NTNU
Norwegian University of
Science and Technology

Heat recovery in combination with different heat pump solutions

Martin Sandvik Svenøy

Master of Energy and Environmental Engineering
Submission date: June 2016
Supervisor: Hans Martin Mathisen, EPT

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

NTNU
Norwegian University
of Science and Technology

Department of Energy
and Process Engineering

EPT-M-2016-135

MASTER THESIS

for

Student
Martin Sandvik Svenøy

Spring 2016

Heat recovery in combination with different heat pump solutions
Varmegjenvinning i kombinasjon med ulike varempumpeløsninger

Background and objective

In highly insulated buildings a ventilation system is necessary. Norwegian regulations demands that at least half the volume of air in the building is exchanged every hour. This requires a lot of energy for heating of supply air, and therefore the standards require a heat recovery system with an efficiency of at least 80%. This is normally combined with mechanical ventilation.
The goal is to compare the total energy efficiency of using a heat wheel with the use of an exhaust air heat pump (CO_2 supercritical heat pump and commercially available compact heat pump) with accumulation tank (so that it can produce domestic hot water and space heating). The comparison to be performed will be on the energy use for space heating and domestic hot water in a residential building. Also costs should be taken into consideration.

The master thesis is a continuation of the student's specialization project work.

The following tasks are to be considered:

1. Literature review on exhaust air heat pumps
2. Improve the heat pump model developed in the specialization project
3. Refine the simulation of case building(s) with IDA-ICE
4. Make LCC comparisons between different solutions

-- " --

Within 14 days of receiving the written text on the master thesis, the candidate shall submit a research plan for his project to the department.

When the thesis is evaluated, emphasis is put on processing of the results, and that they are presented in tabular and/or graphic form in a clear manner, and that they are analyzed carefully.

The thesis should be formulated as a research report with summary both in English and Norwegian, conclusion, literature references, table of contents etc. During the preparation of the text, the candidate should make an effort to produce a well-structured and easily readable report. In order to ease the evaluation of the thesis, it is important that the cross-references are correct. In the making of the report, strong emphasis should be placed on both a thorough discussion of the results and an orderly presentation.

The candidate is requested to initiate and keep close contact with his/her academic supervisor(s) throughout the working period. The candidate must follow the rules and regulations of NTNU as well as passive directions given by the Department of Energy and Process Engineering.

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

Pursuant to "Regulations concerning the supplementary provisions to the technology study program/Master of Science" at NTNU §20, the Department reserves the permission to utilize all the results and data for teaching and research purposes as well as in future publications.

The final report is to be submitted digitally in DAIM. An executive summary of the thesis including title, student's name, supervisor's name, year, department name, and NTNU's logo and name, shall be submitted to the department as a separate pdf file. Based on an agreement with the supervisor, the final report and other material and documents may be given to the supervisor in digital format.

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

Department of Energy and Process Engineering, 13. January 2016

Olav Bolland
Department Head

Hans Martin Mathisen
Academic Supervisor

Research Advisor:

Abstract

The aim for this Master's thesis has been to investigate and compare the performance of different methods for heat recovery from exhaust ventilation air. Energy efficiency of using a heat exchanger is compared to commercial exhaust heat pump (EAHP) products. The heat pump units include accumulation tank so that they can supply domestic hot water and space heating. A life cycle costing (LCC) comparison between the solutions has been made. The basis for the simulation is a single-unit dwelling that could accommodate a family of four with an internal area of 115 m^2. The house is built according to the Norwegian passive house standard.

Five different systems were simulations in IDA Indoor Climate and Energy with two different climates, the cities of Trondheim and Kautokeino. One of the system analyzed have passive heat recovery and electric heaters for addition space heating and DHW. Three of the systems are based on exhaust heat pumps, two from NIBE (F470 and F110) and one from Nilan (Compact P Nordic). The last system is a reference system were electric heaters covers the entire demand.

Without any heat recovery, the total energy demand for ventilation and heating was 106,3 kWh/(m^2*year) in Trondheim and 180,3 kWh/(m^2*year) in Kautokeino. Heat recovery with 80% efficiency and a minimum discharge air temperature of 5 ^oC reduced the energy demand to 56,5 kWh/(m^2*year) and 104,6 kWh/(m^2*year), in Trondheim and Kautokeino respectfully. Heat recovery reduces the delivered energy of 46,8% in Trondheim and 42,0% in Kautokeino. The most energy efficient system was the exhaust air heat pump unit Compact P Nordic from Nilan. The delivered energy for ventilation and heating was reduced by 62,2%, down to 40,1 kWh/(m^2*year) in Trondheim. And in Kautokeino the delivered energy was reduced by 47,6%, down to 94,5 kWh/(m^2*year).

The LCC compare the total annual cost for the five systems. The comparison include annual energy cost and the investment cost for the heating system, ventilation and heat pump units. A calculation tool called LCCWeb was used to calculate the costs.

The cheapest system was the one with only passive heat recovery with an annual cost of 16 856 NOK/year, 17,73% lower than the reference system, for a building in Trondheim. The most expensive system was the EAHP F470 from NIBE with an annual cost 6,86% higher than the reference system, at 18 012 NOK/year.

Sammendrag

Målet for denne masteroppgaven har vært å undersøke og sammenligne ytelsen til ulike metoder for varmegjenvinning fra avtrekksventilasjon luft. Energieffektiviteten ved å bruke en varmeveksler blir sammenlignet med kommersielle avtrekks varmepumpe produkter. Varmepumpe produktene kommer med en innebygd varmvannstank, slik at de kan levere varmt tappevann og romoppvarming. En livssyklus kostands (LCC) sammenligning for de analyserte løsningene har også blitt gjort. Grunnlaget for simuleringene er en enebolig som kan romme en familie på fire med et innvendig areal på 115m^2. Huset er bygget i henhold til norsk passivhusstandard.

Fem forskjellige systemer er simulert i IDA Indoor Climate and Energy med to forskjellige klimaer, byene Trondheim og Kautokeino. Et av systemene som analyseres har passiv varmegjenvinning og elektriske varmeovner for romoppvarming og varmtvann. Tre av de simulerte systemene er basert på avtrekksvarmepumper, to levert av NIBE (F470 og F110) og en fra Nilan (Compact P Nordic). Det siste systemet er et referanse system med elektriske varmeovner som dekker hele varmebehovet.

Uten noe varmegjenvinning er det totale energibehovet for ventilasjon og varme 106,3 kWh/(m^2*år) i Trondheim og 180,3 kWh/(m^2*år) i Kautokeino. Varmegjenvinning med 80% effektivitet og 5 ^oC minimums temperatur på utslipps lufta, reduseres energibehovet til 56,5 kWh/(m^2*år) og 104,6 kWh/(m^2*år), i Trondheim og Kautokeino respektfullt. Varmegjenvinningen reduserte levert energi med 46,8% i Trondheim og 42,0% i Kautokeino. Det mest energieffektive systemet var avtrekksvarmepumpen Compact P Nordic fra Nilan. Den leverte energien til ventilasjon og varme ble redusert med 62,2%, ned til 40,1 kWh/(m^2*år) i Trondheim. Og i Kautokeino ble levert energi redusert med 47,6%, ned til 94,5 kWh/(m^2*år).

LCC sammenligninger den totale årlige kostnaden for de fem systemene. Sammenligningen omfatter årlige energikostnader og investeringskostnader for oppvarmingssystemet, ventilasjon og varmepumpe enhetene. Et beregningsverktøy kalt LCCWeb ble brukt for å beregne kostnadene.

Det billigste systemet var løsningen med bare passiv varmegjenvinning med en årlig kostnad på 16 856 kr/år, 17,73% lavere enn referansesystemet for en bygning i Trondheim. Det dyreste systemet var varmepumpen F470 fra NIBE med en årlig kostnad 6,86% høyere enn referansesystemet, på 18 012 kr/år.

Preface

The work in this Master's Thesis is the final work for a master's degree in the program Energy and Environmental Engineering at Norwegian University of Science and Technology in Trondheim. The thesis is a continuation of the specialization project written during the autumn semester of 2015. The assignment comprises 30 ECTS credits.

I would like to thank my supervisor Hans Martin Mathisen for the support and feedback during my work on the thesis. I would also like to thank employees at the Department of Energy and Process Engineering who have been available for support during the project. Especially Associate Professor Natasa Nord who have been helpful regarding IDA ICE, and Associate Professor Kjell Kolsaker who have been helpful with working with the matlab script.

Martin Sandvik Svenøy Trondheim 23.06.2016

Table of Contents

Glossary and abbreviations

AHU	Air handling unit
AMTD	Arithmetic mea temperature difference
COP	Coefficient of performance
Delivered energy	Energy delivered to the building (e.g. electrical energy from the grid)
DHW	Domestic hot water
Discharge air	Ventilation air that is leaving the building
EAHP	Exhaust air heat pump
Exhaust air	Ventilation air that comes from the zones in the building
GWP	Global warming potential
HFC	Hydrofluorocarbons (type of refrigerant)
IDA ICE	IDA Indoor Climate and Energy, a simulation program
LCA	Life cycle assessment
LCC	Life cycle costing
LCCWeb	A web based calculation tool used for LCC comparison
LMTD	Logarithmic mean temperature difference
NS 3031	Calculation of energy performance of buildings - Method and data
NS 3700	Criteria for passive houses and low energy buildings - Residential buildings
NTNU	Norwegian University of Science and Technology (Norges teknisk naturvitenskapelige universite)
Outdoor air	Air from the surroundings
PV	Present value
Supply air	Ventilation air that is supplied to the zones in the building
TEK10	Norwegian building code
U-value	Overall heat transfer coefficient
UA-value	Overall heating coefficient multiplied with the contact area of a heat exchanger

Nomenclature

Latin letters

a	Annuity factor [-]
Cp	Specific heating capacity [kJ/Kelvin]
e	Energy price [NOK/kWh]
h	Specific enthalpy [kJ/kg]
I	Investment cost [NOK]
$\dot{m}$	Mass flow rate [kg/s]
Q	Thermal energy [kWh]
q	Specific thermal energy [kWh/kg]
r	Discount rate [-]
T	Temperature [°C]
t	Temperature [°C]
W	Compressor energy [kWh]

Greek letters

η	Efficiency [-]

Chapter 1: Introduction

This chapter presents the background for this mater thesis, as well as its objective and structure. This thesis focuses on heat recovery in residential buildings either by passive heat recovery or by active heat recovery.

1.1 Background

Modern buildings in Norway is highly insulated and a ventilation system is required to achieve good indoor air quality. Because of the large amount of air that is regularly exchanged in the building, a lot of energy is needed for heating the supply air. Norwegian standards require a heat recovery system with at least an efficiency of 80%. The most popular method to achieve the requirements is to have mechanical ventilation with heat recovery through a type of heat exchanger with a separate system to warm up hot water and additional space heating.

The heating demand for hot water take up a large part of the energy demand for a house. A system with a heat pump that uses the exhaust ventilation air as a heat source can supply heating for the supply air and domestic hot water. The heat pump can replace the heat exchanger or be installed as an addition.

1.2 Objectives

The main objective of the work in this master thesis have been to compare total energy efficiency of using heat wheel with the use of an exhaust heat pump with accumulation tank. Costs of the different solutions should also be compared. The following tasks are listen in the assignment text:

- Literature review on exhaust heat pumps
- Improve the heat pump model developed in the specialization project work
- Refine the simulation of case building(s) with IDA ICE
- Make LCC comparisons between different solutions

A note has to be made for the second point on the list above. The heat pump model is a matlab model that is based on work done in a master thesis by Atle Solberg. By following some of the points that were made in the suggestions for further work chapter in Atle's thesis, the focused was set on improving the model's gas cooler.

In the end, the work on improving the heat pump model in matlab came to a halt after numerous tries to make a script for the gas cooler that could work with the base of the previous model. Instead of using assumptions of constant water outlet temperature and constant temperature approach value, this report were looking to simulate the gas cooler by solving heat transfer equations by iteration. The main problem was to get the model to converge to a valid state.

After consulting with Kjell Kolsaker, it was concluded that using an iterative method for the gas cooler would not work with the current base model. A control system for the heat pump must be implemented into the model.

A short description of Atle Solberg's model is presented in chapter 4.2.1 and the gas cooler model is further discussed in chapter 4.2.2.

1.3 Structure

- **Chapter 2**: Theoretical background
    - Presents information about passive houses and different heat recovery mechanisms. It also provides a background for how a basic heat pump operates. In addition to some more technical heat pump variations that are interesting for modern houses. There is also some information about calculating costs for comparing different products.
- **Chapter 3:** State of the art
    - Presents information about the exhaust air heat pumps that are analyzed in this paper. The chapter is also presents information from various literature about new research on heat pumps.
- **Chapter 4:** Method
    - Describes the structure of the simulation in IDA ICE. It also goes into detail about the heat pump model in matlab that is compared against the IDA ICE simulations. The final part of the chapter is about the improvement that was worked on for the heat pump model in matlab.
- **Chapter 5:** Results
    - Presents the results from simulations that were done in IDA ICE and the comparison with the heat pump model in matlab.
- **Chapter 6:** Life cycle costing comparison
    - Provides a comparison of costs between three different commercial EAHP units, the system with a passive heat recovery heat exchanger and electric space heating, and a reference system with only electric heating.
- **Chapter 7:** Discussion
    - Discusses the most important aspect with the simulations and the results.
- **Chapter 8:** Conclusion
    - Presents conclusions from the work done
- **Chapter 9:** Suggestion for further work
    - Presents some ideas for further work on the subject

Chapter 2:
Theoretical background

This chapter presents some background information about passive houses, heat recovery mechanisms and heat pumps. The information about heat pumps first goes into some of the more basic aspects before it goes into some more technical variations that are interesting for modern houses. In the end of the chapter is some information about calculating costs for comparing different products.

2.1 Heat loss in houses

The buildings in Norway stands for about 40% of all energy used on Norwegian soil [01], which is why improving how energy is used in buildings can have a large effect of the national total energy usage. Improvements are being made, regarding both new houses and older houses. An investigation made by *Statistics Norway* showed that 36% of household owners responded that measures had been made to reduce energy use. As a result one can see that the energy consumption in households have had a downwards trend since 1990 [02].

For new buildings, new requirements came into effect at the start of this year (2016). Buildings built from the new demands (TEK10) will have better isolation and technical systems that are more effective. It is also stated that new buildings are not allowed to use fossil fuels in their heating installations [03].

As buildings get more energy efficient, they get more airtight in order to have lower heat losses. This means that it becomes harder to meet the demands of a good indoor climate. Ventilation must secure clean fresh air that meet satisfactory demands to prevent health risk or risk of contamination. The occupants and their activities in the building must accounted for. The specific ventilation requirements will be discussed in chapter 4.1.1.

Ventilating the air in a building lead to large heat losses if it is not treated correctly. Recovering the heat from the air going out of the building is the focus of this paper.

2.2 Passive house

One do not have to build a house that meets the passive house requirement today, but it is where the requirements are heading. If we compare a passive house to a house built in 2010, the passive house have about half the energy demand [04]. The energy demand comes down to the building having little heat losses. The components that make up the building envelope have low u-values (heat transfer coefficient), low value for thermal bridges, 80% temperature recovery from ventilation air, and a low leakage number. Table 2.1 sums up the typical values for a passive house.

Table 2.1: Typical values for a passive house building [05]

	Typical values for a passive house
U-value outer wall	0,10 – 0,12 W/(m²*K)
U-value roof	0,08 – 0,09 W/(m²*K)
U-value floor	0,08 W/(m²*K)
U-value window and door	< 0,08 W/(m²*K)
Normalized thermal bridge value	< 0,03 W/(m²*K)
Yearly average temperature recovery	> 80%
Leakage number at 50 Pa, n_{50}	< 0,6 h^{-1}

As I mentioned, there was new demands for buildings introduced this year. However, it is possible that we will see that the bar for new houses will be raised to passive house standard in the next couple of years. In figure 2.1 there is a comparison of energy demands from various building requirements in the recent past, as well as a hope for the future with zero-energy and energy-plus houses. One thing that does not come across in the figure is that the hot water demand steadily becomes a larger part of the total heating demand in the more energy efficient houses.

