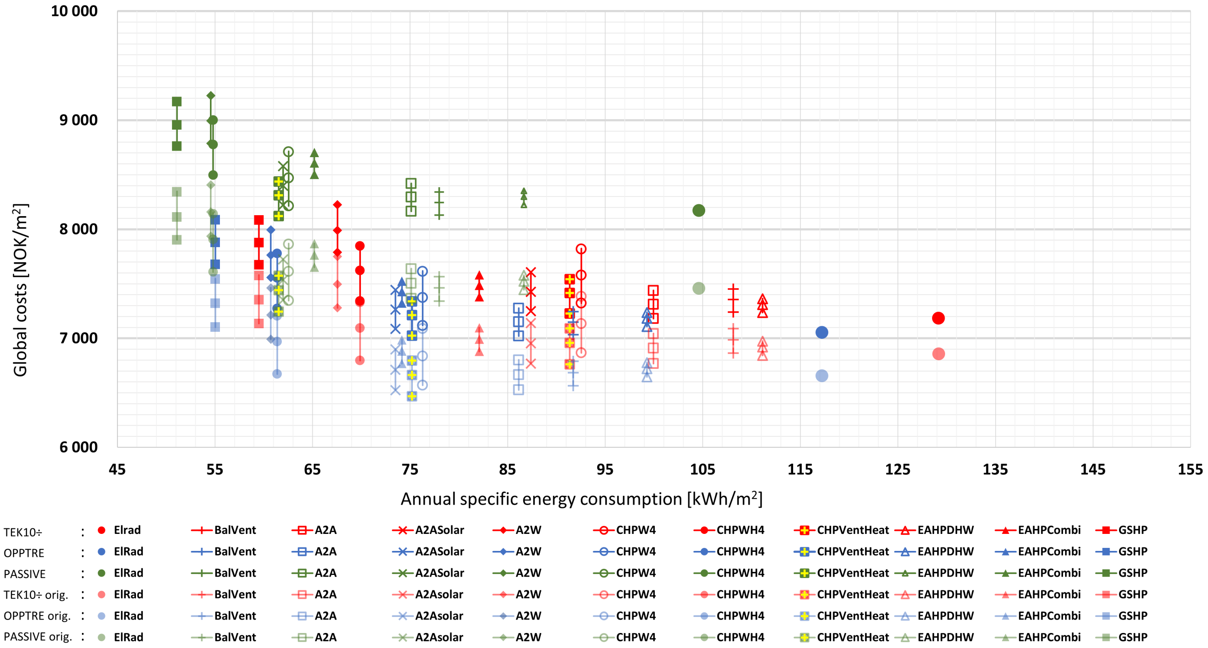


Figure 4.11: *Global costs for the Kristiansand house with a discount rate of 5.7 % and 3.0 % respectively.*

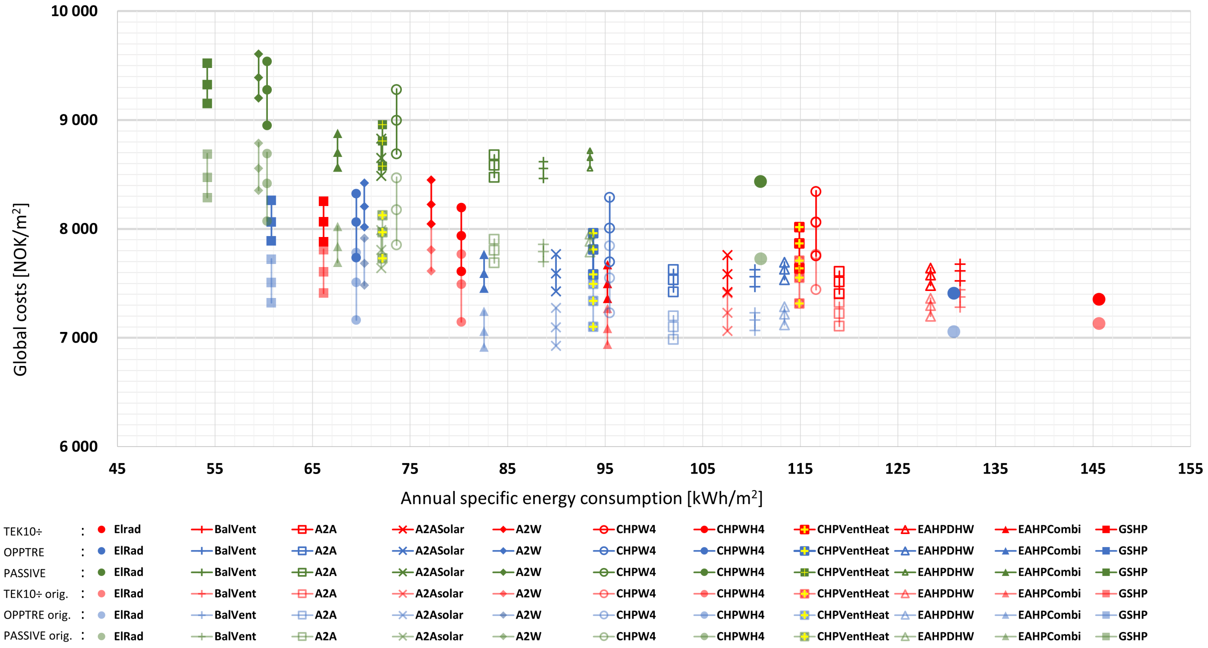


Figure 4.12: *Global costs for the Malvik house with a discount rate of 5.7 % and 3.0 % respectively.*

4.5 Different grid tariffs

The economic performance have also been evaluated with different grid tariffs. The grid tariffs evaluated are the standard and pilot tariffs of the grid companies Glitre, Elvia and Nettselskapet.

4.5.1 Monthly power peaks

As described in section 3.2.3, the fixed fee of the pilot tariffs are based on the highest power peaks induced each month. The monthly power peaks accumulated are presented in Figure 4.13 and Figure 4.14. The GSHP combination yields the lowest power peaks. However, for Kristiansand PASSIVE and Malvik OPPTRE and PASSIVE, this combination yields slightly higher power peaks during the summer months compared with lower insulation levels. The reason for this is the reduced heat pump size in the higher insulated scenarios. This also occurs with the A2W combination at higher insulation levels where smaller heat pumps are installed.

For the Malvik house with TEK÷ envelope, the January peak for the BalVent combination is higher than the January peak for the ElRad combination. This is the opposite of what is expected. However, an electric coil is installed in the balanced ventilation system. Thus, the BalVent combination has a higher total installed heating capacity than the ElRad combination. This causes a few hours of higher power consumption in January for the BalVent combination compared with the ElRad combination.

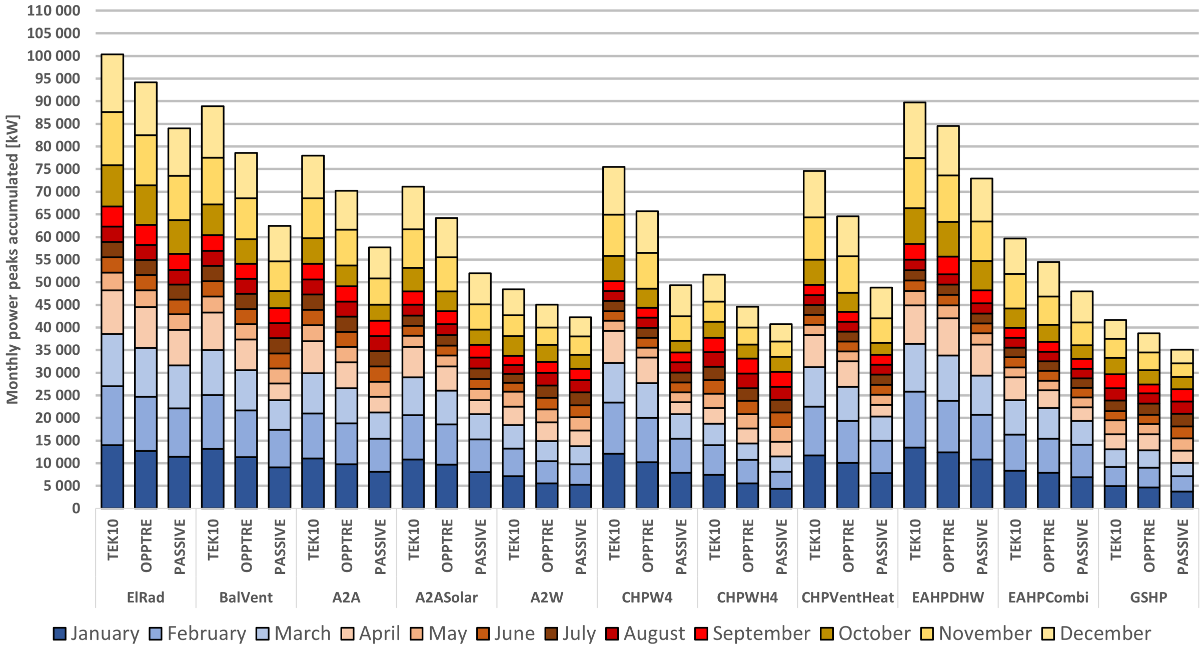


Figure 4.13: *Monthly power peaks of all scenarios for the Kristiansand house accumulated.*