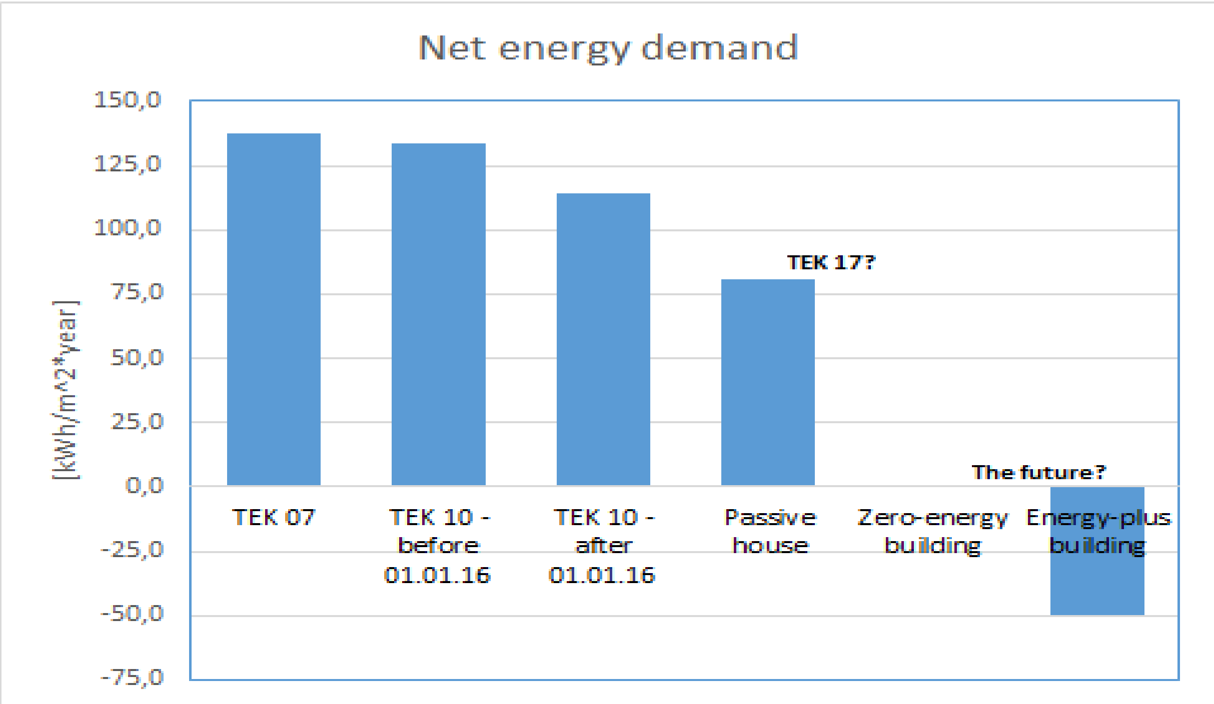

Figure 2.1: Net energy demands according to different Norwegian standards for a house similar to the one in the simulation. Note that value on energy plus houses is just an example [01], [05], [06], [07]

2.3 Heat recovery

The quality of the air inside a building must be satisfying to the occupants. Indoor air quality is controlled with ventilation, which is the process of removing polluted air with outside air. Older buildings use natural ventilation where air change happens because of pressure differences from natural forces. Natural ventilation is without a mechanical system, and do not need electricity to work. A disadvantage to natural ventilation is that there is no way to recover the heat in the air leaving the building.

Newer buildings are built very airtight and natural ventilation will not achieve good indoor air quality. Balanced ventilation with two separate air ducts, one for supply air and one for exhaust air, is the most used ventilation system for modern buildings. Heat can be recovered from the exhaust air very efficiently in a balanced ventilation. In figure 2.2 is a simplified picture of heat recovery. The components used for heat recovery depends on the chosen method. Most commonly used is a heat exchanger or heat wheel too directly transfer heat to the incoming air. A heat pump can also be used, which make for a more complex system, but the heat recovered can be used for other purposes than heating the ventilation air. One can also use a hybrid system that use a heat exchanger and a heat pump.

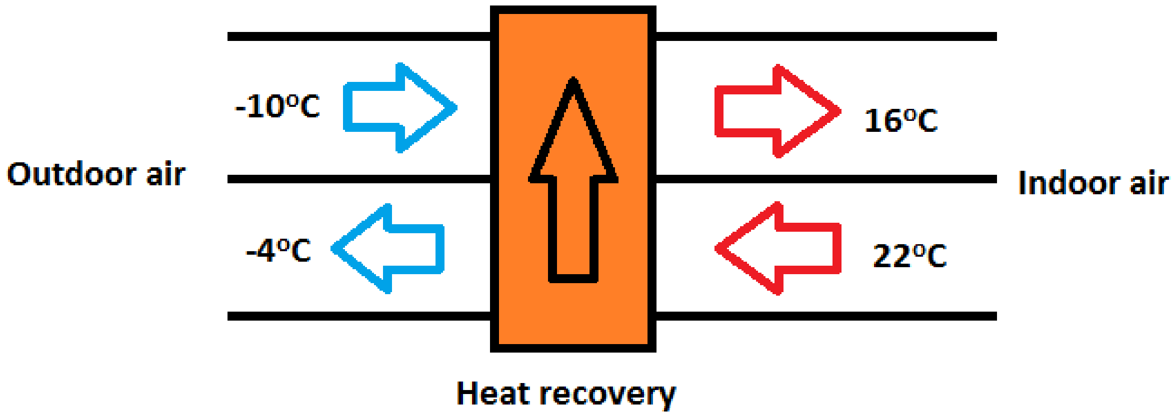

Figure 2.2: Simplified illustration of heat recovery inside a ventilation unit

2.3.1 Heat recovery with heat exchangers

Heat exchangers can transfer heat from the warm air to cold air very effectively with no or only a small amount of energy. The ventilation system must be designed to fit the heat exchanger in most cases. Air must be able to enter and leave the heat exchanger in a specific way for heat to be recovered. It is possible to use an indirect heat recovery system with a fluid to transfer the heat from the exhaust air to the supply air.

Three types of heat exchangers will be presented here; rotary heat exchanger, plate heat exchanger and membrane heat exchanger.

Rotary heat exchanger

A rotary heat exchanger, often called a heat wheel, transfer heat from the exhaust air to the supply air as it rotates. Either it can be a hygroscopic type of metal, or it is non-hygroscopic material. Hygroscopic material can absorb moisture from the exhaust air and transmit both the moisture and heat making it an enthalpy heat exchanger. A wheel made of non-hygroscopic material can only transfer moisture if there is condensation [08].

Rotary heat exchangers will achieve a high efficiency, but will require some energy to rotate. And because it has moving parts, it will require some maintenance. Some of the exhaust air will carry over to the supply air and vice versa. Meaning that some of the polluted air will return to the buildings rooms. The main drawback here is the transmission of odors. On the positive side will the rotary heat exchanger have little problem with frost, especially the enthalpy heat exchanger. Experiments on frost formation in rotary heat exchangers in Norway showed that frost formation is not a frequent problem for a heat wheel [09].

Figure 2.3 shows an example of a rotary heat exchanger.

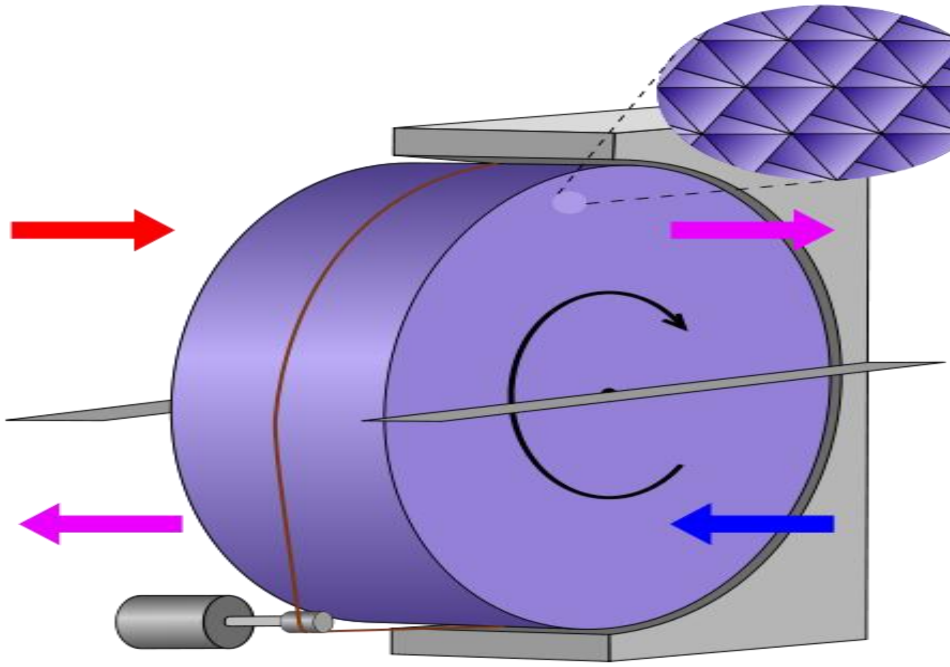

Figure 2.3: Example of rotary heat exchanger [Fig01]

Flat plate heat exchanger

Plate heat exchangers are the most common sort and come in different types. First there are counter-flow or cross flow, which states how the air flows through the heat exchanger. Counter flow heat exchangers will generally be about 10% more effective than cross-flow. The plates can be made out of metal, or they can be made of a semi-permeable membrane. With metal plates, only sensible heat can be removed from the exhaust air. Plate exchangers made out of membrane can efficiently recover sensible and latent heat by moisture transfer. Flat plate heat exchangers will have a larger problem with frosting unless defrosting measures are taken into consideration [09].

Figure 2.4 shows three examples of plate heat exchangers with different profiles.

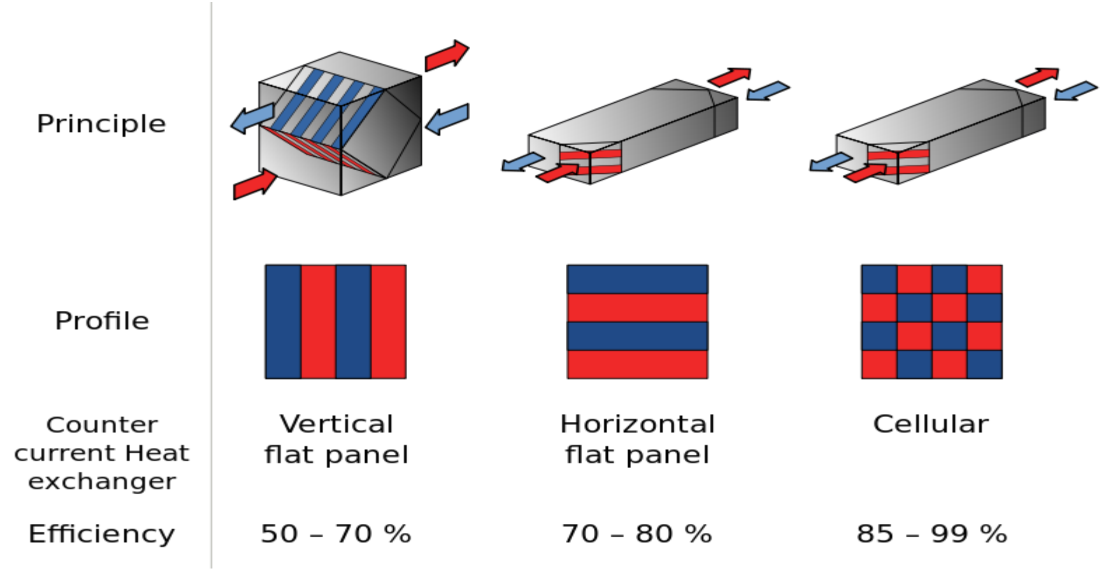

Figure 2.4: Examples of plate heat exchangers [Fig02]

2.3.2 Heat recovery with heat pump

The birth of the exhaust air heat pump (EAHP) happened in Sweden in the late seventies. And on the paper, it came with some major advantages over the heat exchanger. The EAHP can heat hot water in addition to space heating, and it can deliver more energy than the air-to-air heat exchanger [10]. A study based on long term parameters show that is more efficient if it is used for heating domestic hot water (DHW) in addition to space heating. It addresses some factors that are important for the performance of the EAHP, the most important being temperature of the heating system used and the supply temperature of DHW. It can function well in both new and old buildings, but older buildings may have to adjust its heating system to a lower temperature for it to function effectively [11].

The largest disadvantage with EAHP is that it can be more expensive to invest in to than other solutions and it makes for a more complex system overall. If it is economically viable to invest into an EAHP rather than traditional heat-recovery with a heat exchanger will be looked into in chapter 6.

Another advantage with using a heat pump for heat recovery is that it can be used for cooling when the outside temperature is hot. How it is done and how the heat pump actually works will be covered in chapter 2.4.2. Figure 2.5 shows a simple overview of an EAHP used for heating.

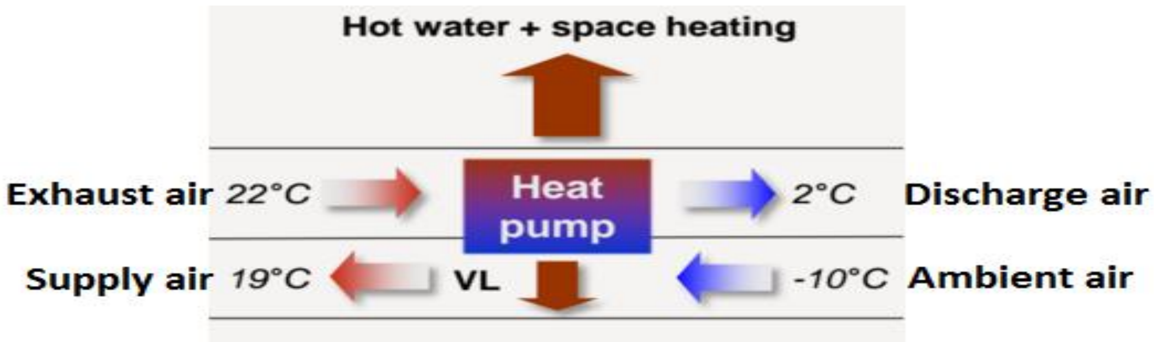

Figure 2.5: A simplified figure of an exhaust air heat pump [Fig03]

2.3.3 Heat recovery with a hybrid system

A hybrid system have both a heat pump and a heat exchanger installed in the ventilation as illustrated in figure 2.6. This system is even more complex and expensive than a normal exhaust heat pump system. The main issue with this system is the low temperature into the heat pump, since the exhaust air already is a limited heat source to begin with. A hybrid system can work well, and there are commercial units that is a hybrid system.

One way to make a hybrid system perform better is to use an additional heat source. The additional heat source can be ambient air (possible preheated through a ground heat exchanger), or an indirect heat source system with a closed loop with an antifreeze fluid absorbing heat from the ground or bedrock. Another option is to use a solar collector as additional heat source, which can work in a northern climate, but is more interesting in areas with more solar potential.

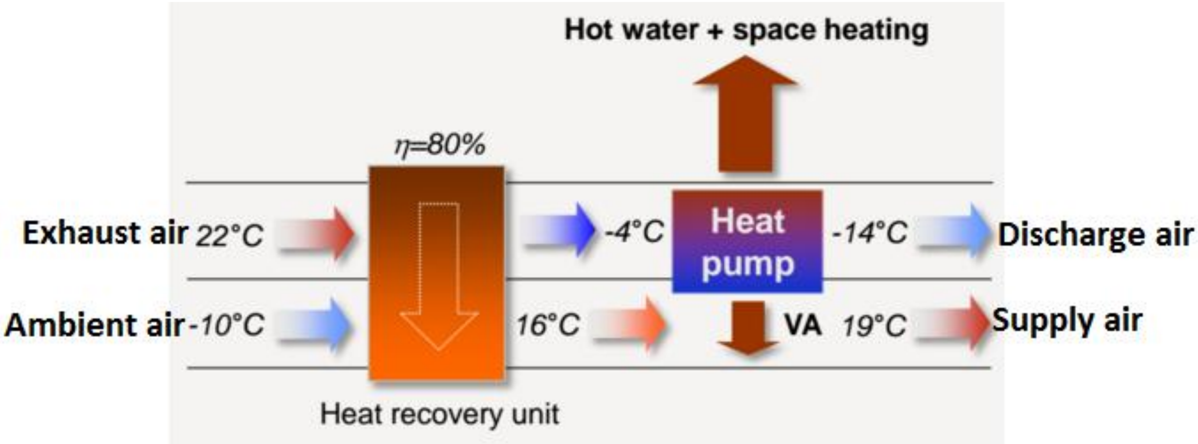

Figure 2.6: A simplified figure of a hybrid heat-recovery system [Fig03]

2.4 Heat pump

This part describes how a basic heat pump works. It also goes over some of the more technical heat pump variations that are interesting for modern houses. Such as; using a heat pump for both heating and cooling, heating hot water with a de-superheater, and the use of CO_2 as a working fluid. In the end is a comparison of different working fluids.

2.4.1 Basic theory for heat pumps

A heat pump wants to take advantage of a heat source with low temperature, and deliver heat at a high temperature using electric energy that is equivalent to only a portion of the delivered heat. The main components of a heat pump are displayed in figure 2.7 are; Evaporator (1), compressor (2), condenser (3) and the expansion valve (4). An electric motor (5) is required to run the compressor. The four main components (1-4) are connected in a closed loop as illustrated in figure 2.7. The last main component is the working fluid (refrigerant) that circulates through the closed loop.

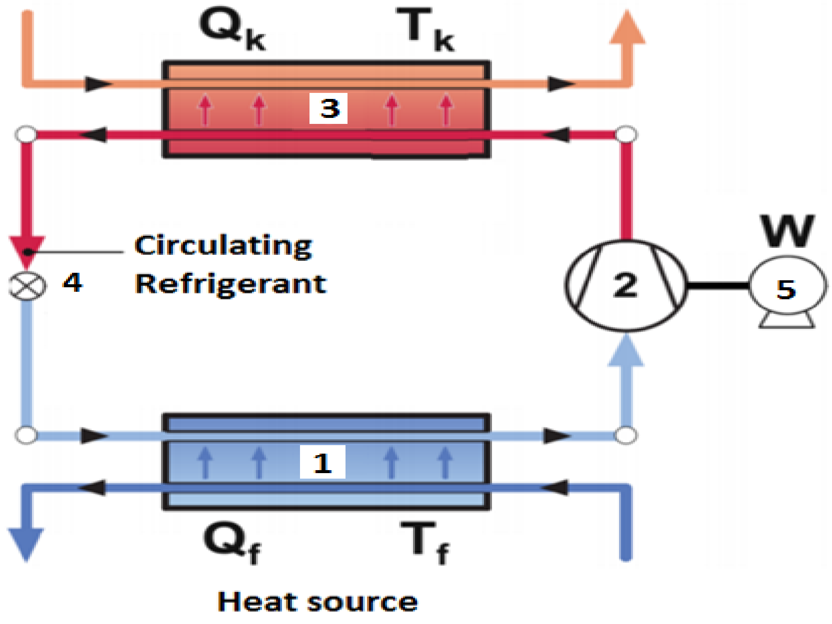

Figure 2.7: Heat pump cycle with the basic components [Fig04]

The thermodynamic state of the refrigerant at a specific point in the cycle is most often found using either pressure-enthalpy (P-h) diagrams or temperature-entropy (T-s) diagrams. An example of a P-h diagram is shown in figure2.8. The black curve is the saturation curve of the specific refrigerant and will be very different depending on what type of refrigerant is chosen. Point 1-4 in this diagram refers points in the working fluid loop at the outlet of the components shown in figure 2.7.

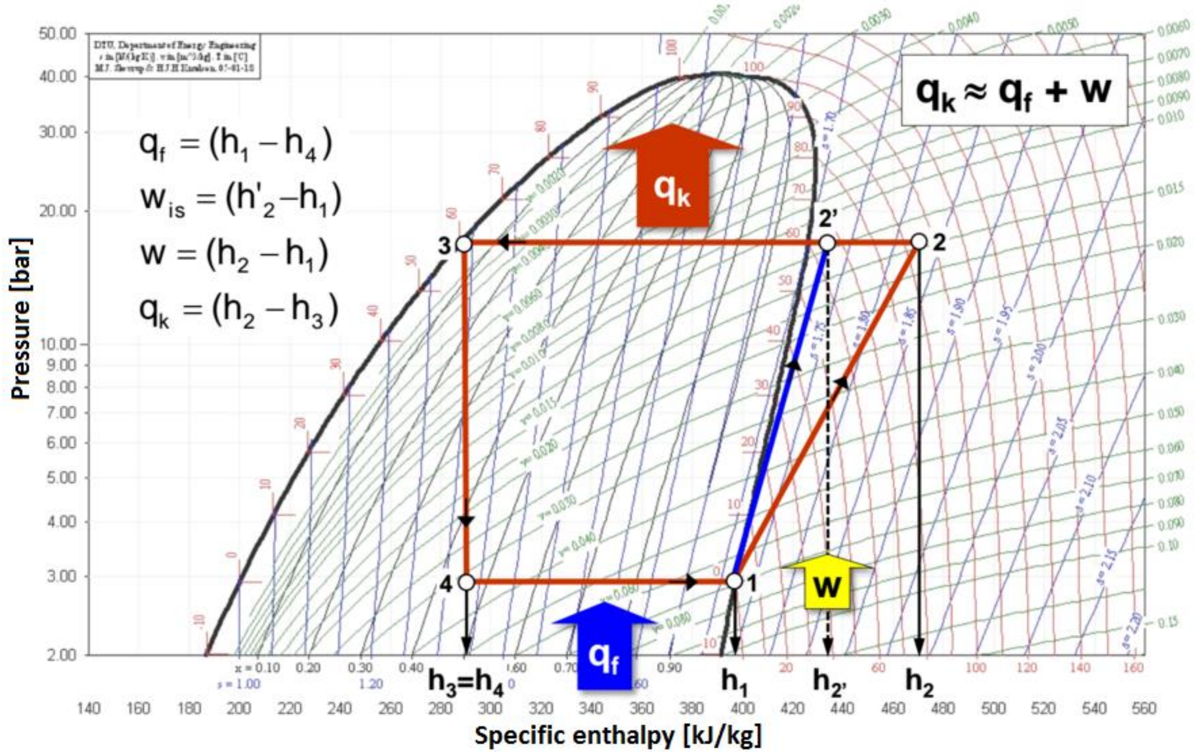

Figure 2.8: A heat pump cycle in pressure-enthalpy diagram [Fig04]

The heat pump cycle that is shows in figure 2.8 is a very optimistic cycle for a heat pump; a real cycle will include some more losses. There will be a pressure loss in all of the components and tubes connecting them. The compressor will have some heat loss during the compression of the fluid, as well as mechanical losses. A bad temperature fit in the evaporator or condenser will lead to losses. In addition, there will be some throttling losses in the expansion valve.

The coefficient of performance (COP), otherwise known as the power factor to a heat pump. The COP is equal to the emitted heating output divided by the input of electric power. Figure 2.9 shows the percentage of electric power that is input for a heat pump with a COP. The portion on the top (red) is electric power, the bottom (green) portion comes from the heat pumps heat source. Which can be outside air, seawater, heat from the ground, exhaust ventilation air, etc.

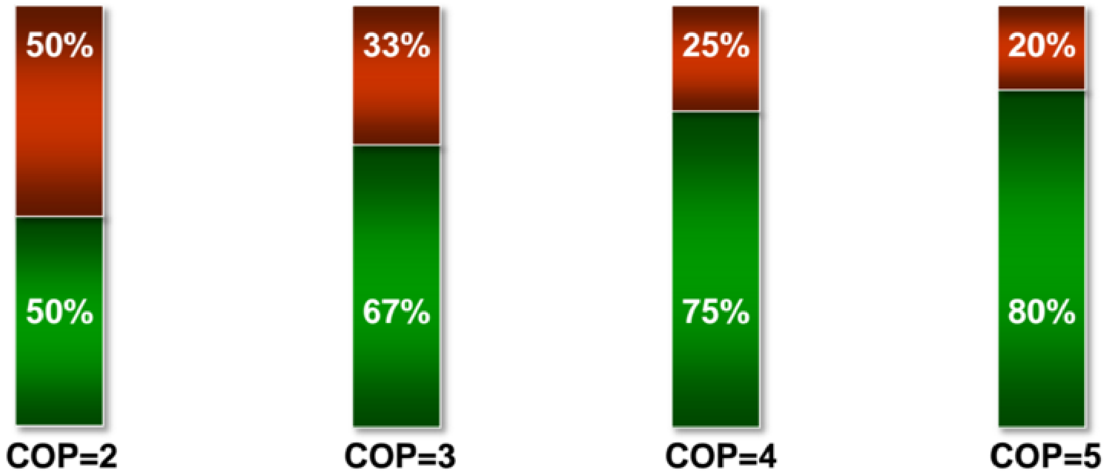

Figure 2.9: The split between energy coming from heat source (bottom/green) and is electric power input (top/red) for different COP values [Fig04]

2.4.2 Heat pump for both heating and cooling

A heat pump can be utilized for both heating and cooling simultaneously. When the refrigerant absorbs heat in the evaporator, instead of absorbing heat from a heat source, the evaporator can deliver cooling. Large office building with computers that need cooling is an example where this application is useful [12]. NTNU have such a system where they use a heat pump too cool supercomputers and server rooms. Such a system has to be design for the cooling demand, which means there has to be a way to reject excess heat if the heat demand is to low, or a peak load system for when the heat demand is too high.

The EAHP can operate in heating mode or cooling mode depending on what the building needs. When in heating mode, outdoor air (T_0) flows through the condenser side of the heat pump and is heated up (T_S). The expelled indoor air (T_I) flows through the evaporator and is used as the heat source, it then leaves the system (T_E). The left side of figure 2.10 shows this operation [13].

When switching to cooling mode, the working fluid will flow in reverse through the heat exchangers. What was previous described as the condenser will now operate as an evaporator and the evaporator as a condenser. The outside air (T_0) will flow through the evaporator and cool down (T_S). The indoor air going out (T_I) will go through the condenser and be a heat sink before it leaves the building (T_E). This is seen to the right in figure 2.10 [13].

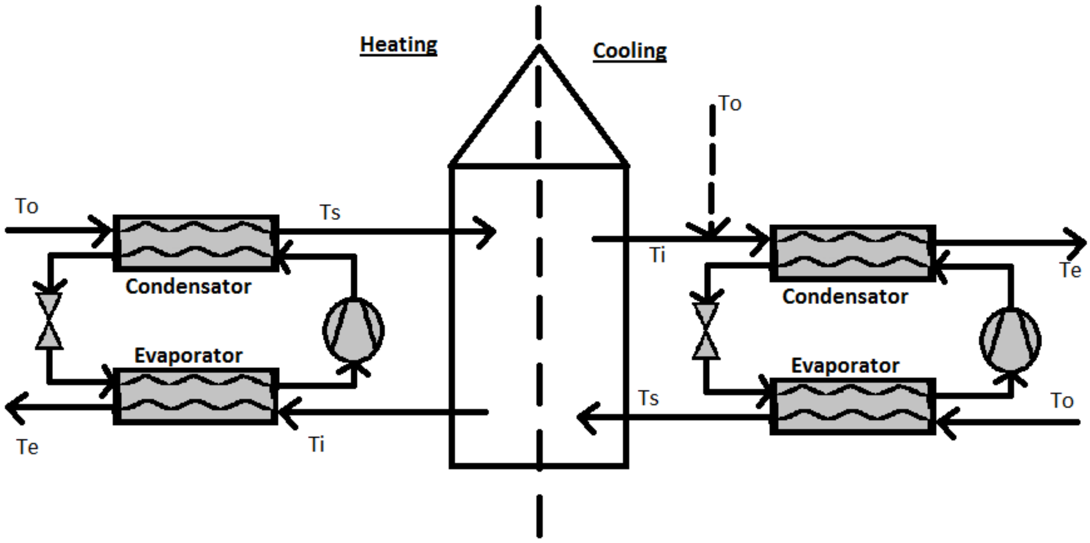

Figure 2.10: Illustrates heating mode and cooling mode for an EAHP [13]

2.4.3 Heating of hot water

The demand for domestic hot water (DHW) becomes a larger part of the total heat demand in new and more energy efficient buildings. Hot water system must have a high temperature because of the legionella bacteria. Legionella grows and can live in water between 25°C and 50°C, in water above 70°C the bacteria dies instantly [14]. Brine-to-water and water-to-water heat pumps can preheat DHW with heat from the condenser and an electric heater can reheat the water to the required level.

One can utilize a de-superheater to achieve the required temperature without additional reheat from another heat source. Note that a de-superheater should be coupled with an internal heat exchanger to reach the high temperature levels out of the compressor that is utilized by the de-superheater. In addition, if the condenser heat is only used for space heating can lead to downtime were the heat pump must be turned off, which limits heating for DHW. Even if it leads to system that is more complex, it will be more energy efficient to use the condenser to preheat DHW in addition to space heating, and use the de-superheater for reheating DHW [15]. The use of a de-superheater cannot be simulated in IDA ICE, but it can fit well into modern buildings with a large DHW demand. A principle sketch of a heat pump system with de-superheater is shown in figure 2.11.

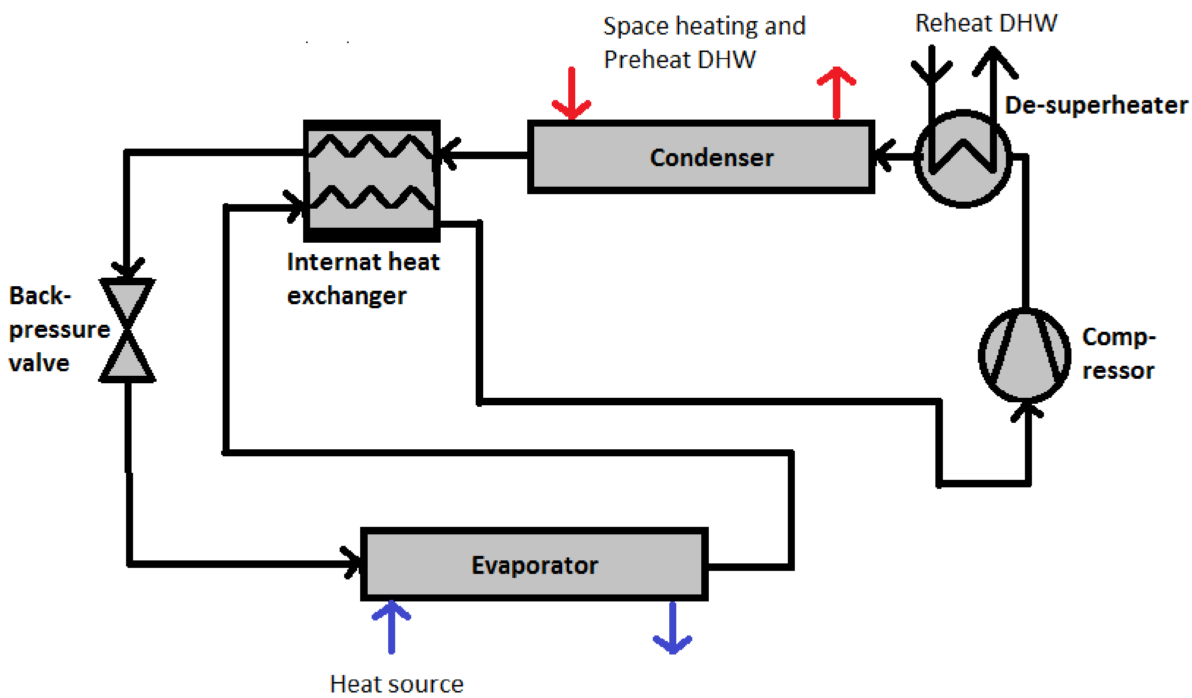

Figure 2.11: Principle sketch of a heat pump system with a de-superheater and internal heat exchanger

2.4.4 CO2 heat pump

Up until now, the component that emits heat from the heat pump has been referred to as the condenser, which comes from that the refrigerant condensate while going through. Because of CO_2's thermodynamic properties, namely low critical temperature, a gas cooler replaces the condenser in CO_2 heat pump systems. CO_2 is at supercritical pressure when it flows through the gas cooler and does not condensate, which means it will have a gliding temperature that can glide from 100ºC to 10ºC [16]. The temperature glide makes it ideal to warm up hot water when the gas cooler arranged as a counter flow heat exchanger. A typical CO_2 heat pump cycle in a temperature-enthalpy diagram is shown in figure 2.12. Point 1-4 refers to the state of the CO_2 at the inlet of the compressor (1), the inlet of the gas cooler (2), the inlet of the expansion valve (3), and the inlet to the evaporator (4). The dotted line that goes from a too b is the temperature of water in the gas cooler from inlet to outlet.