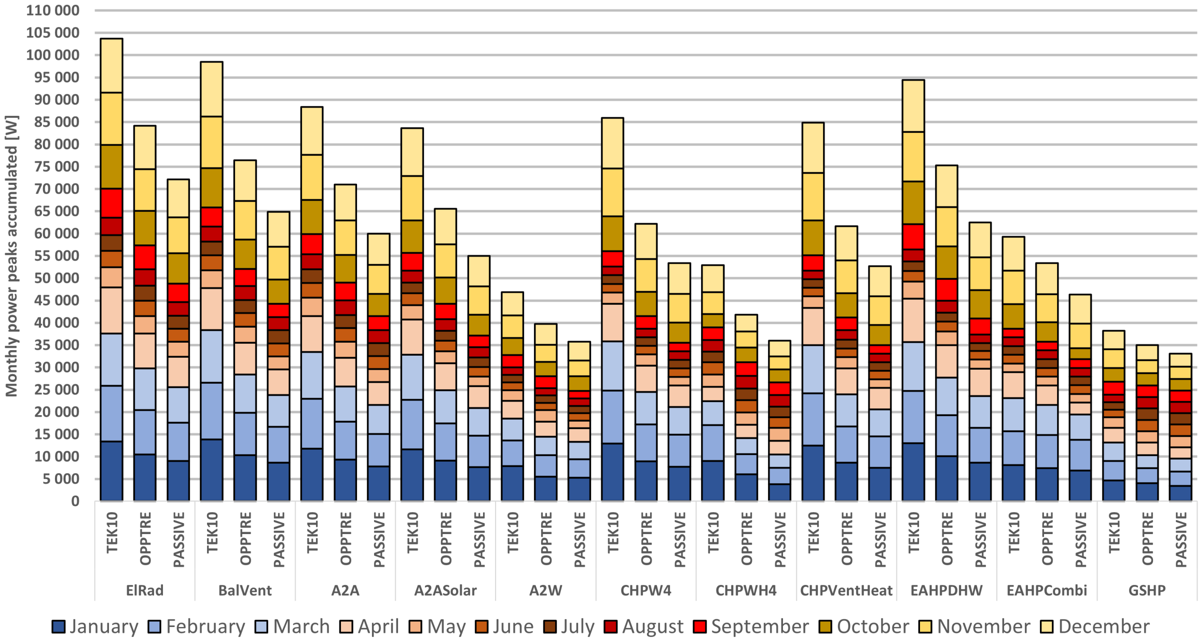


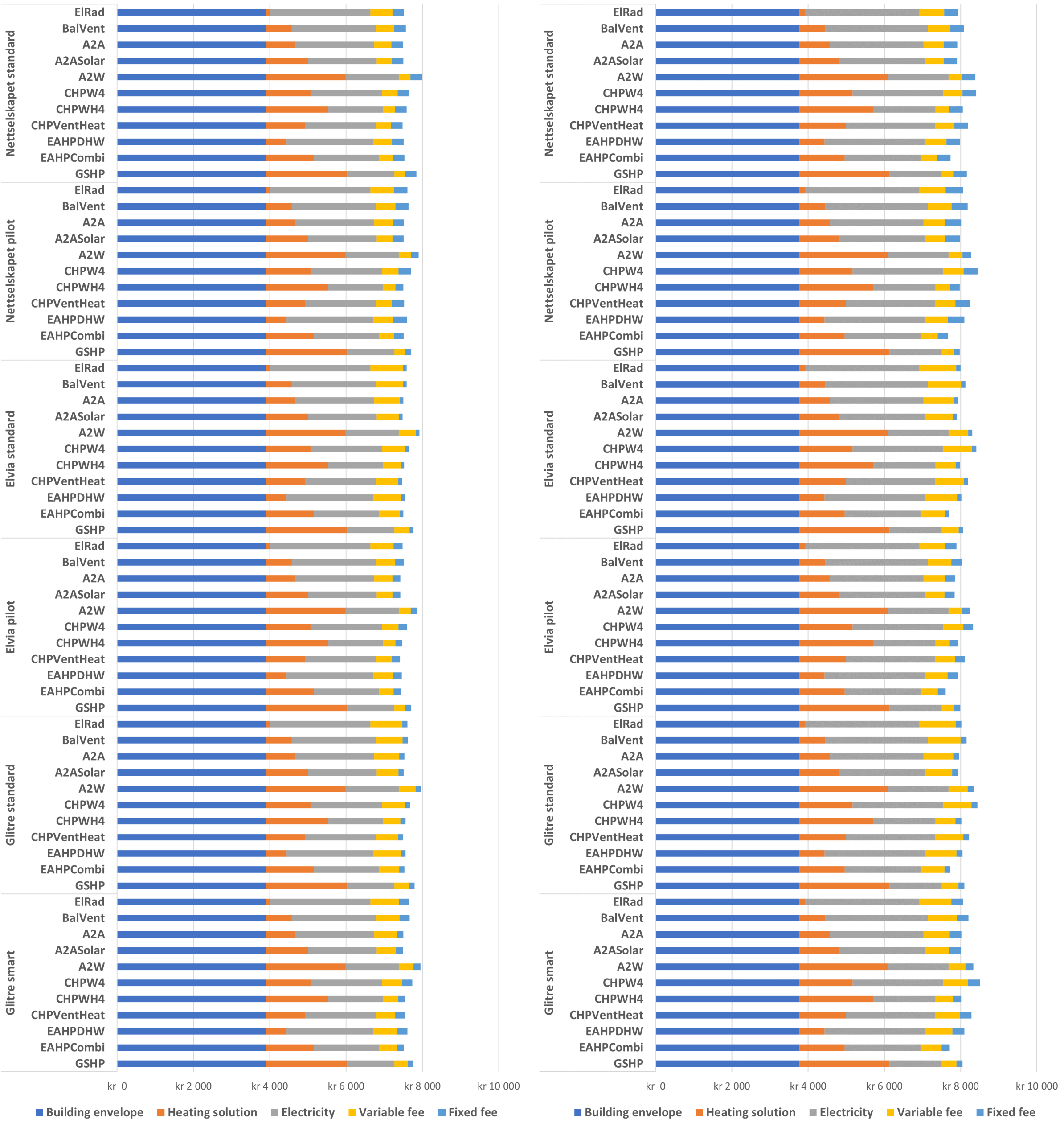
Figure 4.14: *Monthly power peaks of all scenarios for the Malvik house accumulated.*

4.5.2 Global costs

The global costs of both houses with the TEK10÷ renovation level and pilot grid tariffs are presented in Figure 4.15. The global costs with the OPPTRE and PASSIVE envelopes are presented in Figure A.2 and Figure A.3 in Appendix A. The different grid tariffs induce few major changes in the economic performance of the different scenarios. Therefore, only the global costs of the dwellings with the TEK10÷ envelope are highlighted as these scenarios yield the most significant changes in global costs when the pilot tariffs are introduced.

Compared with the default energy price of 1.50 NOK/kWh, the standard tariffs yield no major changes. The electricity price and variable fee of the standard tariffs induce a higher energy price compared with the default energy price. This, in addition to the introduction of the fixed fee, results in higher global costs for all scenarios. The higher energy price of the standard tariffs leads to lower energy costs for the more efficient solutions. The standard fixed fee yields a flat increase in the global costs for all combinations, as this is not dependent on consumer behavior with the standard tariffs.

The pilot tariffs introduces a fixed fee dependent on the monthly power peaks. This introduction is favoring the most efficient heating solution. However, the variable fees of the Glitre and Elvia pilot tariffs are lower compared to the variable fees of the standard tariffs. Thus, the total grid costs of these two pilot tariffs differs only marginally from the standard tariffs of the same companies. There are therefore no significant differences in the most cost efficient combinations compared with the standard tariffs and the default energy prices. However, the pilot tariff of Nettselskapet differs from the other pilot tariffs. Compared to the other grid companies, the pilot tariff of Nettselskapet induces higher variable fee costs compared with its standard tariff. Furthermore, the heavy augmentation of the fixed fee rates at higher monthly power peak levels yields bigger differences in fixed fee costs between different combinations. Both higher variable fee and heavy augmentation of the fixed fee rates benefits the energy efficient combinations the



(a) *Kristiansand*

(b) *Malvik*

Figure 4.15: *Global costs of both houses with new tariffs and TEK10÷ envelope. The costs related to heating solution include the initial investment costs of heating solution, annual maintenance costs and future replacement costs.*

most. This results in the GSHP combination becoming more cost efficient compared to other combinations. This is especially visible for the Malvik house, where the GSHP combination becomes competitive with combinations with lower investment costs such as ElRad, BalVent, A2A, A2ASolar, CHPWH4 and EAHPDHW.

The global costs of the ElRad and GSHP combinations with the TEK10÷ envelope for the Kristiansand house are displayed in Figure 4.16. These two scenarios have been highlighted to show the difference between the combinations with the highest and lowest energy consumption and power peaks for this building envelope.

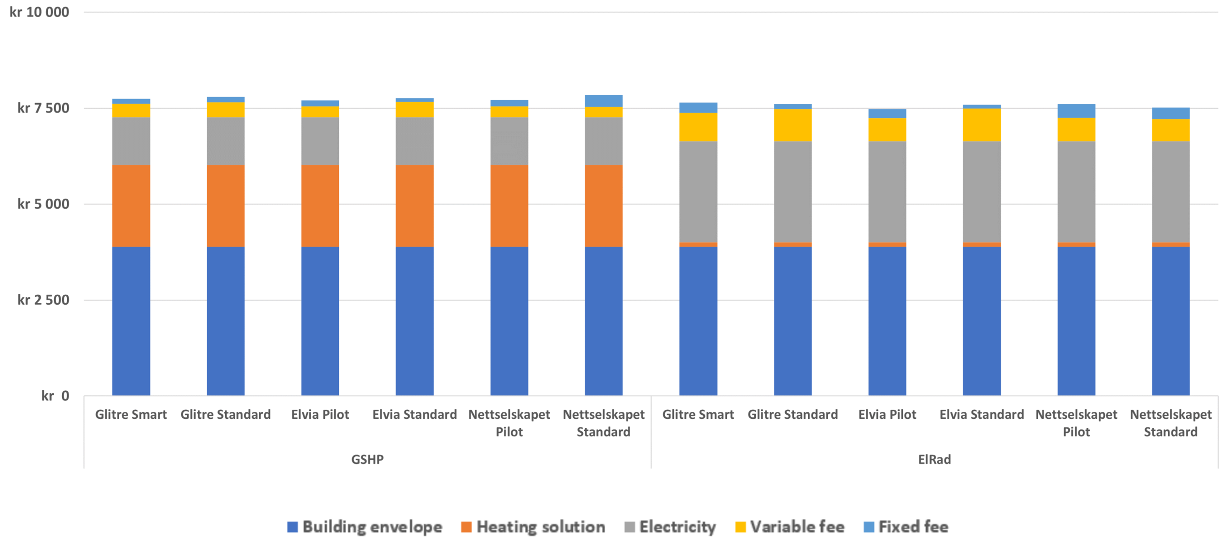


Figure 4.16: *Global costs of the GSHP TEK10÷ and ElRad TEK10÷ scenarios for the Kristiansand house with new grid tariffs. The costs related to the heating system include the initial investment costs, replacement costs and maintenance costs.*

As previously mentioned, switching from the standard tariff to the pilot tariff of the same grid company does not induce any major changes to the global costs overall. However, the effects of the new structure of the fixed fee can be noticed. For the ElRad combination, the costs related to the fixed fee increases for all pilot tariffs when switching from the standard tariffs. This is compensated by a lower variable fee, with the exception of the pilot tariff of Nettselskapet. The GSHP combination generates far lower power peaks than the ElRad combination. Thus, the combination induces lower costs related to the fixed fee. As the fixed fee of the pilot tariff of Nettselskapet augments heavily with higher power peaks, the fixed costs of the GSHP combination are significantly lower than the fixed costs of the ElRad combination. In addition, with the high fixed costs of the standard tariff of Nettselskapet, the fixed costs are heavily reduced when swapping to the pilot tariff for the GSHP combination.

The differences in specific global costs for all scenarios when swapping from the standard tariff to the pilot tariff of the same company are presented in Figure 4.17. Overall, the higher insulated renovation levels and the most efficient heating solutions yield slightly lower global costs when swapping from the standard to the pilot tariffs. As mentioned in the previous paragraph, the differences in global costs are marginal.

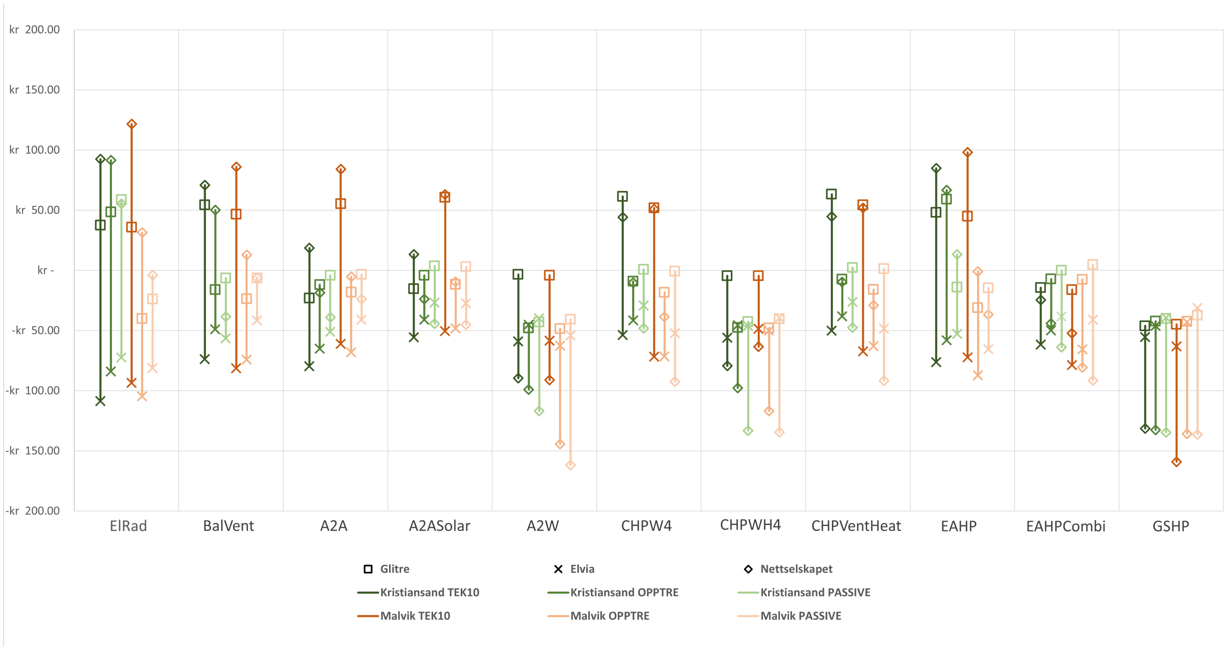


Figure 4.17: *Variation in specific global costs (NOK/m^2) when swapping from the standard tariff to the pilot tariff of the same grid company.*

The highest differences are induced when swapping the tariffs of Nettselskapet. Compared with the standard tariff, the pilot tariff of Nettselskapet favors highly insulated envelopes and energy efficient heating solutions. This is because high power peaks yield a high fixed fee. Furthermore, the total costs of the variable pilot fee is higher than the variable standard fee. A higher variable fee becomes more punishing for scenarios with high energy consumption.

The global costs of the pilot tariff of Elvia are overall lower than the standard tariff. Compared with the standard one, the pilot tariff has a lower variable fee. However, the fixed pilot fee becomes higher for all scenarios, and is augmented heavily for the scenarios with low insulation levels and heating combinations with low efficiency. The low variable pilot fee results in high savings for the low-end scenarios. Thus, the total global costs are reduced for these scenarios despite the higher fixed fee when swapping to the pilot tariff. The scenarios with both lower energy consumption and monthly power peaks benefit less from the reduced variable fee of the Elvia pilot tariff. At the same time, these scenarios are less punished from the fixed fee based on the monthly power peaks.

In many cases, the pilot tariff of Glitre induce only marginal differences in global costs. If the moving average of the five highest monthly power peaks of the last 12 months is lower than 5 kW, the fixed fee remains unchanged compared with the standard tariff. The fixed fee increases above this if the monthly power peaks increase, however the fixed pilot fee of Glitre differs the least compared with the fixed standard fee among all three grid companies. The variable pilot fee is slightly reduced compared with the standard tariff, with a reduced fee during the night and weekends. Therefore, the Glitre pilot tariff yields only marginal differences in global costs compared to the standard tariff in most cases.