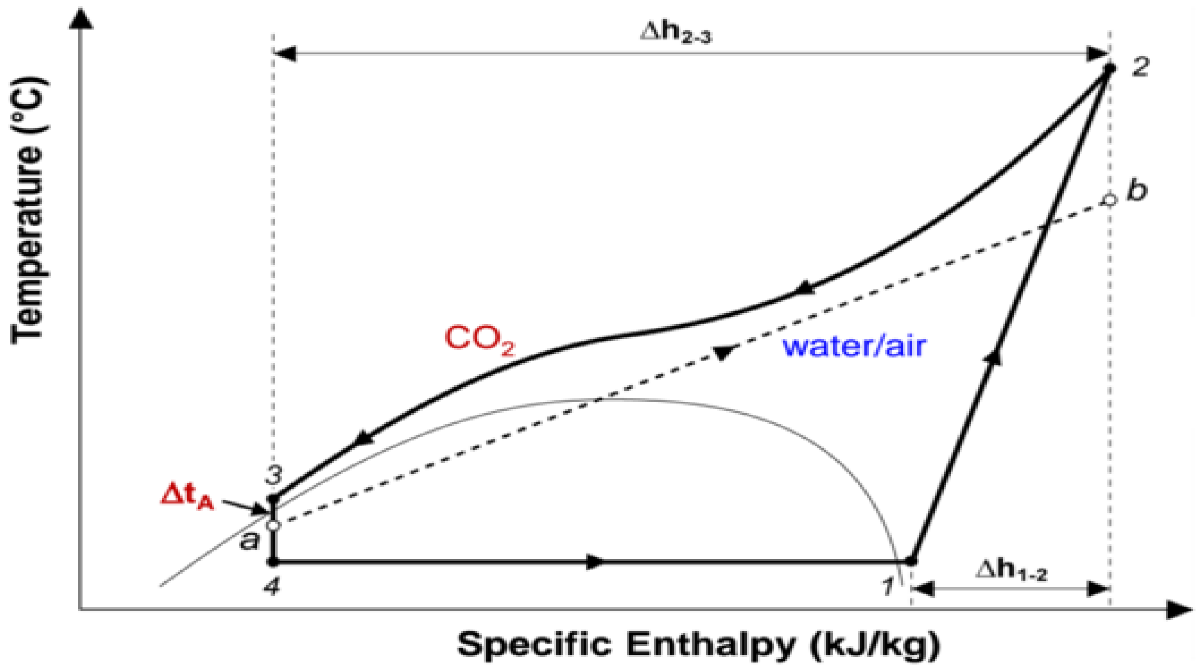

Figure 2.12: CO_2 heat pump cycle in a temperature-enthalpy diagram [Fig05]

Hot water is heated from typically 5°C to 70°C, which is a good fit for a CO_2 heat pump. When a heat pump is only used to deliver heat for space heating, the rise in temperature is lower and heat pump that uses other refrigerants may achieve better performances. Figure 2.13 and 2.14 shows typical temperature graphs for the CO_2 heat pump and the alternative heat pump that uses ammonia (NH_3, R717), R290 or R134a, which are the normal alternatives to a CO_2 heat pump. Figure 2.13 shows the temperature graphs when the temperature rise on the water is low, which results in a much higher average temperature (t_m) during heat rejection for the CO_2 heat pump indicating a low COP. The result is the other way around in figure 2.14 where the temperature rise on the waterside is larger.

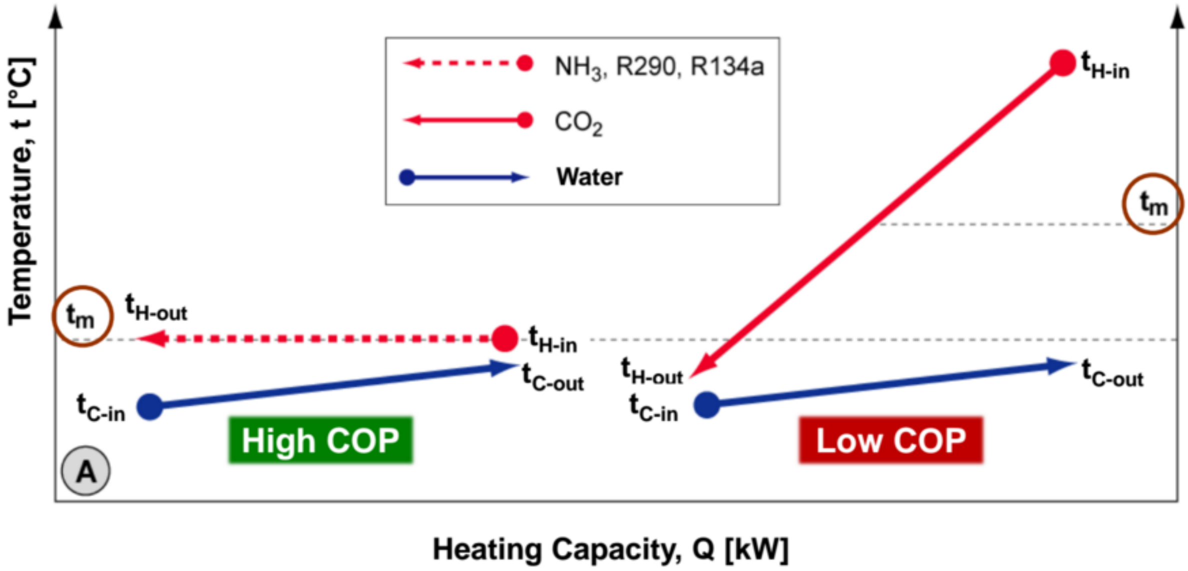

Figure 2.13: Typical temperature graphs in condenser/gas-cooler when temperature rise of the water is low, CO_2 of the right and NH_3, R290 or R134a on the left [Fig05]

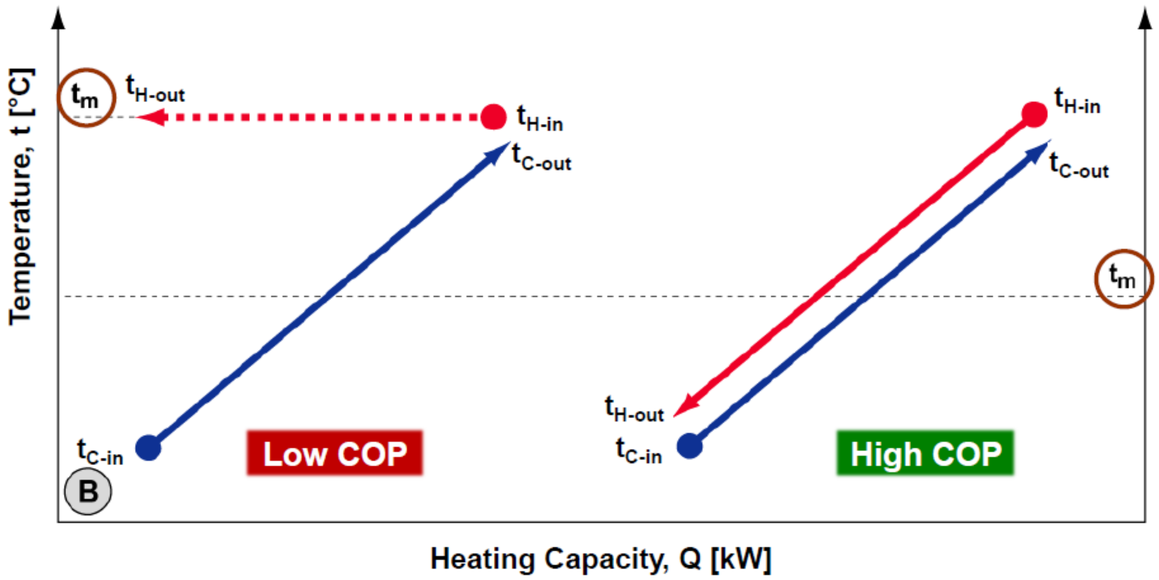

Figure 2.14: Typical temperature graphs in condenser/gas-cooler when temperature rise of the water is high, CO_2 of the right and NH_3, R290 or R134a on the left [Fig05]

The goal for a CO_2 heat pump will often be to have a system that achieves a low CO_2 temperature at the outlet of the gas cooler. That will lead to a high specific enthalpy of evaporation, which again lead to a lower required mass flow rate of CO_2. Combined with a steep saturation pressure curve gives the system high optimum velocities and smaller dimensions for equipment [15].

The high-pressure affect both the heat capacity and the coefficient of performance of the CO_2 heat pump, and for a given situation, there will be an optimum pressure level. This comes from the nature isobars (constant pressure lines) for supercritical CO_2. Some isobars is displayed in figure 2.15, and as you can see, the isobars flattens out close to the critical point. This results in that change in specific enthalpy difference in gas cooler is not proportional to change in the specific compressor work. In short, an outlet temperature from a gas cooler will have an optimum high-side pressure level [15].

Figure 2.16 shows a calculation example by Stene (2004) of the COP as a function CO_2 outlet temperature with different high-side pressure levels. The calculations is done on a single stage CO_2 heat pump where the evaporation temperature is kept at -5°C, 5K suction gas superheat, 60% isentropic compressor efficiency and 10% heat loss from the compressor [15].

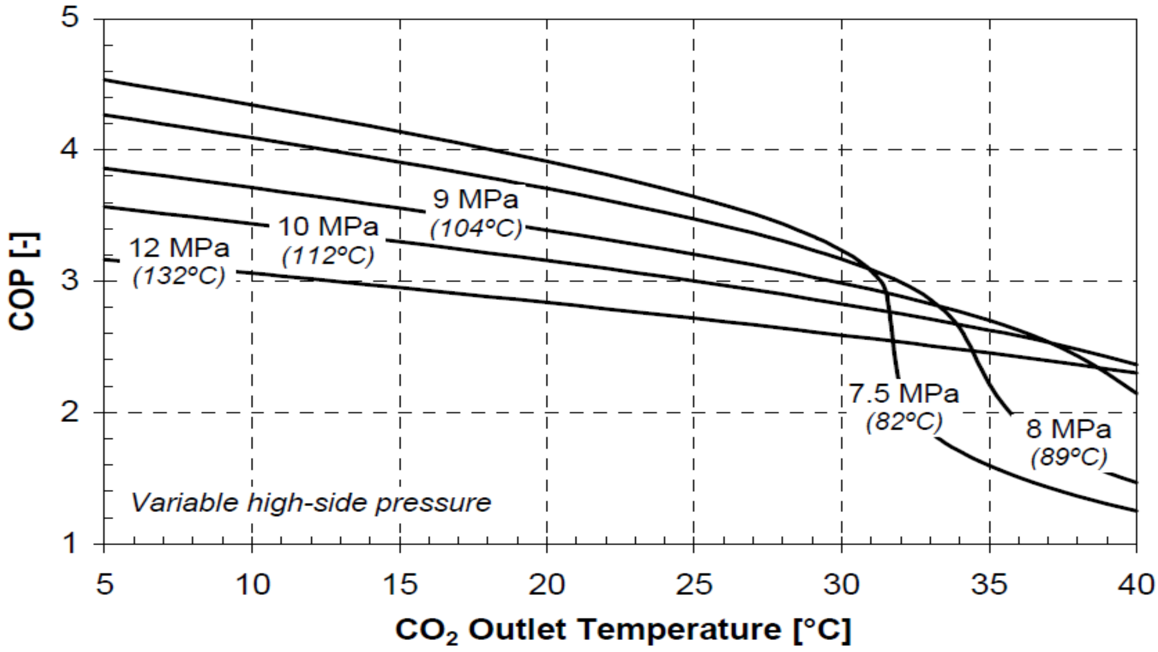

Figure 2.15: COP as a function of CO_2 outlet temperature at constant pressure levels [Fig06]

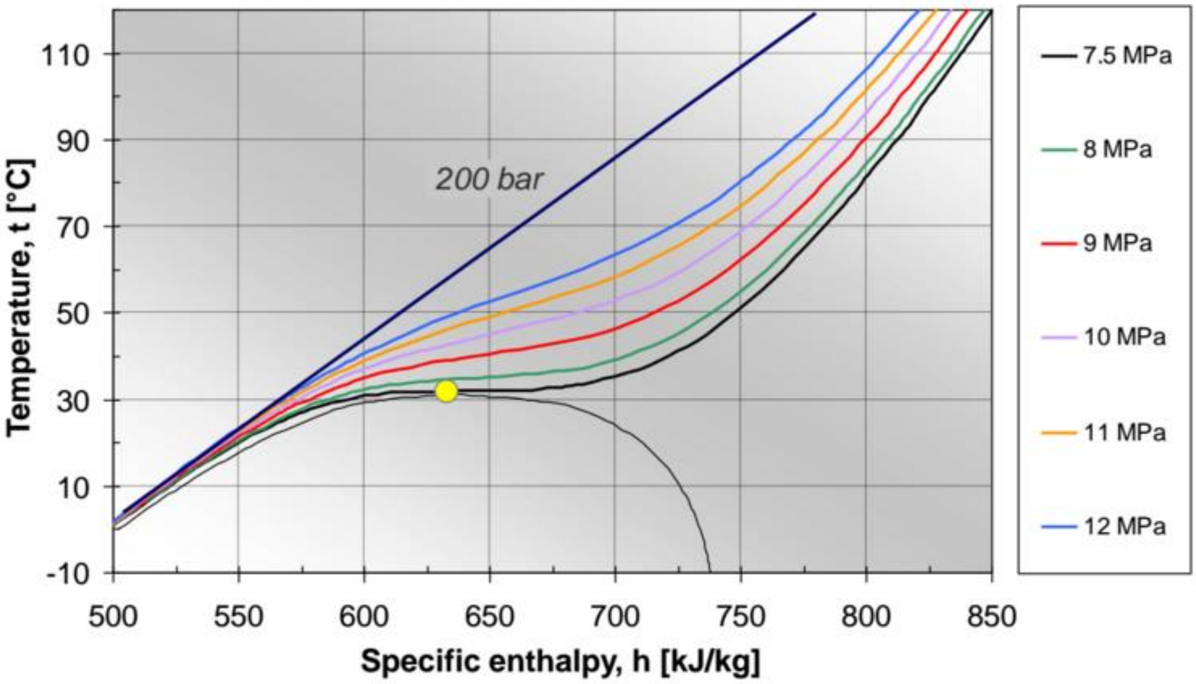

Figure 2.16: Isobars (pressure lines) for supercritical CO_2 [Fig06]

2.4.5 Heat pump working fluids

In January 2015, the F-gas directive came into force, meaning more restrictions on the use of refrigerants with high GWP values (Global Warming Potential). Refrigerants with GWP values over 2500 will be ban from the year 2020 [18]. This will result in more use of natural and low GWP refrigerants. However, even if some HFC's still will be used, there will be implemented other measures and actions to the phase down of HFC's. Since the Paris Agreement now is signed (22 April

2016) by 175 countries, the pressure on reducing greenhouse gasses emission rises [19]. The Paris Agreement is an agreement about dealing with greenhouse gases emissions and is within the framework of United Nations Framework Convention on Climate Change (UNFCCC) [20].