4.5.3 Measures to reduce energy consumption and monthly power peaks

The cost effectiveness of three different measures to reduce the monthly power peaks have been evaluated for all scenarios and pilot tariffs. These measures are no night setback, temperature zoning and heat recovery of DHW, and have been described in section 3.3. The measures have been evaluated both in combination with each other and separately. In addition to reduce the monthly power peaks, the measures also influence the energy consumption. The annual specific costs of energy and fixed fee of the Kristiansand scenarios with both measures and no measures implemented are presented in Figure 4.18. The energy costs consist of the costs of electricity and the variable grid fee. The presented costs are calculated with the pilot tariff of Nettselskapet. The specific energy and fixed fee costs of the pilot tariffs of Glitre and Nettselskapet, and the costs of all pilot tariffs for the Malvik house are presented in Appendix B. The SPF and energy coverage factor of the heat pump systems are not discussed in detail, but are presented in Appendix C.

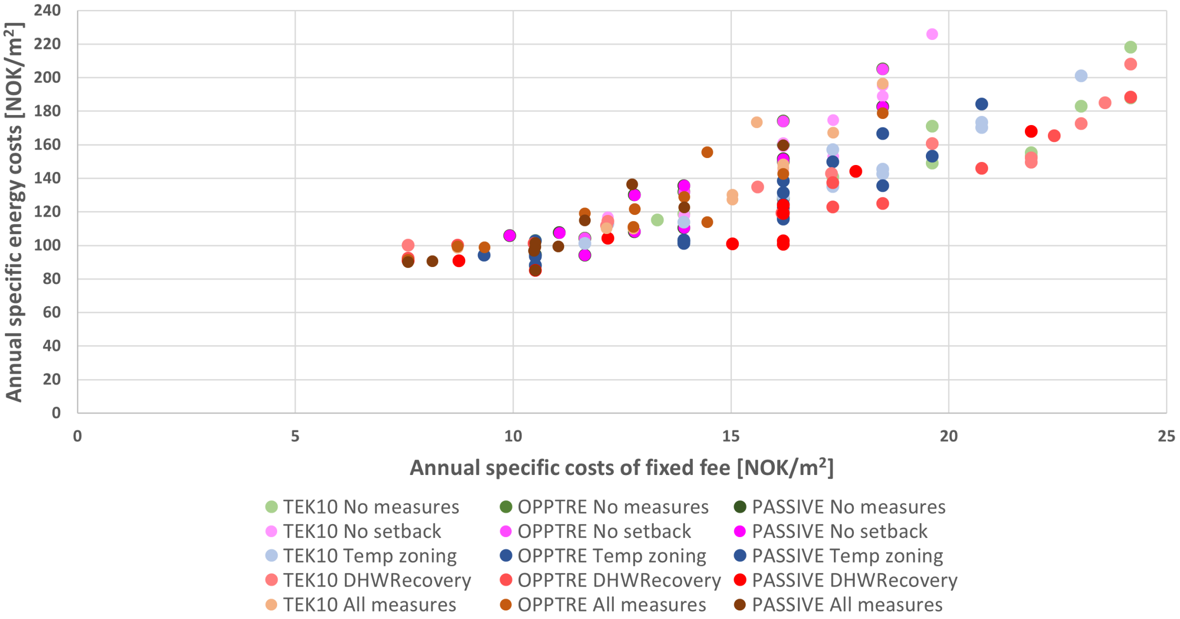


Figure 4.18: *Annual specific costs of energy and fixed fee with different power reducing measures implemented. Nettselskapet pilot tariff.*

No night setback No night setback proves to be the measure that reduces the power peaks the most, especially at low insulation levels and with heating solution with low efficiency. For the least efficient energy combinations with the lowest renovation levels, the costs of the fixed grid fee is reduced by close to 5 NOK/m^2. However, with low insulation levels and low efficiency heating solution, the energy costs increases by almost 10 NOK/m^2 due to a higher temperature set point during the night.

With higher insulation levels and reduced heat losses, the increase in energy costs becomes less significant, and the removal of night setback becomes profitable. Additionally, with the highly efficient GSHP combination, the removal of night setback induces lower energy costs. This is because the removal of night setback lowers the heating demand in the mornings, which in turn reduces the time the electric backup heater operates. This allows the highly efficient ground source heat pump to cover more of the heating needs.

Generally, the effect of night setback is most noticeable when the insulation levels are lower. When the heat losses increase, the energy savings by decreasing the indoor temperature also increase. However, at low insulation levels, the power peaks generated by increasing the temperature set point in the mornings induce higher fixed fees. With the chosen energy prices, the increase of the fixed fee is lower than the energy savings, which makes the night setback profitable at low renovation levels. As the insulation levels increase, both the energy savings and power peaks caused by the night setback decrease, and the effects of the strategy are less noticeable.

Temperature zoning The temperature zoning strategy heavily reduces the space heating demand, and is the single measure which reduces the energy consumption the most at low insulation levels where space heating amount to a large share of the total energy consumption. With this strategy, heat flows from the zones where the temperature set point and night setback remains unchanged to the zones with reduced heating set points.

In the Kristiansand house, the heating set point is mostly reduced in zones with small heating units, such as storage rooms and technical rooms. Furthermore, the house has several bedrooms, in which there are no heating units installed. These zones are therefore not affected by the strategy. The power needed to heat the building in the morning is therefore not reduced significantly, which induces only marginal reductions on the fixed fee.

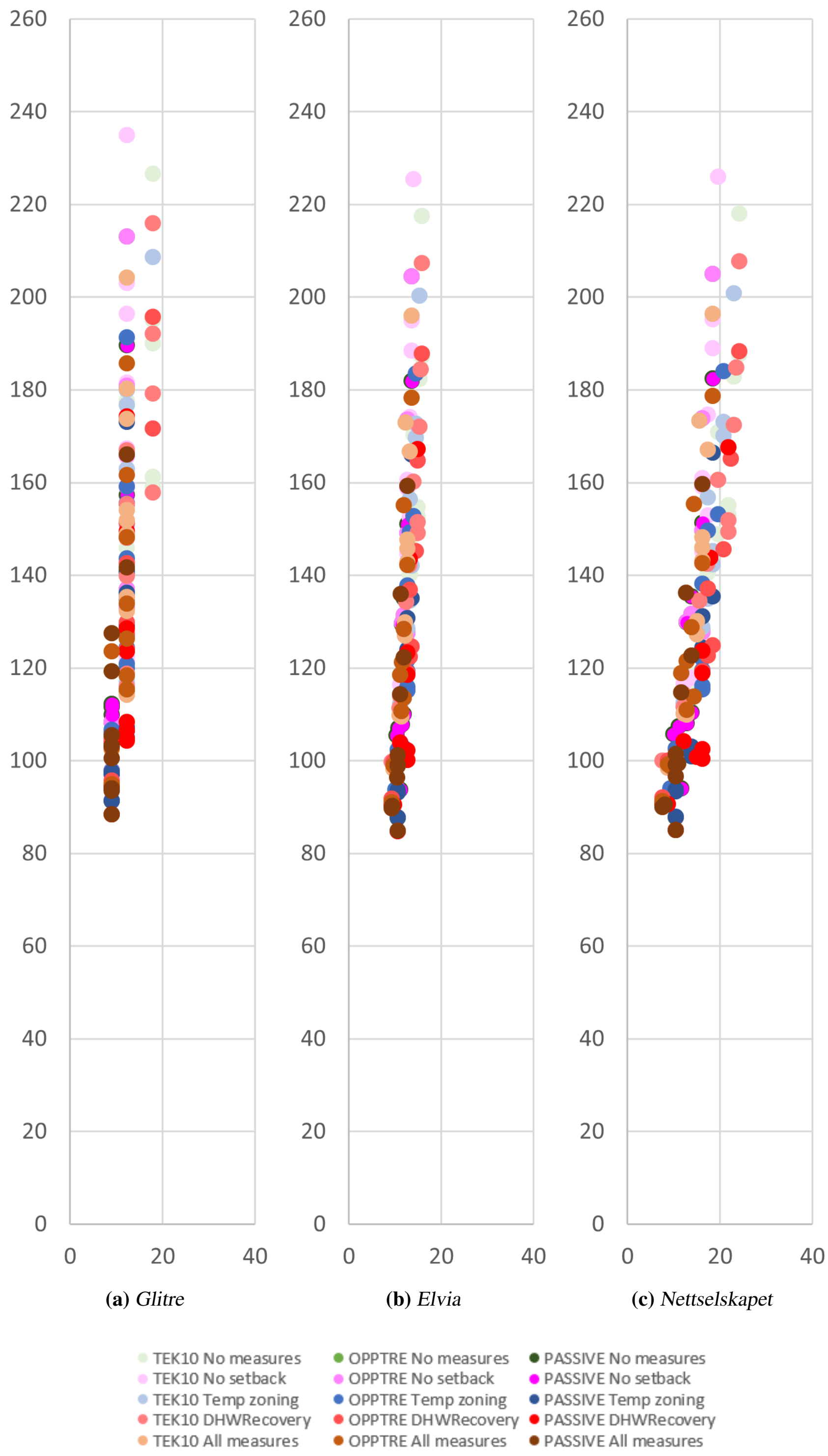
The power peaks in the Malvik house is more affected by the measure compared with the Kristiansand house. The house in Malvik contains fewer bedrooms, and fewer storage rooms and techical rooms with small heating units. Compared with the Kristiansand house, the heating set point is reduced in rooms where the installed heating capacity of the heating units are higher. Thus, the strategy is more effective at reducing power peaks in the Malvik house.

The measure is especially efficient for the A2A and A2ASolar scenarios, as the lower heating set points allow the air-to-air heat pump to distribute heat more efficient to surrounding zones. This results in a higher energy coverage factor for the heat pump and higher energy savings. By reducing the space heating need, the scenarios such as CHPW4, CHPVentHeat and EAHPDHW, which covers DHW only, achieves a higher energy coverage factor. Overall, this measure yields higher effects for scenarios with less efficient space heating solutions and lower insulation levels.

Heat recovery of DHW With heat recovery of DHW, the consumption of DHW is reduced by 25 %. This measure therefore reduces the energy consumption equally for all renovation levels. At low insulation levels, heating of DHW constitutes a smaller share of the total energy consumption, compared with higher renovation levels. The measure is therefore not reducing the power peaks significantly at the TEK10÷ renovation level. However, with increasing insulation levels and reduced heat losses, the reduced DHW consumption becomes more noticeable. Overall, the measure induces high energy savings for all renovation levels, and also lower fixed grid fees at higher renovation levels.

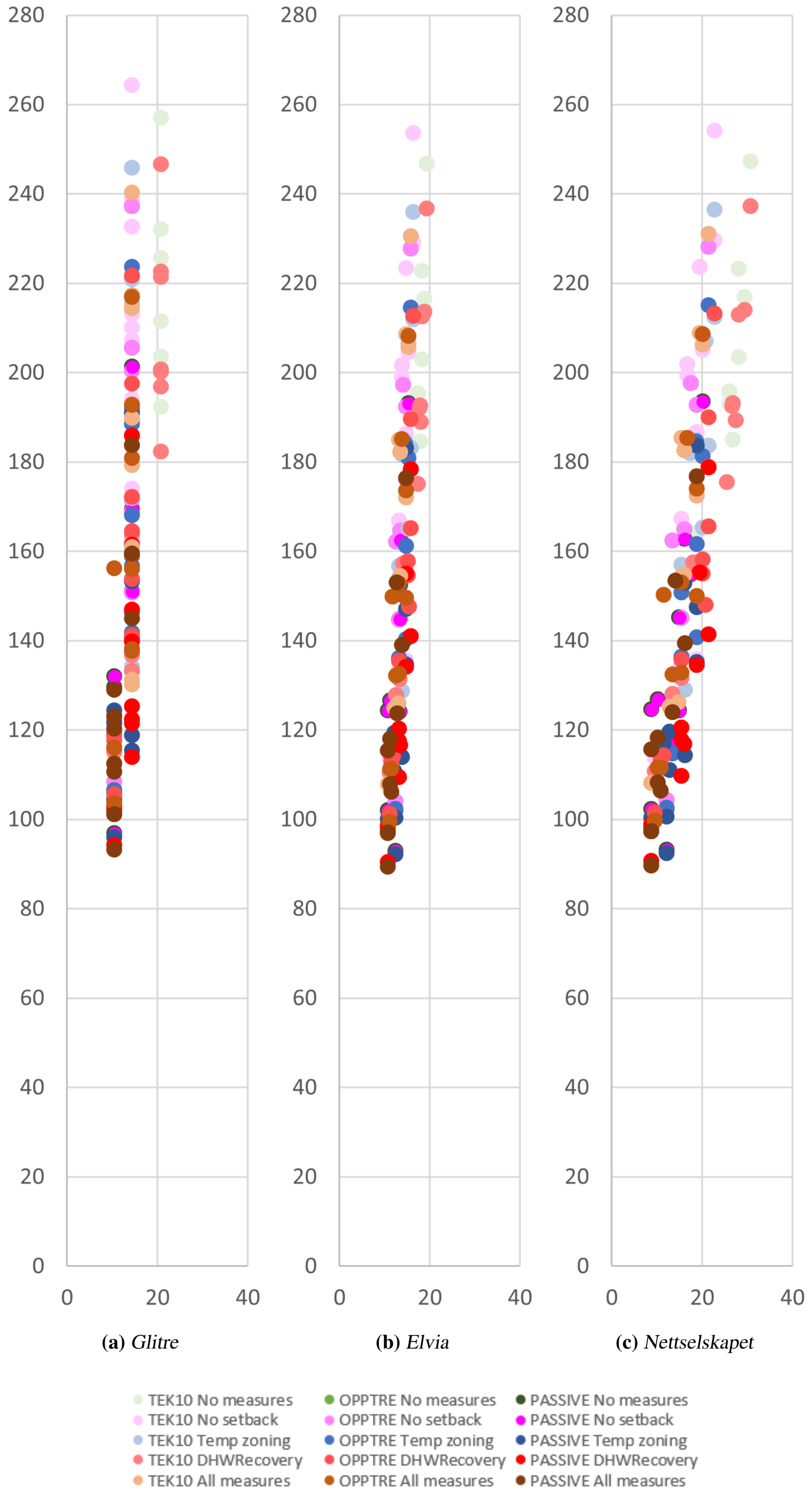
All measures By combining all three measures, both energy consumption and power peaks are drastically reduced compared with the base case where no measures are implemented. The demand for space heating and DHW are reduced due to the temperature zoning and DHW heat recovery respectively. These two measures do not have any influence on each other, and can be effectively combined. The no night setback measure is however influenced by the temperature zoning. When these two strategies are combined, the heating set points in the living room, kitchen and bathrooms are set to 22 °C during both day and night, instead of a set point of 20 °C during the night. With an increased night set point, the heat loss from the living room, kitchen and bathrooms to the surrounding areas with lower temperature set points is increased. However, the reduced power peaks due to no night setback makes it profitable to combine all measures.

The annual energy costs and annual costs of the fixed fee for both houses with all pilot tariffs are presented in Figure 4.19 and Figure 4.20. The figures presents the same information as Figure 4.18 and the similar figures in the appendix, but with the x-axis and y-axis scaled equally. With equally scaled axes, the potential savings related to the energy costs compared to the potential savings related to the fixed fee are highlighted. As displayed, the potential cost savings related to energy are significantly higher than the savings related to the fixed fee. A measure such as *no night setback*, which increases energy costs and reduces the fixed fee, might not be beneficial in some cases.



(a) *Glitre* **(b)** *Elvia* **(c)** *Nettselskapet*

Figure 4.19: *Annual costs related to the variable energy fee and fixed fee for the Kristiansand house with new grid tariffs and different power measures. The costs of the variable fee and electricity are displayed on the vertical axis, the costs of the fixed fee are displayed on the horizontal axis.*



(a) *Glitre* **(b)** *Elvia* **(c)** *Nettselskapet*

Figure 4.20: *Annual costs related to the variable energy fee and fixed fee for the Malvik house with new grid tariffs and different power measures. The costs of the variable fee and electricity are displayed on the vertical axis, the costs of the fixed fee are displayed on the horizontal axis.*

4.5.4 Effects of increasing the rates of the fixed fee

In the future, expansions of the electric grid might be necessary if changes in the user behavior do not occur. Expanding the capacity of the electric grid will induce higher costs for the grid companies, which in turn will induce higher grid tariffs for the consumers. This will most likely be lead to an increase of the fixed fee. Therefore, a sensitivity analysis of the Nettselskapet pilot tariff with increased fixed fee rates have been performed. The increased fixed fee rates that have been used in the sensitivity analysis are presented in Table 4.1. The global costs with the increased fixed fee rates are presented in Figure 4.21.

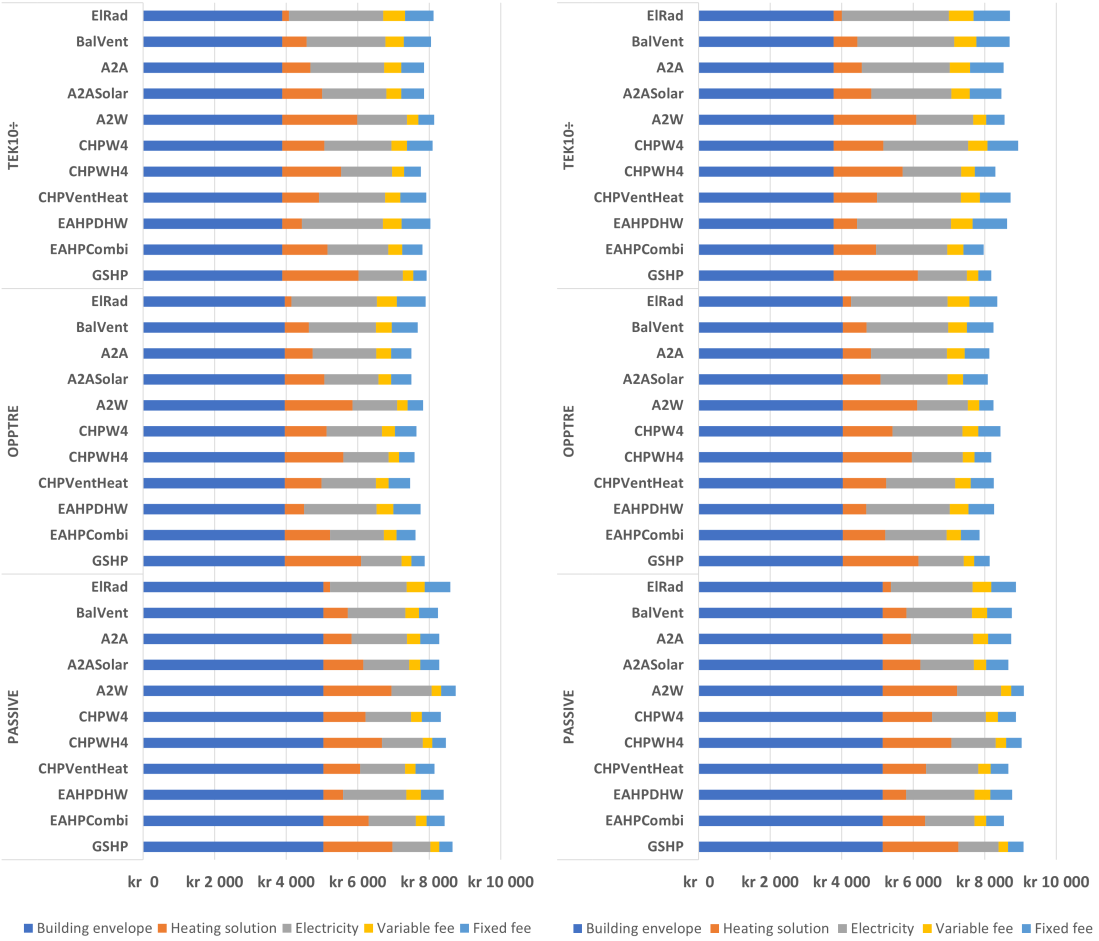
Table 4.1: *Increased fixed fee rates of the Nettselskapet pilot tariff.*

Monthly power peak	Fixed fee	
< 2 kW	150	NOK/month
< 5 kW	450	NOK/month
< 10 kW	900	NOK/month
< 15 kW	1 500	NOK/month

With the increased rates of the fixed fee, the benefits of low monthly power peaks increase. When comparing the economic performances with and without increased fixed fee rates, the relative performance of the GSHP and CHPWH4 combinations compared with the other combinations improve with increased fixed fee rates. This is especially explicit for the TEK10÷ scenarios, where the monthly power peaks of the combinations differ more. For the Kristiansand house, only the A2W, CHPW4 and GSHP combinations yield higher global costs than the CHPWH4 combination with the initial pilot tariff of Nettselskapet at TEK10÷ renovation level. However, with the increased fixed fees, the CHPWH4 combination yields the lowest global costs of all combinations.

For the Malvik house, the GSHP combination benefits the most from the increased rates of the fixed fee. This combination yields the second lowest global costs, and its low costs of the fixed fee compared with other combinations are significant. Only the EAHPCombi combination, which has significantly lower investment costs, yields lower global costs.

For both houses, the increased fixed fee rates have less impact on the global costs at higher renovation levels. This is mainly due to the increased insulation levels equalize the differences in the heating solutions. Although, the balanced ventilation system appears to a important measure at the higher insulation levels. This is especially noticeable when comparing the fixed fees of the ElRad and BalVent PASSIVE scenarios for the Kristiansand house.



(a) *Kristiansand*

(b) *Malvik*

Figure 4.21: *Mean global costs of all scenarios for both houses with increased fixed fee.*

4.6 Optimal combinations

As presented in this thesis, the best performing heating supply solutions in terms of energy are not the most feasible solutions economically. Furthermore, different households may put emphasis on other factors than the energy consumption and the total costs over the economic lifetime. Therefore, several KPI's have been defined in order to propose optimal combinations for the different renovation levels. The optimal solution is considered to be the combination with the highest overall performance when taking all KPI's into account. The overall performance of each combination is decided by a total score, where each KPI awards a score ranging from -2 to +2. A score of +2 is awarded if the combination performs very good, +1 is awarded if the combination performs good, 0 is awarded for an average performance, while scores of -1 and -2 are awarded for bad and very bad performances respectively. The scores are given based on the relative performances compared to the other combinations at the same renovation level. The KPI's which have been taken into consideration are presented in the following paragraphs:

IC, investment costs For most house owners, the initial investment cost of the energy measure is an important factor. As presented in this thesis, the payback time of the investments usually range from 10 to 25 years. Many house owners may consider heavy investments that only become profitable after such time periods to be a too big commitment. Furthermore, some house owners might not even be able to raise the funds needed if the initial investment is too big.

GC, global costs The total costs over the calculation period might be an important factor for the house owners that are not planning to move in the foreseeable future, and are looking to make an economically profitable investment long term.

EC, energy consumption This is the most important factor when considering the environmental impact of the combination. Furthermore, the combinations yielding lower energy consumption are less vulnerable to heavy fluctuations in energy price, and give more stability and predictability in terms future energy costs. Furthermore, the combinations with a low energy consumption yield higher savings if the energy prices increase in the future.

ES/IC The ratio between the energy savings and the capital costs of the combination shows the efficiency in terms of both economy and environment. A high ratio will also shorten the amount of time before the initial investment is recouped.

PT, power tariff This KPI evaluates the annual costs of the fixed pilot fee with increased rates. This indicator is included to evaluate the robustness of each combination when it comes to future changes in the fixed grid fee. Combinations that are more vulnerable to increased rates of the grid tariff in the future might become less profitable. The annual costs of the fixed fee with increased rates that are presented in section 4.5.4 form the basis when evaluating this KPI.

TC, thermal comfort A brief evaluation of the thermal comfort of the combinations is also taken into account. Compared with balanced ventilation, exhaust ventilation systems might cause draught and thermal discomfort, which has been taken into consideration.

The overall scores for the Kristiansand and Malvik house are presented in Table 4.2 and Table 4.3 respectively.