Table 2.2 displays a comparison of some of the characteristics to some of the refrigerants that will be used after 2020.

Table 2.2: Comparison of three HFC refrigerants (R407C, R410A and R134A) and three natural refrigerants (R717, R290, R744) [21]

	R407C	R410A	R134A	R717 (NH_3)	R290 (C_3H_8)	R744 (CO_2)
Pressure level at condensation temperature 50 °C	20 bar	31 bar	13 bar	20 bar	17 bar	80-120 bar[1]
Pressure ratio	High	Moderate	High	Very high[2]	Moderate	Low
Maximum temperature of heated water	65 °C	65 °C	60 °C (90 °C)[3]	50 °C (90 °C)[3]	50 °C	60-90 °C
Mass flow (kg/s)	High	High	High	Very low	Low	Moderate
Compressor volume (m^3/h)	Moderate	Low	High	Low	Moderate	Very low
GWP	1700	2000	1300	0	3	0
Toxic/Flammable	No	No	No	Yes/No	No/Yes	No

[1]: 50 °C is above the critical temperature for CO_2, the pressure levels are what are normally used for CO_2 heat pumps
[2]: R717 compressors can still achieve high energy efficiencies because of low gas density
[3]: 90 °C is achieved by using a 2-stage system in the case of R134A and R717

2.5 Life cycle costing (LCC)

Life cycle costing (LCC) is a method of comparing the economically viability of product by looking at all costs that are connected to said product over a period. The period is often the same as the products lifespan. In this paper, LCC will be used to compare different heat recovery solutions and see of some conclusion can be made.

LCC were applied in the early 20th century in the US for purchasing decisions. It is mainly used to make decisions for large investment in product with a long life span. In the recent years, LCC has often been paired with another type of analysis called life cycle assessment (LCA) which look at a product environmental impact. The common trend for product that are better environmentally is that they have high investment cost but are cheaper to operate.

In many cases where LCC is used there will be solutions that have a high initial cost but will have lower operational cost during its lifetime and another solution that have the level of cost the other way around. Money in the present and the future have different value. In LCC, one can present all cost in present value, which means that future value must be discounted to the present. Another method is to annualize all the costs and compare the total annual cost. The following formula is used to discount a future value to present value:

$$PV = \frac{C_i}{(1+r)^i} \tag{2.1}$$

Where:

C_i = the value in year *i*
r = discount rate (the present interest rate)
i = number of years in the future from the point of interest

Annual costs often occur in an LCC. The energy and maintenance costs for the different solution is simplified to annual costs that will remain constant during the products life cycle. Present value of constant annual costs is simply calculated using an annuity factor:

$$a = \frac{r}{1-(1+r)^{-n}} \tag{2.2}$$

Where:

r = discount rate
n = lifetime of equipment, or number of years for the annual payment

Equation 2.3 calculates total cost, where the energy demand, energy price and maintenance cost is assumed constant annual value:

$$C_{tot} = I_0 + \frac{W_e * e}{a} + \frac{M}{a} \tag{2.3}$$

Where:

I_0 = investment cost
W_e = annual energy demand
e = energy price
M = annual maintenance cost
a = annuity factor

One can also calculate the total annual cost, where the investment cost is annualized. The formula for the total annual cost is:

$$A = I_0 * a + W_e * e + M \qquad (2.3)$$

Chapter 3:
State of the art

This chapter is a kind of literature review that focuses on some of the exhaust heat pump products that is for sale for the northern climate. It also focuses on research papers from the last couple of years that relate to new heat pump technology. First comes a short summary of the thesis that this one extends on.

3.1 Summary of previous thesis

This thesis extends the work done in a previous thesis by Atle Solberg. In his paper, simulations that combined IDA ICE and Matlab were carried out to on different heat-recovery solution solutions with a CO_2 heat pump. Heat demand, temperatures and flows of water for tap water and space heating, and ventilation air flow and temperatures was taken exported from IDA ICE results to a excel file. The excel file was used to simulate six options in Matlab:

- Heat pump using exhaust air and/or outside air as heat source (3 options)
- Combination of heat recovery with heat wheel and a heat pump using exhaust air and/or outside air as heat source (3 options)

The most energy efficient solution were the combination of a heat wheel and a heat pump that uses both exhaust ventilation air and outside air as heat source. However, the extra efficiency from utilizing outside air in comparison to exhaust air only is very limited for the Norwegian climate. The economical aspect was not the focus of the thesis, but it concludes with that right solution can be situational. If the DHW demand is very high, it is most likely not economically profitable to use the CO_2 heat pump for space heating and ventilation heating. It also concludes that a heat wheel increases the performance of the system with a large margin, and is recommended to be utilized [22].

3.2 Exhaust heat pump products

3.2.1 From NIBE – two solutions

NIBE, who is among the leading producers of heat pumps [52], have several exhaust air heat pumps on the market and many other products for heating. One of the solutions they can deliver is an EAHP (F470) that is made to heat space in the house, hot tap water and preheat for the incoming ventilation air. Another EAHP (F110) can deliver heating to hot tap water only, but it can be coupled with a heat exchanger.

F470

F470 is an “all in one” type of product for balanced ventilation. It delivers heat to the building through a water-based heating system, either radiators or floor heating, which must be connected to the F470. It comes with the hot water tank already installed and an electrical coil for added effect when it is needed. This system cannot however deliver cooling to the ventilation air during the summer. A ventilation system with the F470 does not use a heat exchanger for passive heat recovery [23].

A very positive point for the F470 is that it uses propane (R290) as working fluid [23]. R290 is a natural working fluid that typically achieve better performances than systems with HFC's. The major drawback to R290 as a working fluid is that it is very flammable [16].

Surveillance and control of the system is very flexible as it is possible to control it by using SMS (mobile) or via the internet by using NIBE Uplink that alert the owner by sending an email when there is a possible malfunction [24]. This can help decrease the downtime during malefaction, which is important when this is the sole heating system for a building. Optionally electrical radiator or a fireplace can supplement the demand.

An illustration of the F470 is shown in figure 3.1.

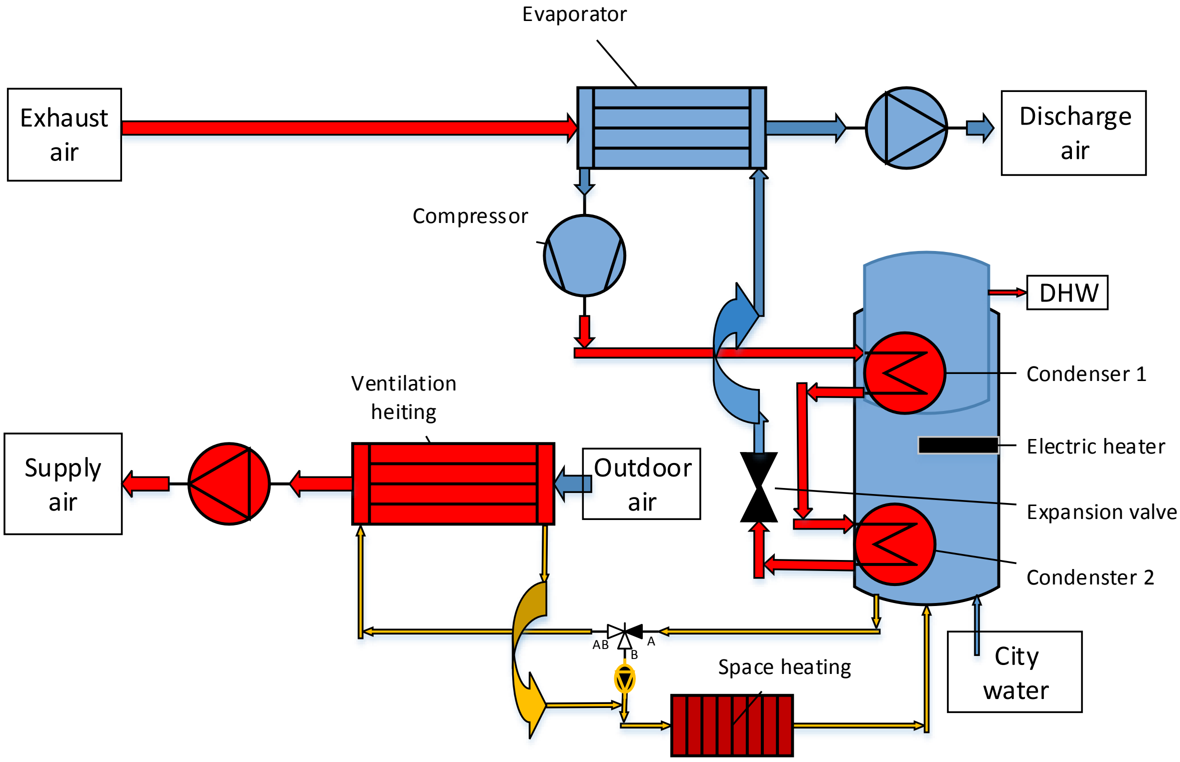

Figure 3.1: Illustration of NIBE F470 [25]

F110

Modell F110 from NIBE is an exhaust air heat pump that it used only to heat domestic hot water. As the F470 model, this also comes with a hot water tank and an electrical coil for added effect installed in the unit [26]. This is can be a good option for new residents when DHW is a large part of the total heating demand, and it fits into older houses looking to replace their hot water tank. It can be installed in several different ways [27]:

- It can use the exhaust air after it has gone through separate heat recovery unit in a balanced ventilation system, making it a hybrid system.
- It can use the exhaust air coming directly from the rooms in the building. The ventilation system is the not require to be balanced.
- It can use air from the outside down to -10°C.

In new buildings with low space heating demand, this will be a cheaper system to invest in to then the F470 since the unit is cheaper and it does not require a hydronic heating system. The F110 uses refrigerant R134A as working fluid [27], which is less environmental friendly than the natural working fluid.

Figure 3.2 shows the F110 connected to a balanced ventilation with passive heat recovery.

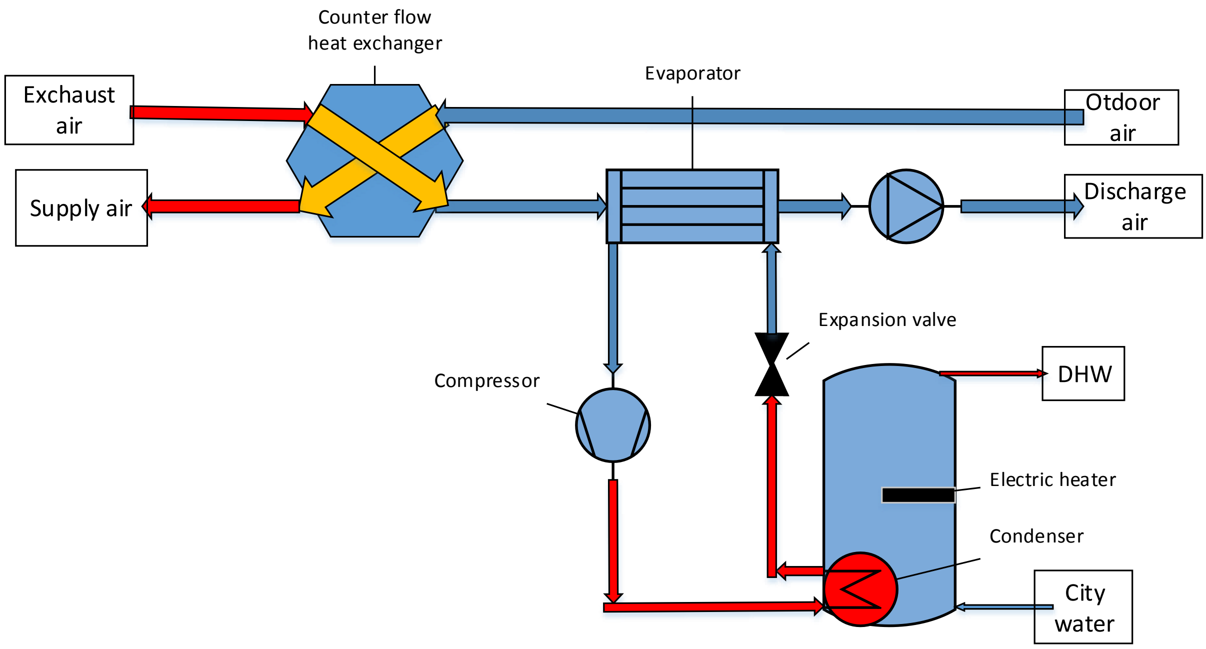

Figure 3.2: Illustration of NIBE F110 connected to ventilation with passive heat recovery [27]

3.2.2 From Nilan – Compact P Nordic

Nilan is another European company that develops and manufactures ventilation and heat pump solutions. One of their product, named Compact P Nordic, is a compact hybrid system with a counter-flow heat exchanger using exhaust air to heat incoming ventilation air, and a heat pump recovering additional heat to a hot water tank. The water tank has an electrical heating element that operates automatically when the heat pump is not sufficient. This unit can deliver cooling to the incoming ventilation air and heating of DHW at the same time during the summer [28]. The heat pump uses the HFC refrigerant R134a [29].

The basic model of the Compact P Nordic does not deliver additional space heating outside heating of the ventilation air. The unit can be modified into a complete solution, but this comes as an additional cost. Modified solutions uses an additional heat source; heat from the ground from a loop of buried tubes, or outside air. The additional space heating can also be covered by electricity, which is cheaper than the two modifications. Note that the modifications using additional heat sources delivers space heating through radiators or underfloor heating [28].

An illustration of the Compact P Nordic is shown in figure 3.3.

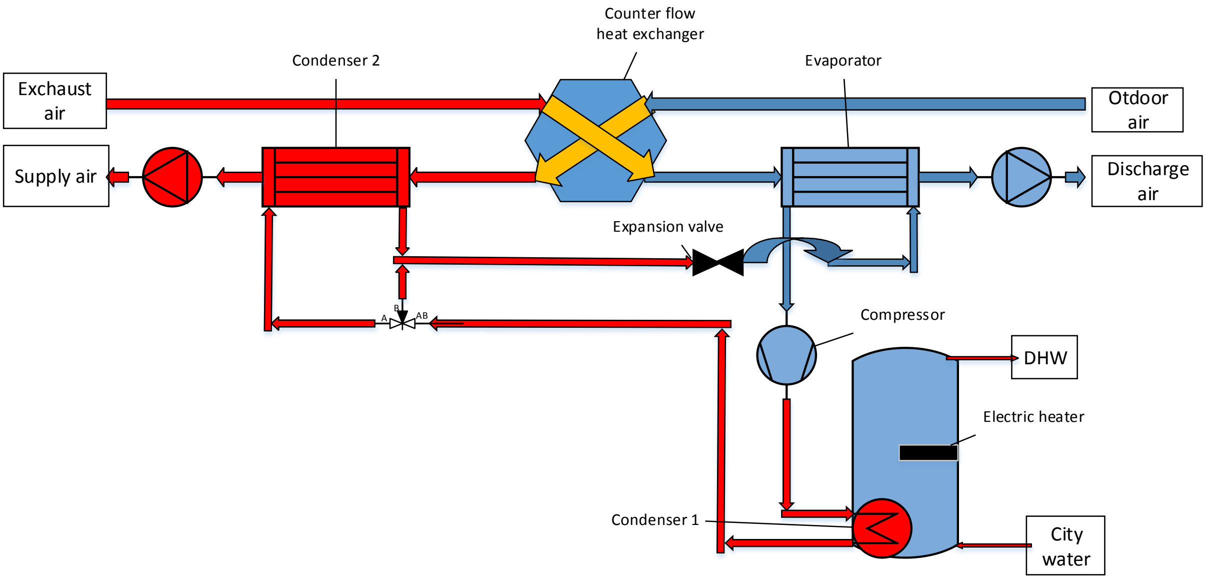

Figure 3.3: Illustration of Nilan Compact P Nordic [29]

3.2.3 Comparison of the three products

Table 3.1 shows a short comparison of the disadvantages and advantages of the three products. A more detailed compassion can be found in the appendix A.1.