Table 4.2: *Overall scores for the Kristiansand house.*

Renovation level	Combination	IC	GC	EC	ES/IC	PT	TC	SUM
TEK10÷	BalVent	⊕⊕	⊕	⊖⊖	⊕	⊖⊖	⊕	1
	A2A	⊕⊕	⊕⊕	⊖	⊕⊕		⊕	6
	A2ASolar	⊕	⊕	⊕	⊕		⊕	5
	A2W	⊖	⊖⊖	⊕⊕	⊖⊖	⊕	⊕	-1
	CHPW4				⊖⊖	⊖	⊕	-2
	CHPWH4	⊖		⊕⊕	⊖	⊕	⊕	2
	CHPVentHeat	⊕	⊕⊕			⊖	⊕	3
	EAHPDHW	⊕⊕	⊕	⊖⊖		⊖⊖	⊖	-2
	EAHPCombi		⊕	⊕			⊖	1
	GSHP	⊖⊖	⊖	⊕⊕	⊖	⊕⊕	⊕	1
OPPTRE	BalVent	⊕⊕	⊕	⊖	⊕⊕	⊖	⊕	4
	A2A	⊕⊕	⊕⊕		⊕⊕		⊕	7
	A2ASolar	⊕	⊕⊕	⊕	⊕		⊕	6
	A2W	⊖	⊖	⊕⊕	⊖	⊕	⊕	1
	CHPW4		⊕	⊕	⊖		⊕	2
	CHPWH4	⊖		⊕⊕	⊖	⊕	⊕	2
	CHPVentHeat	⊕	⊕⊕	⊕	⊕		⊕	6
	EAHPDHW	⊕⊕	⊕	⊖⊖		⊖⊖	⊖	-2
	EAHPCombi			⊕	⊖		⊖	-1
	GSHP	⊖⊖	⊖⊖	⊕⊕	⊖⊖	⊕⊕	⊕	-1
PASSIVE	BalVent	⊕⊕	⊕	⊖	⊕⊕		⊕	5
	A2A	⊕⊕	⊕	⊖	⊕⊕		⊕	5
	A2ASolar	⊕	⊕	⊕	⊕	⊕	⊕	6
	A2W	⊖	⊖⊖	⊕⊕	⊖⊖	⊕	⊕	-1
	CHPW4		⊕	⊕			⊕	3
	CHPWH4	⊖	⊖	⊕⊕	⊖⊖	⊕⊕	⊕	1
	CHPVentHeat	⊕	⊕⊕	⊕	⊕		⊕	6
	EAHPDHW	⊕⊕	⊕	⊖⊖		⊖	⊖	-1
	EAHPCombi				⊖		⊖	-2
	GSHP	⊖⊖	⊖⊖	⊕⊕	⊖⊖	⊕⊕	⊕	-1

Table 4.3: *Overall scores for the Malvik house.*

Renovation level	Combination	IC	GC	EC	ES/IC	PT	TC	SUM
TEK10÷	BalVent	⊕⊕	⊕	⊖⊖	⊖	⊖⊖	⊕	-1
	A2A	⊕⊕	⊕	⊖	⊕⊕	⊖⊖	⊕	3
	A2ASolar	⊕	⊕		⊕	⊖	⊕	3
	A2W	⊖⊖	⊖⊖	⊕⊕	⊖	⊕	⊕	-1
	CHPW4	⊖	⊖⊖	⊖	⊖⊖	⊖	⊕	-6
	CHPWH4	⊖⊖		⊕⊕	⊖	⊕	⊕	1
	CHPVentHeat			⊖	⊖⊖	⊖	⊕	-3
	EAHPDHW	⊕⊕	⊕	⊖⊖	⊖	⊖⊖	⊖	-3
	EAHPCombi	⊕	⊕⊕	⊕	⊕	⊕	⊖	5
	GSHP	⊖⊖	⊖	⊕⊕		⊕⊕	⊕	2
OPPTRE	BalVent	⊕⊕	⊕	⊖⊖	⊕	⊖⊖	⊕	1
	A2A	⊕⊕	⊕⊕	⊖	⊕⊕	⊖	⊕	5
	A2ASolar	⊕	⊕⊕		⊕	⊖	⊕	4
	A2W	⊖⊖	⊖⊖	⊕⊕	⊖	⊕⊕	⊕	0
	CHPW4	⊖	⊖		⊖⊖		⊕	-3
	CHPWH4	⊖⊖		⊕⊕	⊖	⊕⊕	⊕	2
	CHPVentHeat				⊖		⊕	0
	EAHPDHW	⊕⊕	⊕	⊖⊖	⊖	⊖	⊖	-2
	EAHPCombi	⊕	⊕⊕	⊕	⊕	⊕	⊖	5
	GSHP	⊖⊖	⊖	⊕⊕		⊕⊕	⊕	2
PASSIVE	BalVent	⊕⊕	⊕	⊖	⊕⊕	⊖	⊕	4
	A2A	⊕⊕	⊕	⊖	⊕⊕	⊖	⊕	4
	A2ASolar	⊕	⊕		⊕		⊕	4
	A2W	⊖⊖	⊖⊖	⊕⊕	⊖⊖	⊕⊕	⊕	-1
	CHPW4	⊖			⊖⊖	⊕	⊕	-1
	CHPWH4	⊖⊖	⊖	⊕⊕	⊖⊖	⊕⊕	⊕	0
	CHPVentHeat		⊕		⊖	⊕	⊕	2
	EAHPDHW	⊕⊕	⊕	⊖⊖	⊖		⊖	-1
	EAHPCombi	⊕	⊕	⊕		⊕	⊖	3
	GSHP	⊖⊖	⊖⊖	⊕⊕	⊖⊖	⊕⊕	⊕	-1

Among the Kristiansand TEK10÷ scenarios, the best performing appears to be the A2A combination, closely followed by A2ASolar. A2A performs well, despite the high energy consumption compared with other solutions. The major benefit of this combination is the low capital costs, which also yield a high energy savings per NOK invested. The A2ASolar combination does not score +2 in any of the KPI's, but is an overall solid performer. The worst performers are CHPW4 and EAHPDHW, as well as A2W. CHPW4 and EAHPDHW only cover heating of DHW, which yield a bad performances in terms of energy consumption. The CHPW4 is also a very expensive combination compared to the energy savings it provides. EAHPDHW has no ventilation heat recovery, which affects its performances related to energy consumption, fixed fee costs and thermal comfort. The A2W performs badly due to its high investment costs, high global costs, and a low energy savings per NOK invested ratio. Thus, the total score is negative despite being a robust choice in terms of energy and power consumption, as well as thermal comfort.

For the OPPTRE renovation level, the best performing combination is still the A2A combination, followed by A2ASolar and CHPVentHeat. The total score of the A2A combination is higher with the OPPTRE envelope than with the TEK10÷ envelope. This is caused by a higher score in energy consumption with the OPPTRE scenario, which is a result of the differences in energy consumption among the combinations decrease as the renovation level increases. The CHPVentHeat combination performs significantly better with the OPPTRE envelope compared with the TEK10÷ envelope. With higher insulation levels, this combination is less punished for the low efficient space heating system when it comes to energy consumption and fixed fee costs. Meanwhile, the combination has competitive investment costs, and it is the best performer in terms of global costs. Also with the OPPTRE envelope, the worst performer is EAHPDHW, where no changes in terms of performance compared with the other combinations appear. EAHPDHW is followed by GSHP, which has too high capital costs compared with the energy savings it is able to provide.

With the PASSIVE envelope, the best performers all have low investment costs in common. With the high insulation levels, the differences in energy consumption for space heating is reduced. This results in all combinations with high investment costs perform badly in terms of economical KPI's, while they gain only small benefits energy wise. Overall, the best performing combinations are A2ASolar and CHPVentHeat, closely followed by A2A and BalVent. CHPVentHeat is a fairly cheap solution which covers the DHW, while the solar panel heaters cover a high amount of the DHW during the summer months. As these combinations also have balanced ventilation installed, they are very well suited for houses with low space heating demand, and high DHW consumption.

For the Malvik TEK10÷ scenarios, the optimal combination appears to be the EAHPCombi solution. As mentioned previously, the balanced ventilation system yields low energy saving in this house due to exhaust ventilation terminals being placed in the unheated basement. Thus, the exhaust air heat pump performs well for all KPI's, except for thermal comfort. Due to the low DHW consumption in this house, the CHPW4 combination yields low energy savings. This, in addition to the ineffective balanced ventilation and high investment costs, make this combination the least optimal by a large margin.

With the OPPTRE renovation level, the most optimal combination remain EAHPCombi, along with A2A. The EAHPCombi solution still performs well across all KPI's, while A2A benefits heavily from low investment costs. Additionally, the balanced ventilation system becomes more efficient with the OPPTRE envelope compared with the TEK10÷ envelope due to a lower infiltration rate. This results in both low global costs and high energy savings per NOK invested. The CHPW4 combination remains the least optimal combination, but achieves a higher score than with the TEK10÷ envelope. This is mainly because of the more efficient balanced ventilation and the DHW constituting a higher share of the total energy consumption.

As with the Kristiansand house, the BalVent and A2A combinations score high due to the low capital costs. These two are the optimal combinations, along with A2ASolar. While investment costs of A2ASolar are higher compared to BalVent and A2A, the combination performs better in terms of energy consumption and fixed grid fees. As with the Kristiansand house, the low space heating need gives a low potential for energy savings, resulting in all combinations with high capital costs among the least optimal combinations.

5 Conclusion

In this thesis, the simulation models from the previous work have been revised and validated, and exhaust air and compact heat pumps have been modeled in IDA ICE. The models have been validated by comparing the SPF of the models with the SPF for similar systems found in literature. The results show that the simulated models in most cases perform similarly to the systems described in literature. However, the performance of the air-to-air heat pump systems are hard to validate as few studies investigate the SPF of such systems. Furthermore, the air-to-air heat pump performance is heavily influenced by both climate and the floor plan of the house. When several factors impact the system performance, it gets harder to properly compare different air-to-air systems. Furthermore, it can be argued that the performance parameters set in the simulation models of the exhaust air heat pumps are somewhat over tuned.

In terms of energy performance, the results show that the GSHP combination yields the lowest annual energy consumption for all renovation levels for both houses. However, with increasing insulation levels, the potential energy savings compared to the reference scenario decreases. Thus, the differences in energy consumption of the GSHP compared with the other combinations decrease. At higher insulation levels, the most important measures to reduce the energy consumption are balanced ventilation with heat recovery and an efficient heating system for the DHW. As opposed to the lower renovation levels, the potential energy savings related to space heating are low. Thus, investing in efficient space heating systems yields lower energy savings compared with the lower renovation levels.

The trends in the energy performance are also reflected in the economic performance of the combinations. As the infiltration rate decreases with higher insulated envelopes, the savings yielded by a balanced ventilation system increase. Balanced ventilation is the only single measure that is more profitable at higher renovation levels than lower levels. Measures that reduce the energy consumption related to heating of DHW are unaffected by insulation levels, while space heating measures become less profitable at higher insulation levels. Thus, combinations that include upgrades to the ventilation system and heating of DHW, such as CHPVentHeat and A2ASolar, are more cost efficient at higher insulation levels. Furthermore, the economic performance is highly affected by the initial investment costs of the combinations. Thus, cheaper combinations such as A2A and BalVent are more cost efficient than expensive combinations like GSHP, CHPWH4 and A2W.

Sensitivity analysis on the economic performance have been conducted by excluding the economical grants by Enova and increasing the discount rates. Increased discount rates reduces the profitability of all combinations, mainly due to future benefits related to energy savings and the discounted residual values are reduced. However, the increased discount rates induces only marginal relative changes in the economic performance between the different combinations. Excluding the Enova subsidies induces bigger relative changes in the economic performance between the combinations. Several combinations are depending on the grants to be profitable, especially with higher insulation levels. The most affected combination is GSHP, which yields grants of 50 000 NOK.

The effects of different grid tariffs on the economic performance have also been evaluated. Grid tariffs with fixed grid fees based on monthly power peaks have low influence on the global costs. However, sensitivity analysis on the power based fixed fee rates show that expensive combinations that yield low power peaks such as GSHP, CHPWH4 and A2W might become more profitable compared with other combinations. This is especially noticeable at the lower insulation level. Operational measures to reduce power peaks and energy consumption are also profitable, but this is mostly due to reduced energy costs. Operating with night setback is profitable at lower insulation levels with inefficient heating supply combinations, despite yielding higher power peaks and fixed fee costs.

Optimal combinations have been proposed based on key performance indicators related to energy and economic performance, and thermal comfort. For the Kristiansand house, the optimal combination for the TEK10÷ and OPPTRE levels is A2A. Meanwhile, both A2ASolar and CHPVentHeat are considered optimal for the PASSIVE level. For the Malvik house, EAHPCombi is the optimal combination with TEK10÷ envelope. At OPPTRE level, both EAHPCombi and A2A are considered optimal, while three combinations are considered optimal at PASSIVE level; BalVent, A2A and A2ASolar.

6 Further work

While working on this thesis, several interesting issues and and possibilities for further work occurred. One of these is modeling of occupant adaption to power based fixed fees. In this thesis, the electricity consumption related to occupant behaviour is standardized. The standardized schedules for DHW consumption and technical equipment yield high electricity peaks during the morning and afternoon. For further work, it can be interesting to investigate the effects on fixed fee costs of flattening the peaks and distributing the electricity consumption more evenly throughout the day

Furthermore, woods stoves are very commonly used in Norway for heating during cold days. Woods stoves are not included in the scope of this thesis, but the effects of these on the power peaks and electricity consumption could be interesting to investigate further.

The new grid tariff models were adjusted during the work of this thesis. These changes have not been included in this thesis, and the grid tariffs that are induced the from the 1st of July are therefore slightly different than those who have been investigated. Looking into differences in economic performance with these changes might therefore be interesting.

The implementation of the of the exhaust air and compact heat pumps can be revised and further refined. As mentioned previously in this thesis, the performance parameters of the exhaust air heat pump are likely over tuned. Furthermore, the models implemented are simplified. Thus, more detailed implementation of these might yield different results.

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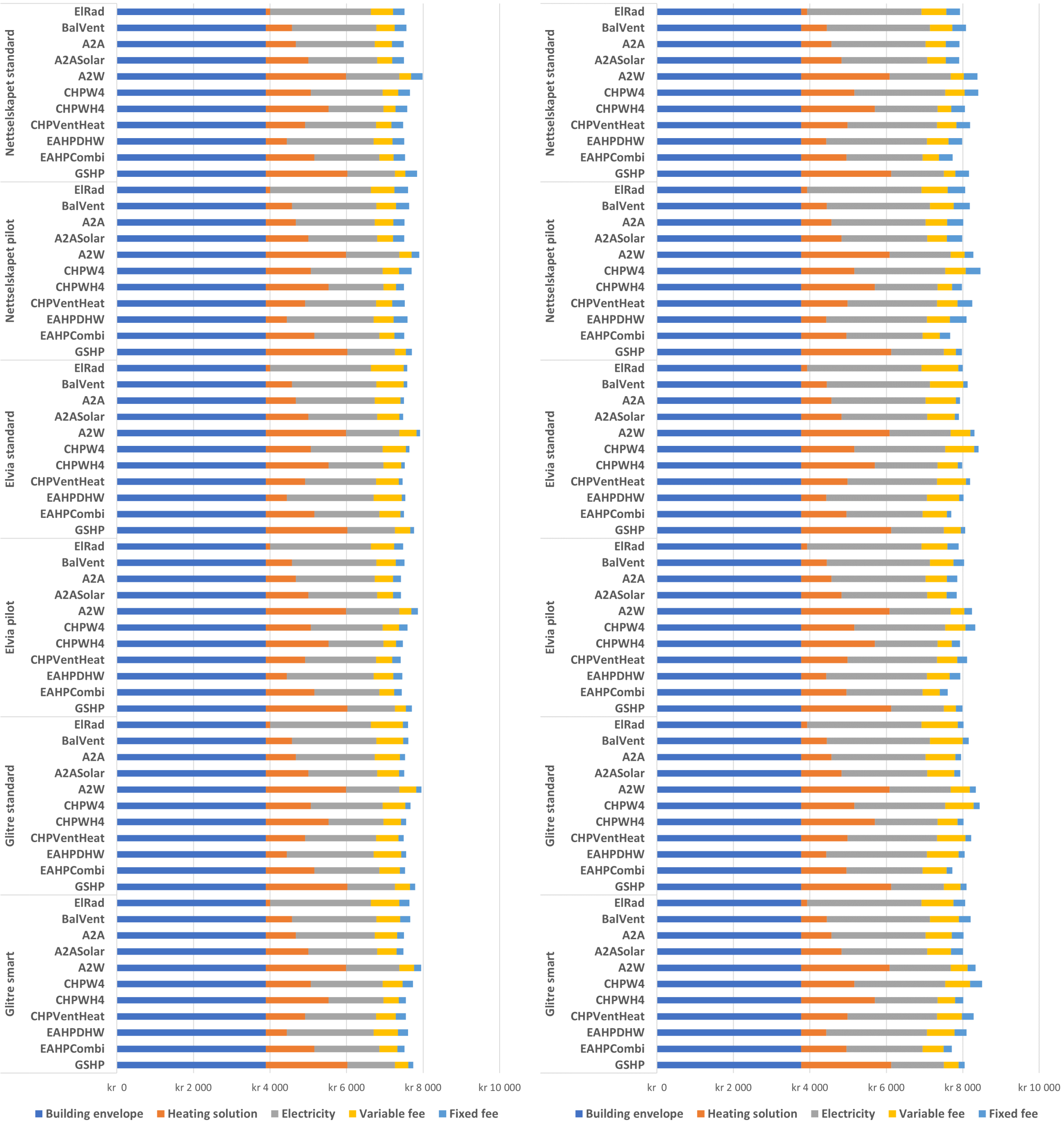
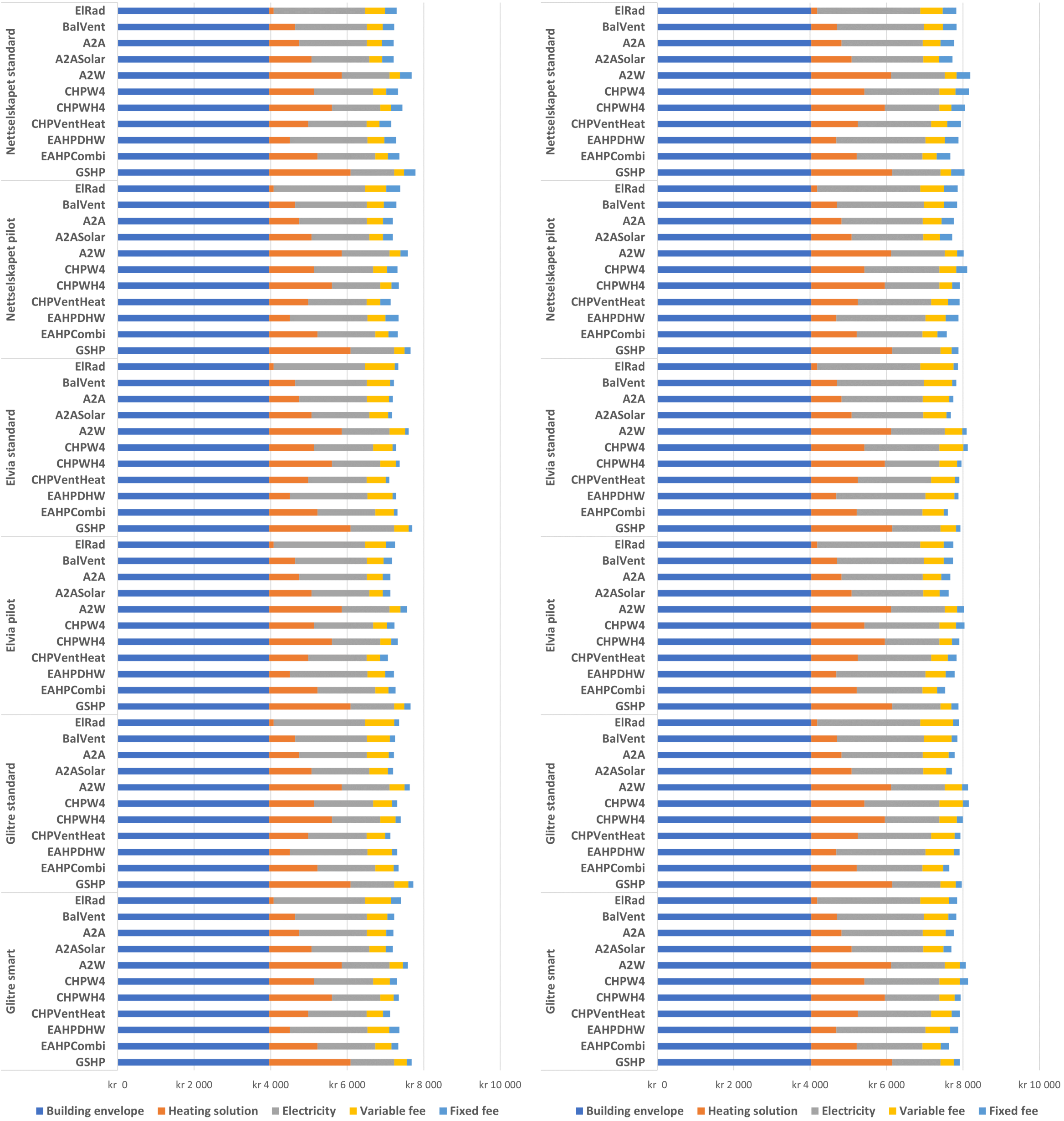
A Global costs with pilot grid tariffs



(a) *Kristiansand* **(b)** *Malvik*

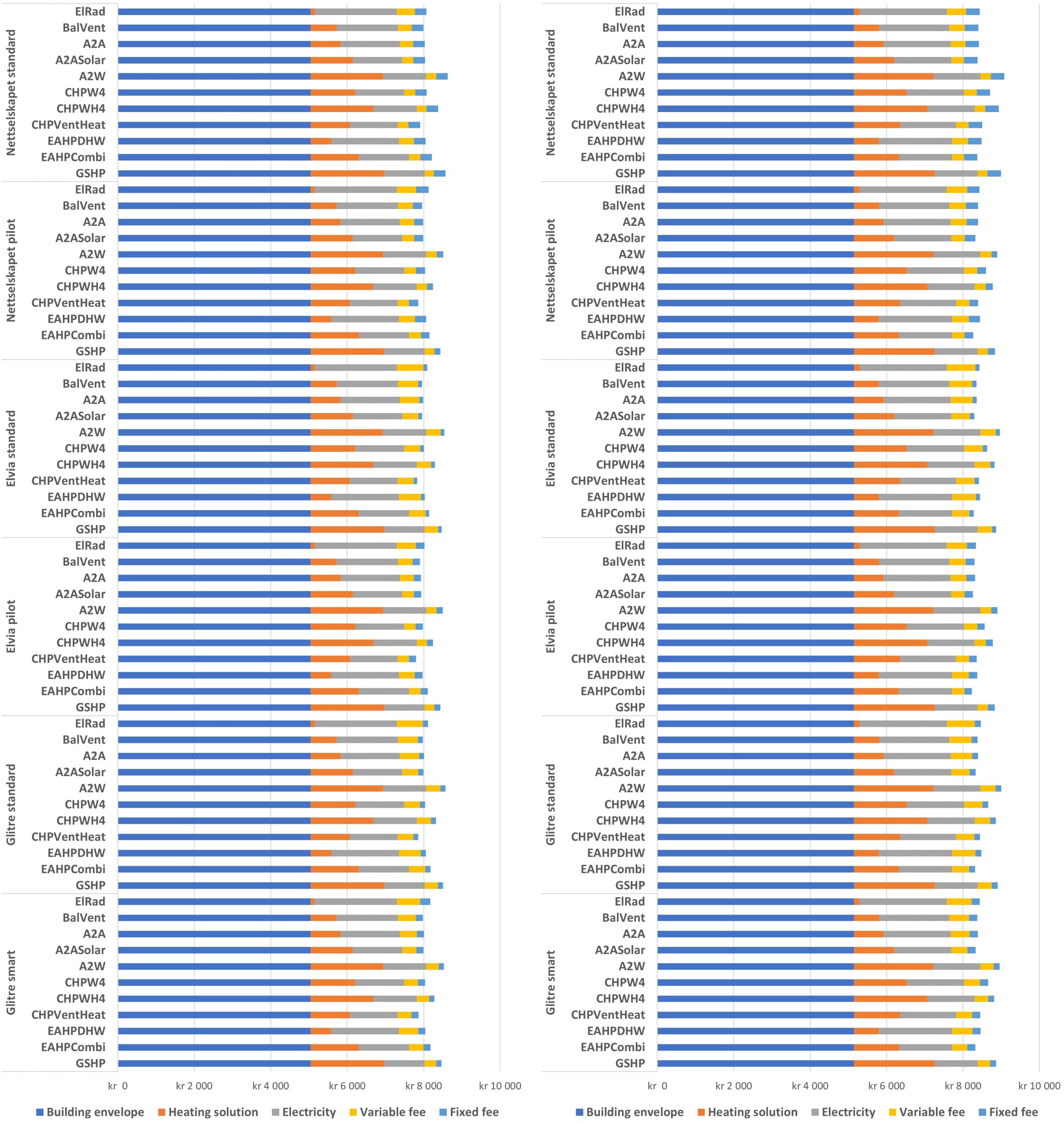
Figure A.1: *Global costs of renovation level TEK10÷ with new grid tariffs for both houses.*



(a) *Kristiansand*

(b) *Malvik*

Figure A.2: *Global costs of renovation level OPPTRE with new grid tariffs for both houses.*



(a) *Kristiansand*

(b) *Malvik*

Figure A.3: *Global costs of renovation level PASSIVE with new grid tariffs for both houses.*

B Energy costs and costs of the fixed fee

B.1 Kristiansand

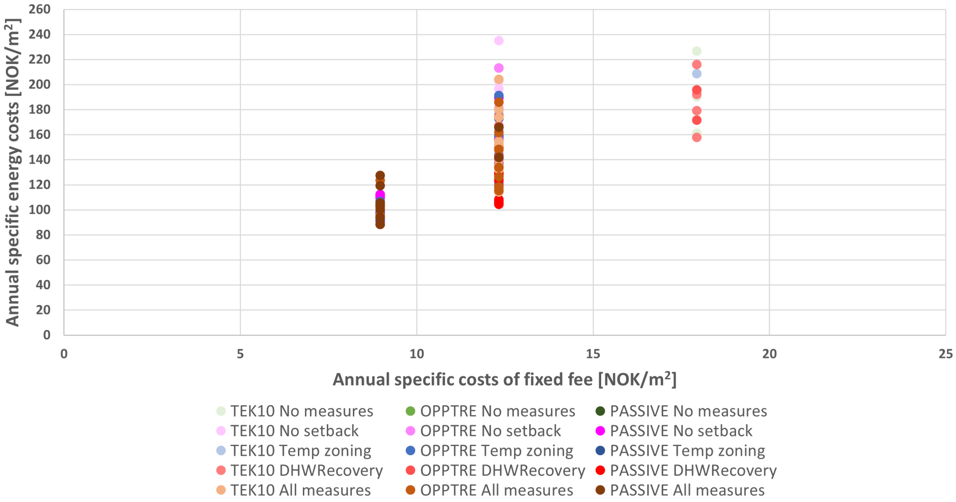


Figure B.1: *Annual specific costs of energy and fixed fee with different power reducing measures implemented. Glitre pilot tariff.*