Table 3.1: Comparison of the disadvantages and advantages of the three products

	Advantage	**Disadvantage**
NIBE, F470	Natural refrigerant	Must have hydronic heating system installed in the building
	A complete solution that comes in one compact unit	No passive heat recovery
		Not possible to cool incoming ventilation air
NIBE, F110	Can work without balanced ventilation and hydronic heating system	Uses HFC refrigerant (R134a)
	Can have passive heat recovery	Can only deliver heating for DHW
	Cheaper installation	Not possible to cool incoming ventilation air
Nilan, Compact P Nordic	Have passive heat recover	Uses HFC refrigerant (R134a)
	Can cool supply air and heat DHW simultaneously	Only work with balanced ventilation
		Can only deliver heating for ventilation and DHW

3.3 Hydronic heating vs. electrical heating

For a complete solution with EAHP with the solutions mentioned, NIBE F470 or modified Compact P Nordic from Nilan, a hydronic heating system must be installed. A waterborne heating system is great in that it can utilize energy of lower quality than electricity for heating. The largest disadvantage is the installation cost, which is much larger than for a heating system based on electricity.

The key to have a good waterborne heating system that is economically viable lies in design phase. Choosing layout and dimensions correctly can greatly reduce the installation costs of the heating system [30]. Low-temperature waterborne heating systems in combination with heat pump have been seen to be a good combination [31]. Lower temperature will lead to a larger flow and bigger tubes, resulting in higher investment costs. However, it can give better performance results from the heat pump paying off for the extra investments.

There is a positive trend for waterborne heating in Norwegian households. According to Statistics Norway, there is more and more that moves away from combustion heating to either heat pumps or waterborne heating [32].

3.4 Resent research

Development to reduce energy consumption is very prominent, and research is done by intuitions all over the world. Much of the relevant literature reviewed in this chapter comes from the following databases:

- Science Direct
- IEEE Xplore Digital Library
- DiVA portal

The literature was found using the search engine Google Scholar. Other literature is older master thesis from NTNU's institutional archive NTNU Open and papers from the database Fridoc. Fridoc is a database of scientific and technical documents that can be accessed at a cost, a member of the International Institute of Refrigeration (IIR) can download a quota free of charge [33]. Students can get a free 18 months membership through a professor who is a full member [34].

Much research is done here in Norway on the subject of energy efficiency. The incentive to do research however may be much larger in other parts of the world. Many countries have based their electricity production around fossil fuels and do now see that this must change because of shortage of resources or environmental reasons. Several countries have had an enormous growth the past few decades and have now run into a problem where they are not able to supply electricity to everyone. I experienced this first hand when I studied abroad in South Africa, there they had load shedding and we had to live without electricity a couple of hours per week.

China is a country that have both based a large part of their electricity production on fossil fuels and had recently large economic growth. In a review of heat pump systems in China, it is stated that the development of heat pump system is very rapid. There are many upsides to this development, but according to the review, there are some issues regarding use geothermal energy [35].

3.4.1 Integrating solar heat as additional heat source

Solar energy is one of the most promising renewable energy sources. Solar water heating is most commonly used to heat water. In addition, just by looking at the amount of articles published with this theme is proof that this subject is being explored heavily. EAHP in combination with solar heating can be a good option in many cases. Solar heating have not been the focus in the simulations, but it is something that could be included for further work on the subject.

An assessment of a system with active solar heating and an air-source heat pump (ASHP) was done in northern China. The system analyzed uses a set of solar water heaters on the roof coupled with an air-source heat pump giving off heat through waterborne floor heating system. Passive solar heating was also available for the test building, which is more situational since it requires a large widow façade that can receive solar heating. The study does conclude that it achieves comfortable indoor thermal environment in Chinese rural houses and the electricity consumption by the ASHP account for 1/3 of the total heating supplied in the coldest periods [36]. This system shows promise, but if it does not deliver heating for DHW and it is not certain that it will work in Norway. In the cold period studied, the average temperature was -4°C (range: -10,2 to 4,9°C). The average indoor temperature achieved during this period was about 16-17°C [36], which is below the standard values given by NS3031 [37].

Another way to have a heat pump use both air- and solar heat as a heat source is presented in a comparison analysis of different refrigerants. The system presented have a secondary loop with either water or brine that goes through a collector and to the evaporator. The design of such a collector is special since it must be able to be good at absorbing heat from both solar radiation and the air. The results show that the natural refrigerant R744 (CO_2) can be a good substitute for R22, which exist in many of such systems today. Ambient temperature was between 5 and 35°C for the tests.

3.4.2 Ground source heat pumps

Worldwide installed capacity of ground source heat pumps (GSHP) is steadily growing, as is the number of countries with GSHP installations [38].Temperature levels in the ground stay relative stable over the year, making a very good heat source for a heat pump. However, a heat pump cannot only absorb heat from the ground without delivering heat back, the imbalanced degree of earth's energy is a term used. It was mentioned in a review about development of heat pump systems in China, there was some problematic results concerning ground source heat pumps. There it was said that some researchers think of shallow geothermal energy as a kind of resource to be used [35]. If heat is only removed from the ground for a long period, the temperature of the ground will decrease making the heat pump worse. There can also be other unpredictable effects as a result.

The most common way to decrease the imbalanced degree of earth's energy is to use a hybrid system. An option studied in a paper is a R744 heat pump with ambient air-cooled and water-cooled gas coolers. Where the earth's imbalanced degree can be decreased to zero by adjusting the air-cooling load portion. The system is firstly design for cooling dominated climates. In the study different climates where both cooling and heating is required was studied, all warmer than in Norway [38]. GSHP installations is very expensive, but is also a system that could be investigated in further work on the subject.

3.4.3 CO_2 heat pump systems

Since Lorentzen reintroduced the CO_2 heat pump in 1994, much research has been done to make it a good option for heating and/or cooling. The first commercial CO_2 heat pumps appeared 2001 [15], and there is still a considerable market for heat pump water heaters that uses CO_2 there today [39]. In Europe, there is a big push for replacing old heat pump technology. Old heat pumps typically use refrigerants with high global warming potential (GWP). Over a year ago, new regulations came into force [40].

CO_2 heat pumps can be complex and will not perform well in all situations. A paper that tries to optimize a CO_2 water heater illustrated some of this complexity when looking for the most economical solution [41]. Air conditioning units will very rarely consider CO_2 as a suitable working fluid. When a rooftop CO_2 air-to-air heat pump was analyzed, it was deemed ineffective compared to similar units using HFC's [42].

A review that was done on the residential use of CO_2 heat pump water heater in Japan came to some interesting conclusions. One of the conclusion was that the two main thing to look at for improvement was to use a two-stage compressor system, or try to improve heat transfer between CO_2 and water on the high-pressure side [39]. Two-stage CO_2 heat pump can have better performances than the single-stage type [43][44], but the question of economic viability will often rise.

Many studies are now run where CO_2 and other natural refrigerants are compared to HFC's with high GWP values. One such study directed at very cold climates is a master thesis (Nils Eivind Eriksen, 2014). He used simulations to compare four refrigerants, the HFC R410a and the natural working fluids R290, R717 and R744. The simulation used climate data from Karasjok, a town in the inland of northern Norway. The thesis come the conclusion that R744 and R290 have potential to operate in very cold climates and replace the HFC's. However, one should keep in mind that this is only based on simulations and products that use R744 or R290 is not that common as commercial product yet [43].

Considering warmer climates where buildings have a large cooling demand part of the year, on can use a reversible heat pump. A comparison study of CO_2 and R410a simulated a year in northern Italy were the heat pump delivered heating for DHW, space heating and cooling. Overall, the R410a performed best [45], but the test only used a two-part gas cooler, a tripartite gas cooler could turn up with different results. A second solution using CO_2 was also analyzed in the last mentioned study, where the expansion valve in normal circuit is replace with an ejector. The CO_2 heat pump with ejector ended up with similar efficiencies as R410a [45]. An ejector is especially attractive for high performance CO_2 heat pump system as it recover throttling losses [46]. Based on headlines from search results in Fridoc, one can see many new papers posted recently on this subject.

Chapter 4: Method

This chapter will describe the structure of the simulation. Starting with the building model, including internal loads and the air conditioning, which is chosen so that the model satisfies the Norwegian passive house standard. The chapter also goes into some of the details in the IDA ICE simulation. The last part is a summary of how the heat pump model in Matlab works.

4.1 Simulation in IDA Indoor Climate and Energy

IDA ICE is a good simulation tool for simulating building performance. It can handle very advanced designs with reliable results. The software started out as a prototype made by Magnus Lindgren, Lars Erikson, Axel Bring and Per Sahlin in 1989 [47].

One can create a building in IDA ICE either by using IDA ICE's drawing tools or by importing a drawing made in another program. Then IDA ICE have many built in components that can be used to customize the buildings ventilation unit and heating plant.

4.1.1 The building

The building used for the simulation is one of Mesterhus's catalog named Siv. Specifications are chosen to satisfy the Norwegian passive house standard (NS3700). Siv is a single-unit dwelling with a heated area of 115 m^2. Locations of windows and doors are kept to the specifications from Mesterhus, but factors such as wall thickness, window U-value and other thermal properties is decided by NS 3700. Table 4.1 summarizes the thermal properties. An illustration of the building is shown in figure 4.1 and figure 4.2; illustrations are taken from the simulation in IDA ICE.

Table 4.1: Thermal properties and energy efficiencies of the simulated building [03]

	House	NS 3700
U-value, external walls	0,11 W/(m^2*K)	0,1 – 0,12 W/(m^2*K)
U-value, window glazing	0,6 W/(m^2*K)	0,8 W/(m^2*K) **
U-value, window frames	0,9 W/(m^2*K)	0,8 W/(m^2*K) **
U-value, roof	0,81 W/(m^2*K)	0,8 – 0,9 W/(m^2*K)
U-Value, ground floor	0,78 W/(m^2*K)	0,8 W/(m^2*K)
Thermal bridges, normalized	0,03 W/(m^2*K)	0,03 W/(m^2*K)
Solar heat gain coefficient	0,55	0,55
Air leakage number	0,6 h^{-1}	0,6 h^{-1}
Specific fan power	1,5 kW/m^3/s	1,5 kW/m^3/s

** 0,8 W/(m^2*K) is average u-value for entire window

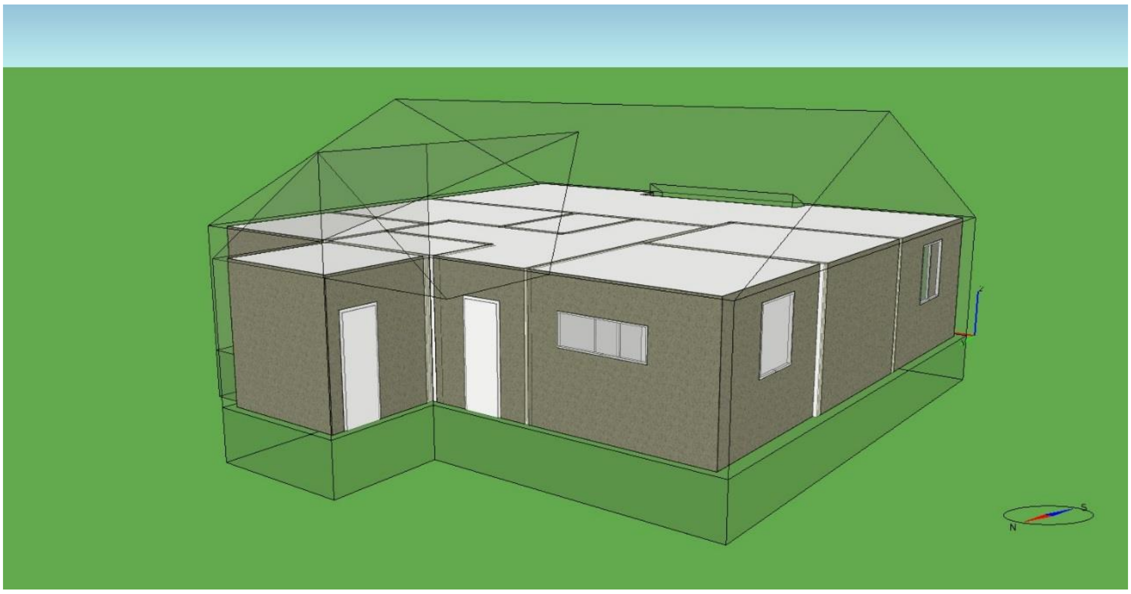

Figure 4.1: Illustration of simulated building, 3D view

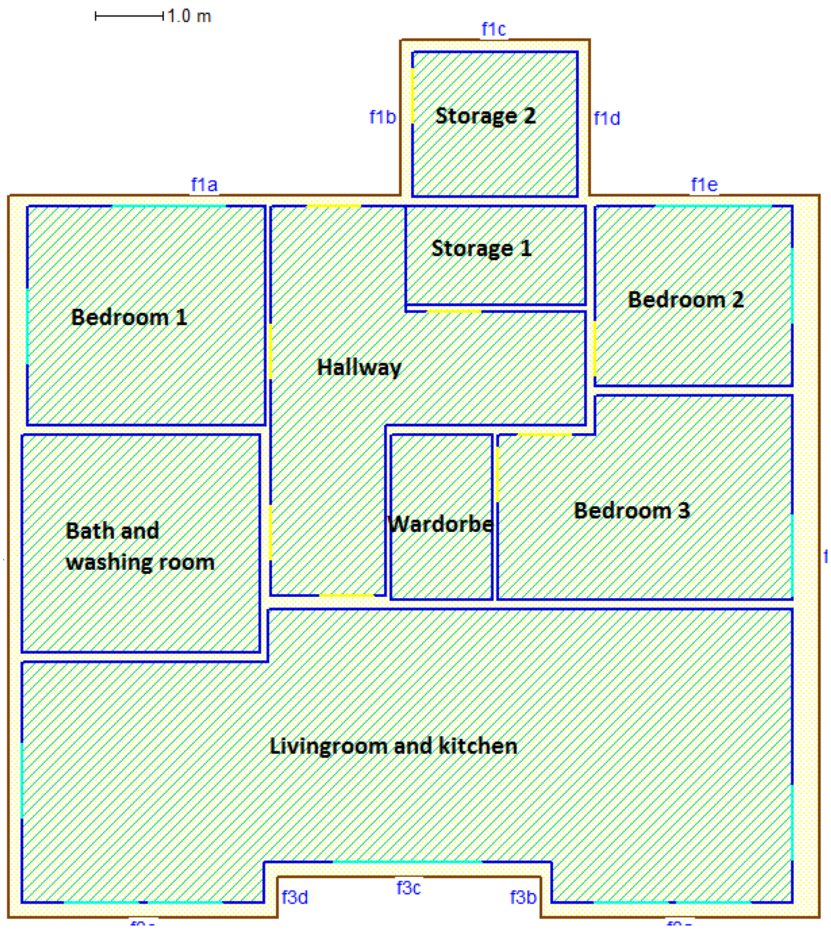

Figure 4.2: Illustration of simulated building, floor plan

External walls and window shading

An example from SINTEF Byggforsk was used as the outer walls for the building. The walls consist of ventilated cladding on the outside, a wind barrier, and two layers of wooden frames with insulation separated by a continuous layer of insulation and a vapor barrier, ending with plates of gypsum on the inside. The different layers are illustrated in figure 4.3.

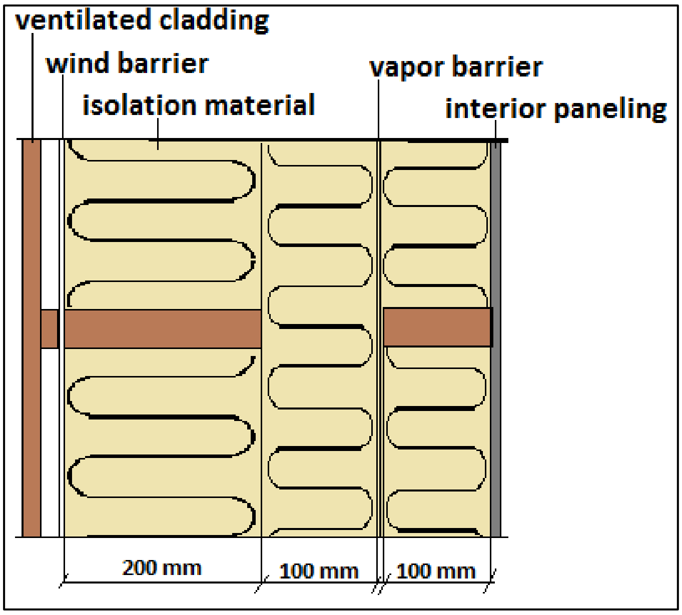

Figure 4.3: Cross section of the outer wall [48]

There is a large amount of heat coming in to the building in the summer from the sun because of the large window area on south façade. Temperature controlled shading was added to the windows in the living room and kitchen to avoid too high temperatures. A similar control system was used in the master thesis written by Atle Solberg [22]. A figure of the control system is found in the appendix A.2.

Internal heating contribution and indoor air quality

NS 3700 contain standard values for occupants' behavior, DHW, lighting and equipment. Both demand and energy converted to heat is specified and used in the simulation. Equipment and lighting is set to operate 16 hours per day every day at a constant value. DHW is used a constant rate 16 hours per day, but no heating from DHW is leaking into the zones of the building. Occupants provide heat to the building 24 hours per day in this simulation. Table 4.2 lists the values used in the simulation, which are according to NS 3700.

Table 4.2: Power- and energy demand and heating to zones from lighting, equipment, DHW and occupants [05]

	Use time	**Power requirement W/m²**	**Yearly energy requirement kWh/(m²*year)**	**Heating to zone W/m²**
Lighting	16h/7d/52w	1,95	11,4	1,95
Equipment	16h/7d/52w	3,00	17,5	1,8
DHW	16h/7d/52w	5,1	29,8	0,0
Occupants	24h/7d/52w	-	-	1,5

A balanced mechanical ventilation system is installed to secure good indoor climate, which is a very important component in new airtight buildings. To secure a good indoor climate the Norwegian building guidelines in TEK10 have specified the amount of fresh air that should be supplied to the building. The minimum requirement for air supply is 1,2 $m^3/(m^2*h)$ for rooms in use and 0,7 $m^3/(m^2*h)$ when the room is not in use. In this simulation only the wardrobe and the two storage areas falls under the lowest requirement.

Some rooms have special requirements based on the use. Bedrooms must be supplied with a minimum of 26 m^3/h per person when in use. Bedroom 1 and 2 is design for one person, while Bedroom 3, which is the biggest, is design for two persons. Kitchen and toilet must minimum be supplied with 36 m^3/h fresh air when in used, and baths must be supplied with 54 m^3/h when in use. For the simulation in IDA ICE, the zones is supplied with a constant airflow that is summarized in table 4.3.

Table 4.3: Exhaust volume, calculated from tek10 [07]

	Areal [m^2]	**Ventilation flow [specific/total]**	**TEK10**
Livingroom and Kitchen	43,98	1,67 $m^3/(h*m^2)$ / 73,32 m^3/h	1,2 / 73,32*
Bath and Wash-room	11,3	4,78 $m^3/(h*m^2)$ / 54,0 m^3/h	1,2 / 54
Bedroom 1	11,37	2,23 $m^3/(h*m^2)$ / 26,0 m^3/h	1,2 / 26
Bedroom 2	7,74	3,36 $m^3/(h*m^2)$ / 26,0 m^3/h	1,2 / 26
Bedroom 3	12,29	4,23 $m^3/(h*m^2)$ / 52,0 m^3/h	1,2 / 52
Wardrobe	3,65	0,7 $m^3/(h*m^2)$ / 2,55 m^3/h	0,7 / -
Hallway	15,26	1,2 $m^3/(h*m^2)$ / 18,31 m^3/h	1,2 / -
Storage room	3,86	0,7 $m^3/(h*m^2)$ / 2,70 m^3/h	0,7 / -
Sport equipment storage	5,27	0,7 $m^3/(h*m^2)$ / 3,69 m^3/h	0,7 / -
Total	**114,72**	**258,57 m^3/h**	

*73.32 m^3/h is calculated from 54 m^3/h + 1.2 * (Livingroom area)

4.1.2 Climate data

The climate will affect the heat losses in a building and it will have an impact on heat pumps that uses outside air as a heat source. When designing a building one should always use local climate data. The simulations done in this paper is done for the same building, while in reality some properties would be different (thickness and U-value of walls, U-value for windows, etc.). Following the passive house standard there are some differences in the maximum net heating demand that is dependent on the mean outdoor temperature. Houses built to the TEK 10 standard does not have restrictions that is dependent on the local climate.

Outdoor temperature will also affect heat pump performances, especially when both an EAHP and a passive heat recover heat exchanger are installed. The exhaust air will pass through the heat recovery heat exchanger first, so the temperature of the exhaust air will be lower when it comes to the evaporator. Houses in a climate with lower outdoor temperature will have more heat absorbed by the supply air, leaving a lower amount of heat to be absorbed by the evaporator.

Another problem with low outdoor temperature is frost formation. NS 3031 lists typical values for minimum discharge temperature. As mentioned in chapter 2.3.1, rotating heat exchangers can have lower temperature than other heat exchangers leading to a recommend minimum discharge temperature of -10 °C. Other heat exchangers, including typical evaporators, is recommended to have minimum 5 °C discharge temperature for optimum reduce frost formation. Minimum 5 °C have been used in the simulation which results are used in the LCC comparison. The impact of lowering or removing this demand is investigated in chapter 5.3.

The climates chosen to simulate for is the cities Trondheim and Kautokeino. Trondheim is located in the middle of the country and have a typical Norway climate very similar to the capital city Oslo. Kautokeino is located in the inland of northern Norway where it is known have extreme cold winters.

The climate files imported into IDA ICE is from the ASHRAE IWEC 2 database. Table 4.4 shows the mean, min and max temperatures from for the climates used in the simulations.

Table 4.4: Average, min and max temperatures in Trondheim and Kautokeino in for the year used in the simulation

	Mean	Min	Max
Trondheim	6,254 °C	-17,78 °C (date: 02.24)	29,91 °C (date: 07.06)
Kautokeino	-1,883 °C	-40,62 °C (date: 01.24)	25,82 °C (date: 19.07)

4.1.3 Heating and cooling distribution

Heating is supplied trough radiators to all rooms in the building to keep the temperature above 19.0 °C except the storage rooms. The radiator object are called “WatRad” in IDA ICE and each unit have the capacity to heat the zone they are placed in. Storage 2 has a very small heating unit only to avoid temperatures below 0°C. This can be done since it assumed that the storage units will be unoccupied by people. Supply and return temperature for the hydronic heating system is chosen to be 45 °C and 35°C respectfully at maximum heating output.

Cooling demand in general is not very large for buildings in Norwegian climate. Cooling is supplied differently depending on the heating system. In the case of the reference system that consists of a passive heat recovery unit and an electric boiler, an electric cooler supply the incoming ventilation air with cooling after the heat recover unit. For a system with an EAHP, it is possible to supply free cooling to the building in the summer. With a central cooling unit in the building, the EAHP can heat DHW and cool down the zones in the building simulations. The automatic window shading and the utilization of free cooling is enough to have comfortable temperatures indoor.

4.1.4 Plant and AHU for reference system

The reference system in IDA ICE is the basic plant and AHU models. AHU is equipped with a heat exchanger for heat recovery, a heating coil and cooling coil for heating and cooling the supply air. The coils are connected to an electric boiler and chiller in the plant that can also deliver heating and cooling to the zones in the building. The plant for the reference system only delivers cooling to the supply air, there are no cooling units in other parts of the building.

4.1.5 EAHP system plant and AHU:

To build the exhaust air heat pump in IDA ICE, a recipe suggested from the EQUA team was used as base. The response from the EQUA team, the plant design and the air handling unit design is found in the appendix A.3.

Appendix A.4.1 shows how the AHU is modified so that the heat pump can use exhaust air as a heat source.

The base of the plant model is what in IDA ICE is called an ESBO (Early Stage Building Optimization) plant. ESBO is a tool within IDA ICE that is meant to use for experimenting with variations in heating and cooling design [49]. The base template that is chosen in the general tab include:

- Generic hot water tank, capacity is specified by products
- Generic cold water tank 20 liters capacity (acts as a buffer for the secondary brine circuit)
- Generic topup heater, COP = 1
- Brine to water heat pump
- Room supply temperature is set to 45 ^{o}C for the distribution system

Under the schematics tab, the plant is further customized. Fist using the recipe from EQUA, then to have the plant function as the products from NIBE and Nilan.

The topup heater is an electric heater, but in the simulation, the energy carrier for the topup heater is chosen to be fuel. The reason for fuel to be the energy carrier is only so that it is easier to separate heat supplied in the result. The efficiency of the fuel is 1, so it behaves as an electric heater.

For all simulations, the hot water tank is set to be non-ideal and have water going to be heated come from the bottom of the tank and come in on the top. Water going out to the building for either space heating or DHW goes out from the top and come back in on the bottom.

NIBE F470

The plant looks like the picture in appendix A.4.2 and have the following parameters set [25]:

- Electric boiler max heating capacity: 10 kW
- Heat pump max heating capacity: 2.2
- Max discharge temperature: 90 ^{o}C
- Min evaporation temperature: -33 ^{o}C

In the AHU, the passive heat recovery heat exchanger is turned off (effectiveness set to 0) and the heating coil that preheats supply air is turned on.

This setup is used for the sensitivity analysis where the effect of changing key parameters is tested.

NIBE F110

The plant looks like the picture in appendix A.4.3. This is customized so that zone heating comes from a separate unit since the F110 only can supply heating for DHW. The following parameters set [27]:

- Electric boiler max heating capacity: 1.3 kW (excluding zone heating)
- Heat pump max heating capacity: 1.32 kW
- Max discharge temperature: 95 ^{o}C

- Min evaporation temperature: -33°C (not given in product brochure, assumed as F470)

In the AHU both the passive heat recovery heat exchanger is turned on with effectiveness 0.8 and the heating coil that preheats supply air is turned off.

Nilan Compact P Nordic

The plant looks like the picture in appendix A.4.3; this is the same case as NIBE F110. The following parameters are set [29]:

- Electric boiler max heating capacity: 1,5 kW (excluding zone heating)
- Heat pump max heating capacity: 3,2 kW
- Max discharge temperature: 95 °C (not given in product brochure, assumed as F110)
- Min evaporation temperature: -33 °C (not given in product brochure, assumed as F470)

In the AHU both the passive heat recovery heat exchanger is turned on with effectiveness 0.8 and the heating coil that preheats supply air is turned on.

IDA ICE heat pump

The customization of the heat pump unit in IDA ICE could be better. It is for example not possible to specify working fluid for the heat pump circuit. There are two types of heat pumps available, one uses ambient air as heat source and water as heat sink. The other is a brine to water heat pump where the source is either ambient air, solar thermal heat, ground heat or exhaust air as I have used.

In the heat pump model menu the rated conditions properties that one can specify is:

- Total heating capacity
- COP
- Compressor type
- LMTD in evaporator
- Minimum evaporator temperature
- LMTD in condenser
- Maximum condensation temperature

The compressor type is always a reciprocating type in the simulations. In addition, the default setting of rated LMTD of 8 K on both compressor and evaporator side were kept constant.

The user guide for ESBO plant actually says that it is not recommended for most users to change other parameters than total heating capacity. However, it also says that if the parameters is identified with respect to data from a real device, and that the model will predict the performance over the whole operating range [49]. In chapter 5.4 is a sensitivity analysis where some of the parameters to the heat pump is tested.

4.1.6 Outdoor air as additional heat source

During the specialization project, work was started on a model in IDA ICE with a heat pump that could use outside air as a heat source in addition to the exhaust ventilation air. There was not time to complete that model then. However, with the help from the EQUA team a functioning model that can add outdoor air as an additional heat source. A separate fan, which is controlled by sensors, will provide outdoor air. Similar to Atle Solberg's matlab model, when outdoor air fan is running, the exhaust air and outdoor air are mixed after the exhaust air has gone through the passive heat recovery.

There are two temperature sensors controls the fan. One for the brine that flows between the AHU and the heat pump, the second one sensor outside the building. The outdoor air fan will run when the temperature of the brine going into the heat exchanger in the AHU and the outdoor temperature is above a set limit. Simulations were carried out with different limits to the outdoor air temperature, and different maximum for outdoor air mass flow.

The heating plant is the same as for NIBE F470, but the AHU is modified. A picture of the AHU in IDA ICE is shown in appendix A.4.4.

4.1.7 Plant for output for Matlab

Only the heat pump is simulated in Matlab, so choices such as climate and if the building has passive heat recovery carries over from the model in IDA ICE. The input from IDA ICE simulations is stored in an excel file.

Separate heating units for DHW heating and space heating is built in the plant, both with their own storage tanks. The heating distribution system is hydronic with radiators dimensioned as before. The heaters have 100% efficiency since losses are handled in matlab. No cooling units are installed in this simulation. There is a figure that shows the plant in appendix A.4.5.

List of inputs into Matlab, the time step is one hour (8760 values total):

- Temperature of exhaust air after heat exchanger [^oC]
- Exhaust air flow [m^3/h]
- Total heating demand [W]
- Temperature of water coming from DHW tank into heater [^oC]
- Mass flow of water coming from DHW tank into heater [kg/s]
- Temperature of water coming from space heating tank into heater [^oC]
- Mass flow of water coming from space heating tank into heater [kg/s]
- Outdoor air temperature [^oC]
- Temperature of exhaust air before heat exchanger [^oC]

All 8760 values for each variable is copied into a excel sheet, with the variables in order top to bottom goes into column A to I in excel. The imported file is named “input.xlsx” inside the folder “input”. The folder must be in the same folder as the folder with the Matlab script.

4.2 Matlab simulation

One of the goals for this paper was to look at the heat pump model made by Atle Solberg [22], that simulates a CO_2 heat pump, and try to improve it. The model has some flaws that was pointed out in Atle’s thesis, and it was suggested that future development of the model should focus on heat transfer, especially in the gas cooler [22]. Creating a model for a CO_2 heat pump is a very complex task. So given the large scope of the complete report, the choice was made to use the base of the existing model and focusing on the gas cooler.

A function could that can find the properties of CO_2 at the outlet of the gas cooler is made in matlab and described in chapter 4.2.2. However, as it was pointed out in the introduction, there needs further work put in to the base of the heat pump model.

Chapter 4.2.1 is a short summary of how the heat pump model made by Atle works, for a more condensed list of what happening in the various functions in the model see appendix B1. This model is compared to the heat pump model in IDA ICE in chapter 5.5.

4.2.1 Heat pump simulation in matlab

The Matlab script takes the input from IDA ICE, which is described in chapter 4.1.7, and calculates the energy that can be covered by the heat pump for each time step. An electric heater covers the demand that the heat pump is not eligible to supply. There are three options when it comes to heat source for the heat pump in the simulation:

- Exhaust air
- Outside air
- Exhaust air and outside air

Here is a short description of the main file that was made by Atle Solberg [22].

The top of the main file declare set the input variables as strings and check for errors in the input. Variables that are heat pump parameters or constants are declared through separate files, called *parameters.m* and *constants.m*. The third file that is rut to at the start is *preallocations.m*, which as the name might indicate, preallocates space for parameters that is calculated.

The core of the main file is the loop that calculates viable operating conditions for each time step. For each time step, the temperature of the discharge air after the evaporator is found through iterations. *Thermodynamics.m* calculates the heat pump' state of operation from the input parameters and guessed value for discharge air temperature. A check is then done to see if heat pump operates at viable conditions. If the heat pump falls outside the viable operating range, the discharge air temperature is adjusted up or down.

The simulation with outside air as heat source runs the same way as with exhaust air, but the air flowing through the evaporator changes to the outside air with a flow specified in *parameters.m*. If both outside and exhaust air is chosen as heat source, it does so by mixing outside and exhaust air before the evaporator. The program will also check for the performance without adding the outside air, so it only uses outside air if it is beneficial.