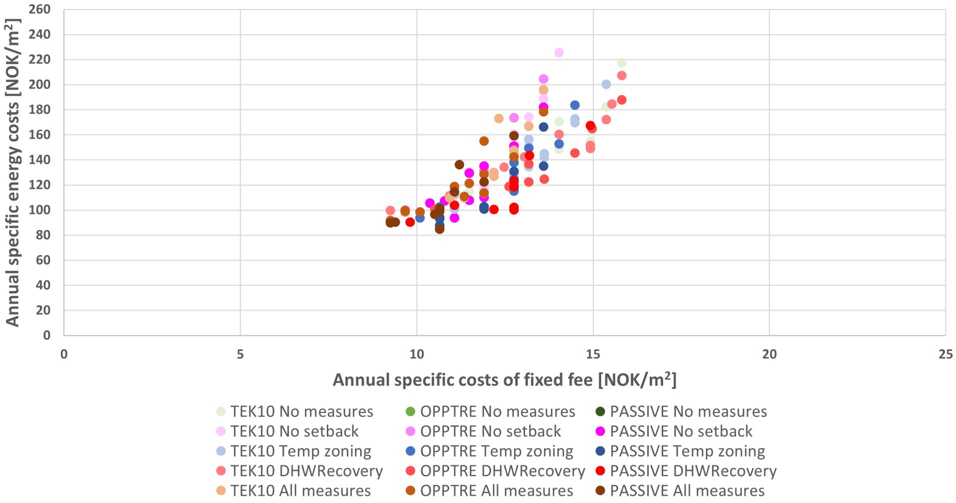


Figure B.2: *Annual specific costs of energy and fixed fee with different power reducing measures implemented. Elvia pilot tariff.*

B.2 Malvik

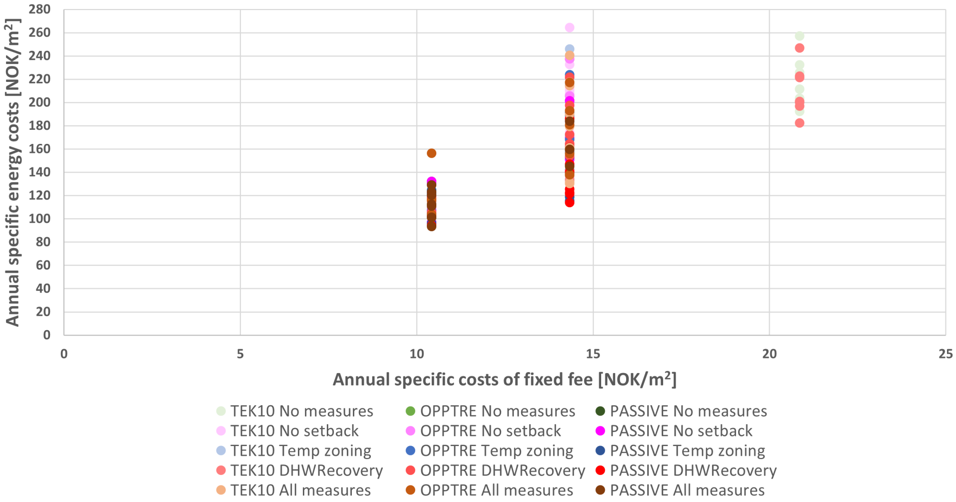


Figure B.3: *Annual specific costs of energy and fixed fee with different power reducing measures implemented. Glitre pilot tariff.*

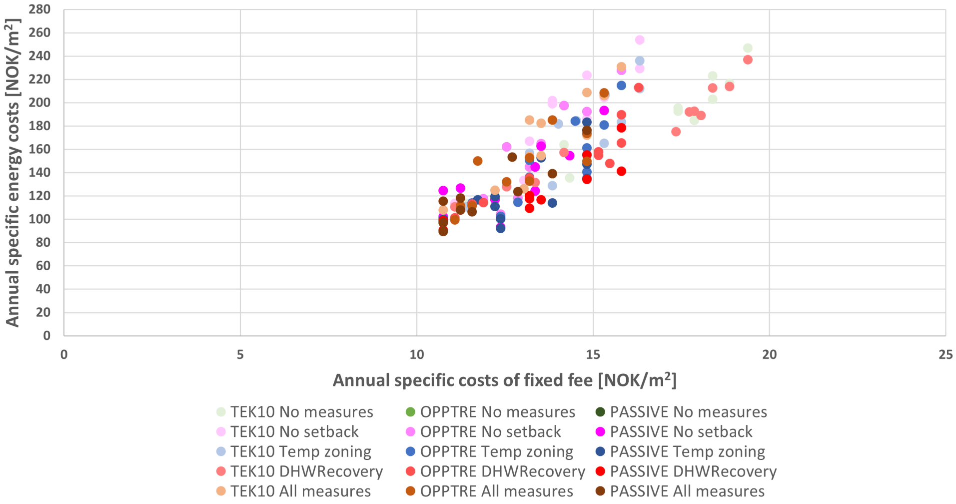


Figure B.4: *Annual specific costs of energy and fixed fee with different power reducing measures implemented. Elvia pilot tariff.*

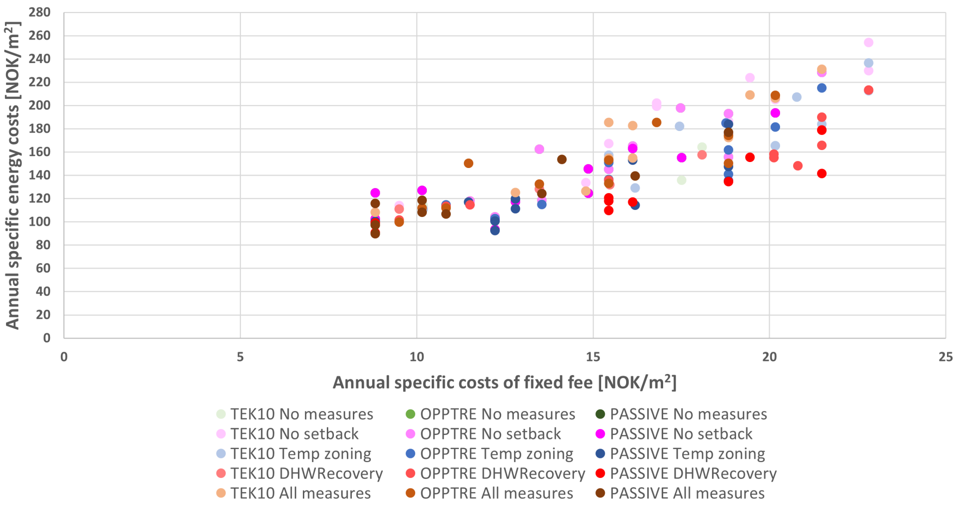


Figure B.5: *Annual specific costs of energy and fixed fee with different power reducing measures implemented. Nettselskapet pilot tariff.*

C Heat pump system performance with energy and power saving measures

C.1 No setback

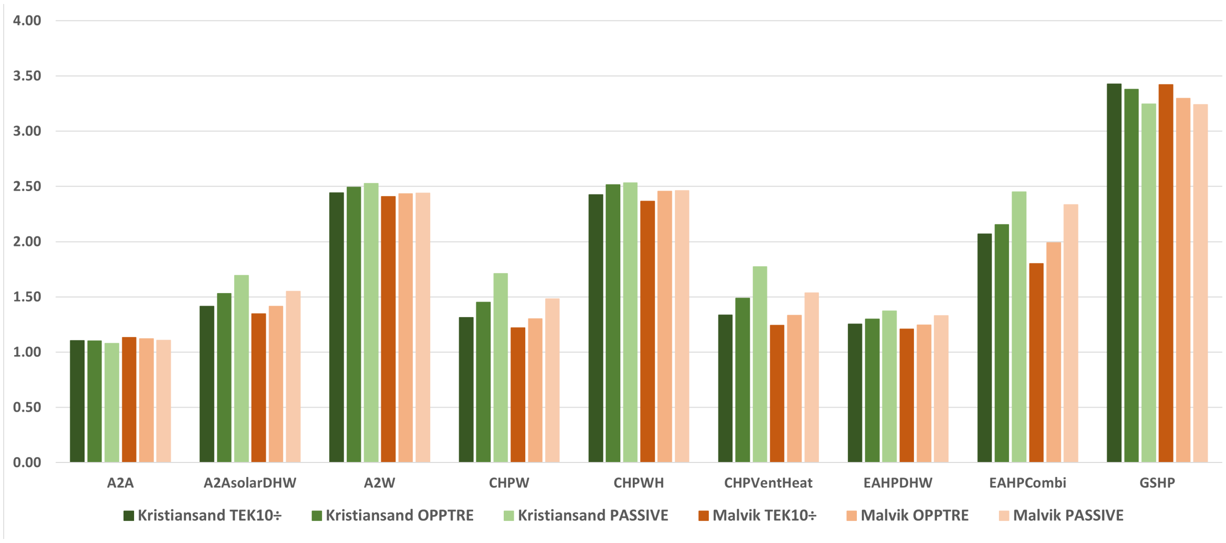


Figure C.1: *SPF for all scenarios with no night setback implemented.*

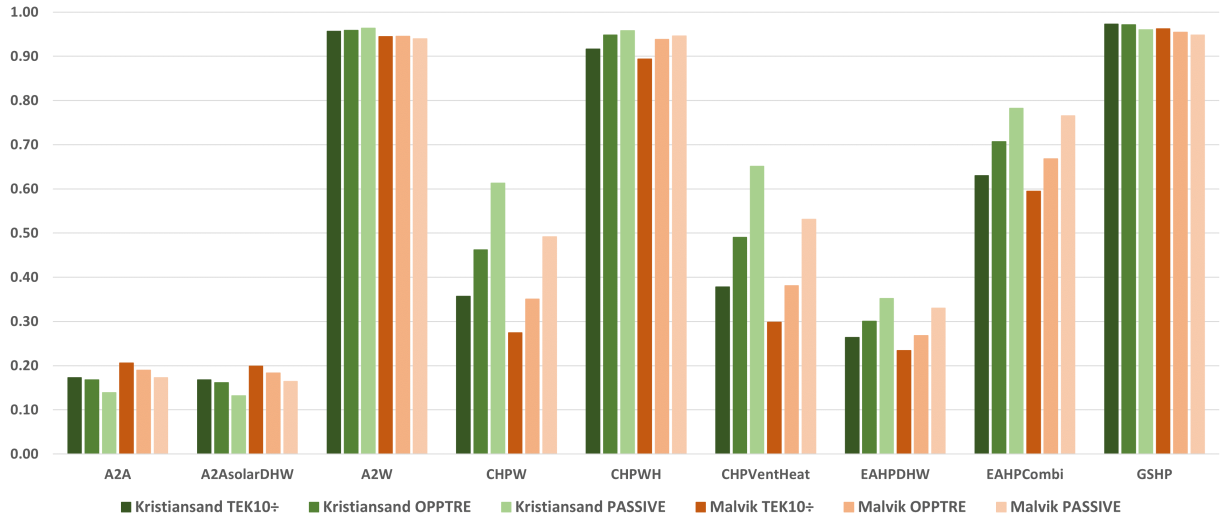


Figure C.2: *Energy coverage factor for all scenarios with no night setback implemented.*

C.2 Temperature zoning

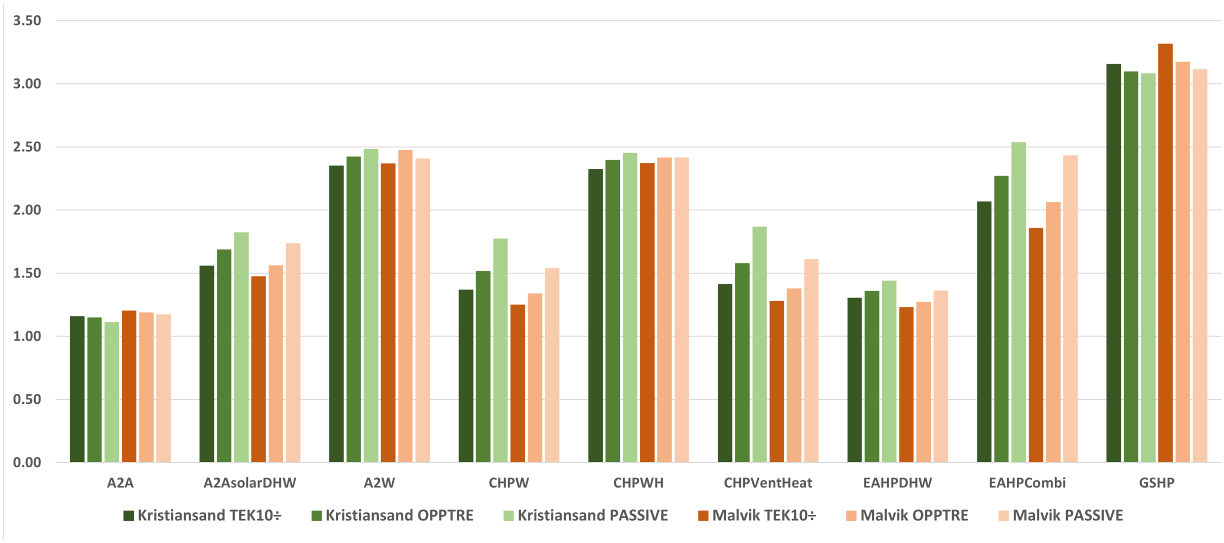


Figure C.3: *SPF for all scenarios with temperature zoning implemented.*

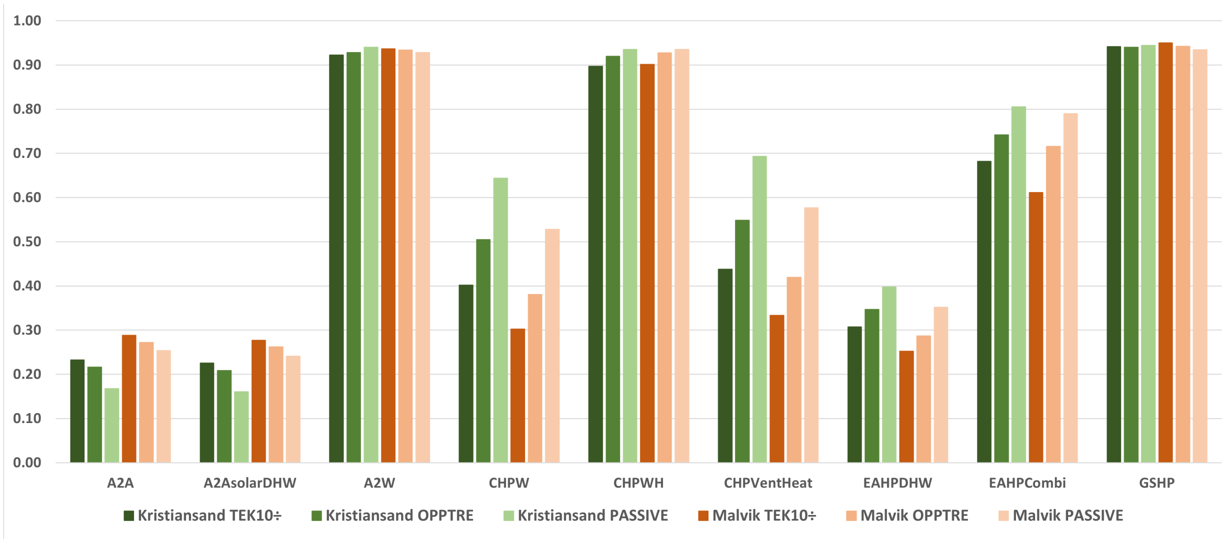


Figure C.4: *Energy coverage factor for all scenarios with temperature zoning implemented.*

C.3 DHW heat recovery

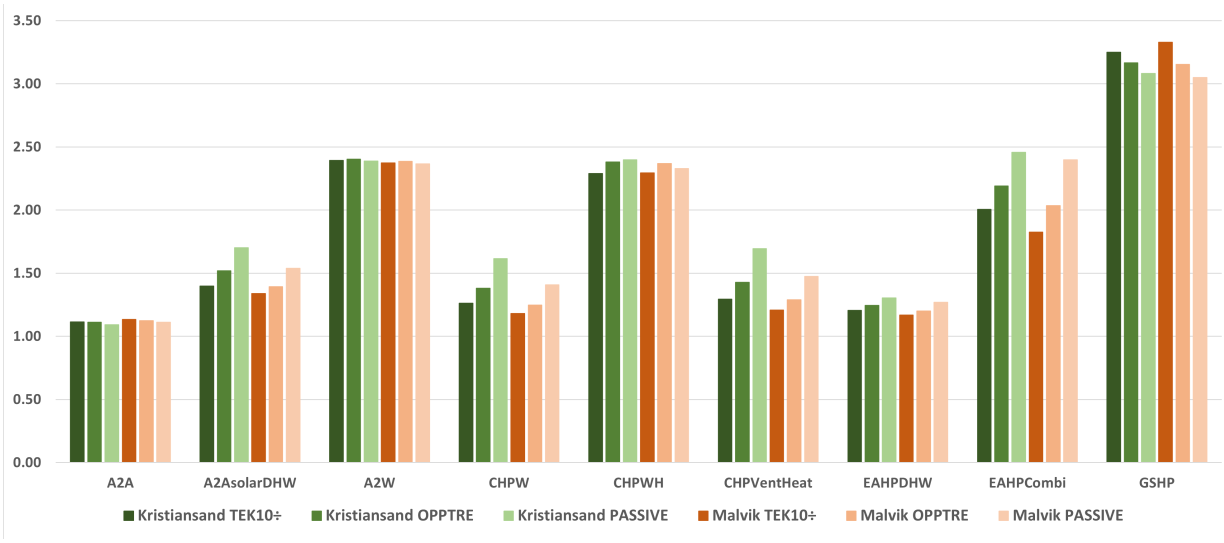


Figure C.5: *SPF for all scenarios with DHW heat recovery implemented.*

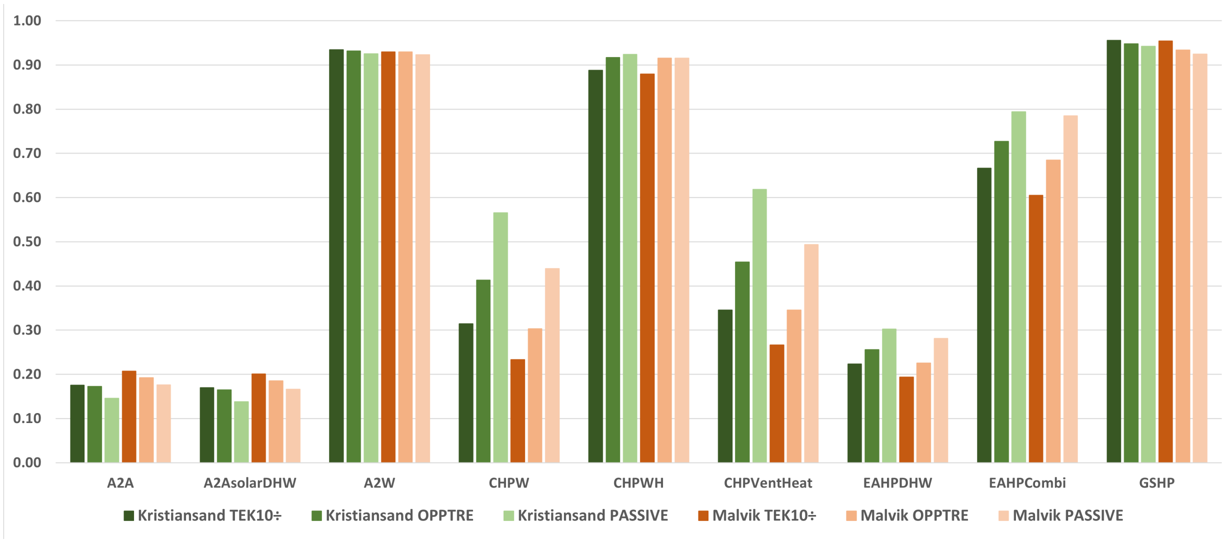


Figure C.6: *Energy coverage factor for all scenarios with DHW heat recovery implemented.*

C.4 All measures

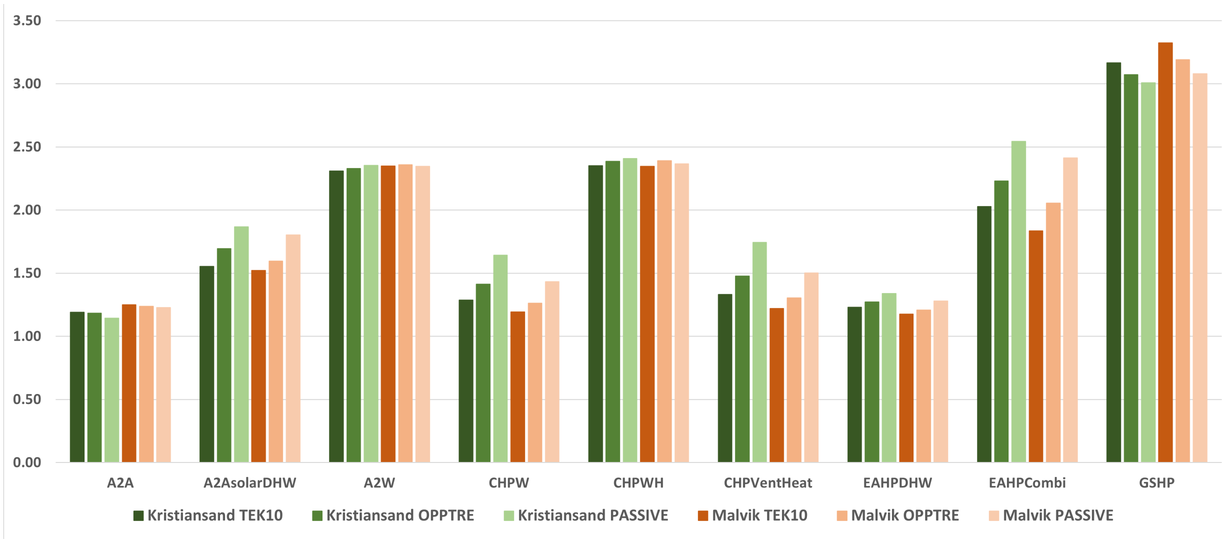


Figure C.7: *SPF for all scenarios with all power reducing and energy saving measures implemented.*

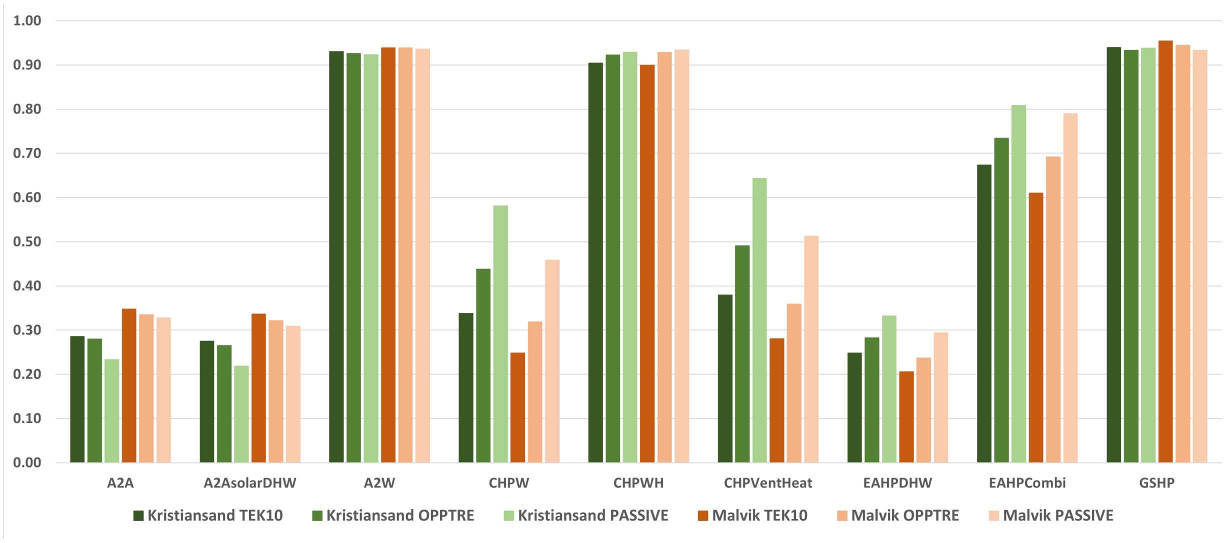


Figure C.8: *Energy coverage factor for all scenarios with all power reducing and energy saving measures implemented.*

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