The heat pump operation is calculated in the function *thermodynamics.m*. Input for this function is values from the simulation done in IDA ICE and the discharge temperature. CO_2 properties if the state is known is found using the software REFPROP by calling on the function *refpropm.m* in Matlab. The wanted property is returned if valid input is given. Output and input can for example be; temperature, pressure, enthalpy, entropy, density and vapor fraction.

The output of *thermodynamics.m* is:

- Heat transferred to the water from the gas cooler [Wh]
- Heat transferred from the air to the evaporator [Wh]
- CO_2 discharge temperature [K]
- CO_2 evaporator temperature [^oC]
- Energy input required to run the compressor [Wh]
- CO_2 volume flow [m^3/h]

4.2.2 CO_2 heat pump gas cooler

The heat pump model created by Atle assumes constant water outlet temperature and constant temperature approach value. With the assumption of constant temperature approach value in combination with constant gas cooler pressure level, the state of CO_2 at the outlet of the gas cooler is only decided by the water inlet temperature. A different approach was taken to the gas cooler in the work done for this report.

The gas cooler is divided into a number of parts. A constant UA-value was assumed for the whole gas cooler that is divided equally for the parts. These equations is then used to find the state of the CO_2 and water at the outlet of each part, equation 4.1 for the CO_2 side and equation 4.2 for the water side.

$$\dot{m}_{co2} * \left(h_{co2_{in}} - h_{co2_{out}}\right) = UA_{part} * AMTD \tag{4.1}$$

$$\dot{m}_{water} * Cp_{water} * \left(T_{water_{out}} - T_{water_{in}}\right) = UA_{part} * AMTD \tag{4.2}$$

Where AMTD is the arithmetic mean temperature difference. It is preferable to use logarithmic mean temperature difference (LMTD), but it will not work with a solver in matlab. The equation for AMTD is as follows:

$$AMTD = \left(\frac{T_{co2_{in}} + T_{co2_{out}}}{2}\right) - \left(\frac{T_{water_{in}} + T_{water_{out}}}{2}\right) \tag{4.3}$$

The points below explains the gas cooler model step by step:

1. Start with a constant water temperature equal the temperature at the inlet
2. Use equation 4.1 to find the specific enthalpy at the inlet/outlet for each gas cooler part for the current water temperatures.
3. Use equation 4.2 to find the water temperature at the inlet/outlet for each gas cooler part for the specific enthalpy found at point 2.
4. Repeat 2 and 3 until the specific enthalpy for CO_2 stabilizes

The gas cooler function also uses REFPROP to find temperature values for the CO_2 gas, as the gas cooler pressure is still assumed constant.

The CO_2 will have a large temperature glide in the gas cooler, which makes modelling a CO_2 gas cooler more complicated than a for a condenser in a subcritical heat pump cycle. In reality, it will not have a constant gas cooler pressure and UA-value. The UA-value will depend on flow rates of CO_2 and water.

4.2.3 Tips for future work

This chapter gives a short description of some challenges that came with making the gas cooler model in matlab. Hopefully, this can be of some use if future work is aimed at improving the existing or making a new model in matlab to simulate CO_2 heat pumps.

Using REFPROP in a solver

It is possible to create functions for a solver in matlab that uses the equations unknown parameter to look up values in REFPROP. An example of an equation that does this is shown in equation 4.4. Solving an equation like the one shown can be done by matlab, but there is a set range of input parameters that REFPROP will operate with. The problem occurs when the solver looks for solutions outside of REFPROP's range, which will cause the program to crash.

Since the program now use iterations to find a valid state of operations, these crashes can happen frequently if not handled. If the solver only work with one fluid at the time, as the script described in previous chapter does, the solver will not look for solutions outside the valid range. Another way to solve it is to run an "if" check within the function used by the solver, that way the solver can be stopped before the entire program crashes.

$$F(x) = \dot{m} * (h_1 - \boldsymbol{x}) - UA * \left(\frac{T_1 + refprop('T','P',p_{gc},'H',\boldsymbol{x},'co2')}{2} - \frac{T_{w1} + T_{w2}}{2}\right) \tag{4.4}$$

Runtime

By changing the model to find a solution for the gas cooler without some of the previous assumption will increase the runtime of the model. Some alternatives that can improve the runtime is:

- Split the gas cooler into a fewer number of parts and then increase the number to what is wanted.
- With a constant gas cooler pressure, one can use the built in function "interp1" to create vectors of temperature and specific enthalpy values. That way values can be found by looking up values in the vectors instead of REFPROP for every iteration and time step, which can save some time.

Chapter 5: Results

The results from simulations is presented in this chapter. Simulations were primarily done in IDA ICE, while a comparison is done against a model made in matlab. Most of the results here is in the form of delivered energy per square meter for heating and ventilation in the house described in chapter 4.1.1.

The main focus in the result from the simulations based on exhaust heat pump products. Three heat pump products and two systems with electric heaters are simulated in IDA ICE. The results from the simulation there is used in chapter 6.3 for a cost analysis.

Frost protection was also investigated in this chapter, and what impact it has on the heat pump performance and energy requirements. The impact of other parameters were also tested.

5.1 Heating demands

Heating demand for a building depend on many factors, as is discussed in the «Method» chapter. The building created in IDA ICE has been simulated with two different climates, Kautokeino and Trondheim. Figure 5.1 shows the heating demand for the building in the two different climates with and without passive heat recovery. The house was design to meet the requirements for a passive house in Trondheim when heat recovery is installed. Kautokeino has a very cold climate and have a much higher heating demand. Heating demand with and without passive heat recovery is very large and is a large factor when the different exhaust air heat pumps is compared.

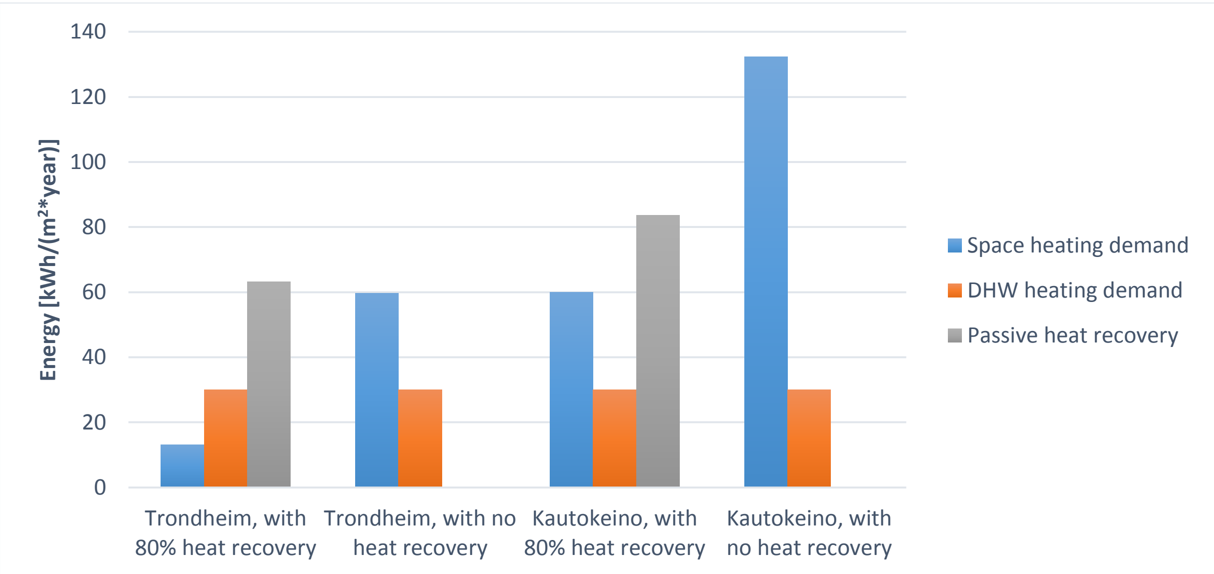

Figure 5.1: Shows the net heating demand for space and DHW as well as eventual recovered heat by passive heat recovery.

The demand for space heating when the building is placed in Kautokeino is over three times larger than when it is located in Trondheim. As a result, it fails the requirement in NS 3700 for maximum net energy demand for heating with only electric heating to supplement the heat recovered. The annual mean temperature in Kautokeino is -1,883 °C, which for this building means a maximum heating demand of 46,09 kWh/(m^2*year) [05]. In order for this house to be a passive house in

Kautokeino, either the envelope of the house must be improved or a heating system that utilizes energy better must be installed.

The difference of heating demand is very large for a house that have passive heat recovery and one that do not. Recovered energy in Kautokeino is only 32% larger than for Trondheim, while the increase in space heating that comes forward in the simulations without heat recovery is 122%.

Figure 5.2 and 5.3 shows the duration curves for space heating demand for the building in Trondheim and Kautokeino respectfully. The difference between the net demand with and without heat recovery is also highlighted here.

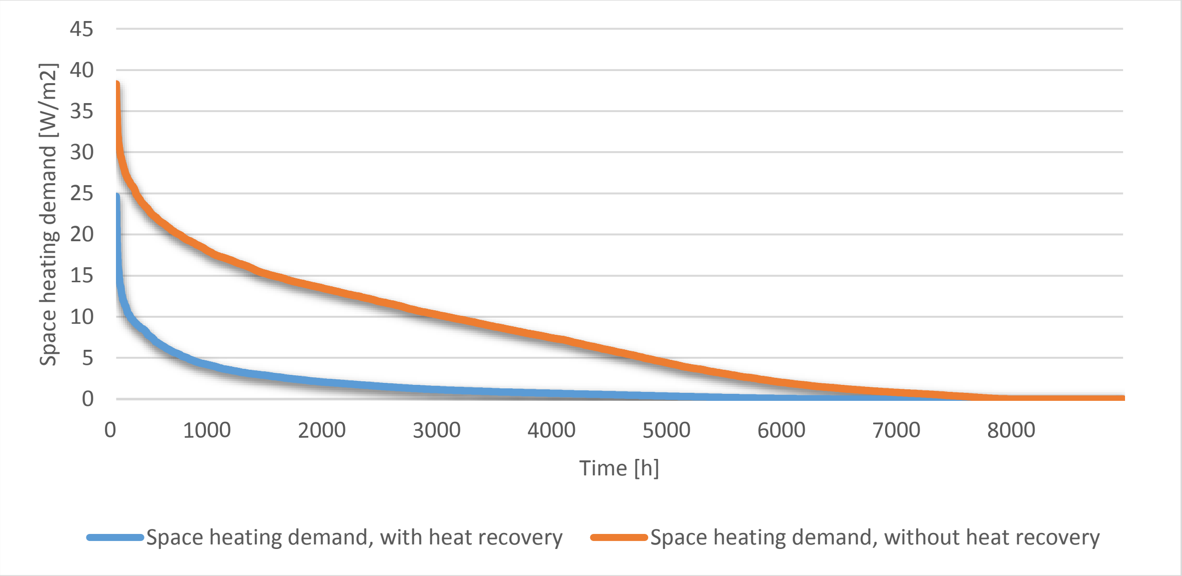

Figure 5.2: Duration curve for space heating demand in Trondheim

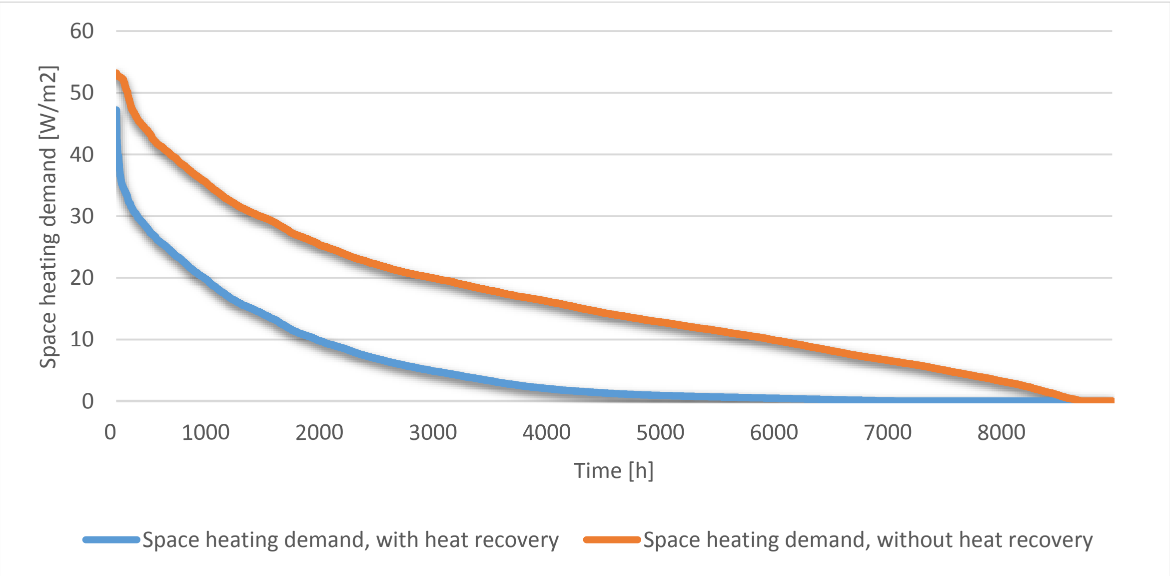

Figure 5.3: Duration curve for space heating demand in Kautokeino

The peak demand is not that different between the case with heat recovery and not in Kautokeino. The slopes of the curves for the two cases is however very different both for Trondheim and Kautokeino.

5.2 Product comparison

This chapter will compare the energy usage from simulations in IDA ICE of the EAHP products from NIBE and Nilan. The results shown in this chapter will be used in the LCC comparison in chapter 6.3. The three products are compared against each other and up against the alternative of having only electric heating with and without passive heat recover. Figure 5.4 and 5.5 shows the net energy delivered for heating and ventilation for the five options in Trondheim and Kautokeino respectfully.

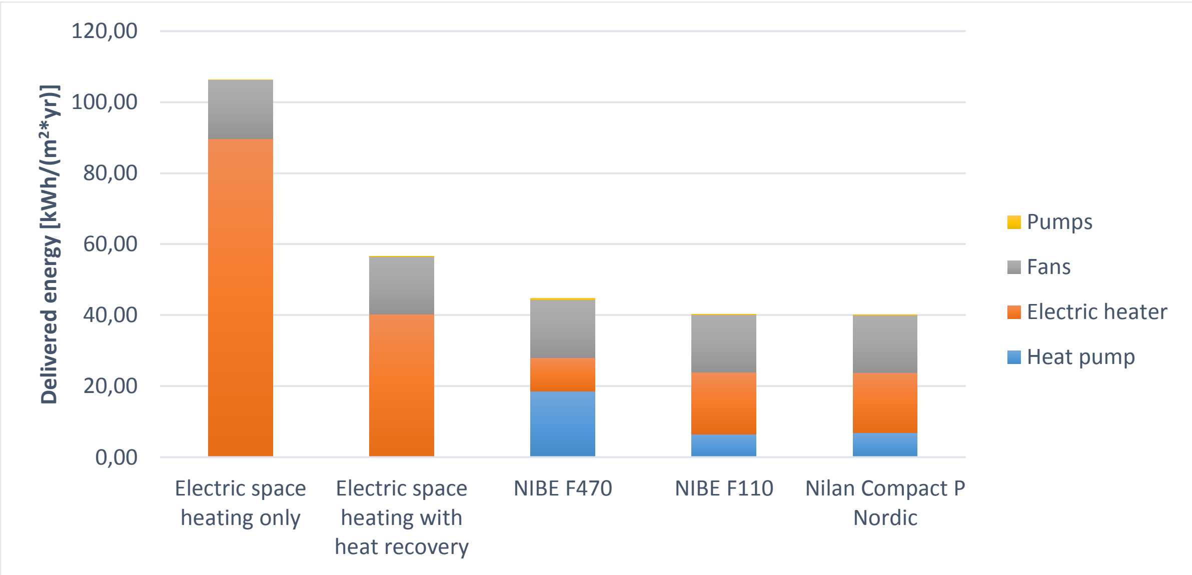

Figure 5.4: Net energy delivered for heating and ventilation in Trondheim

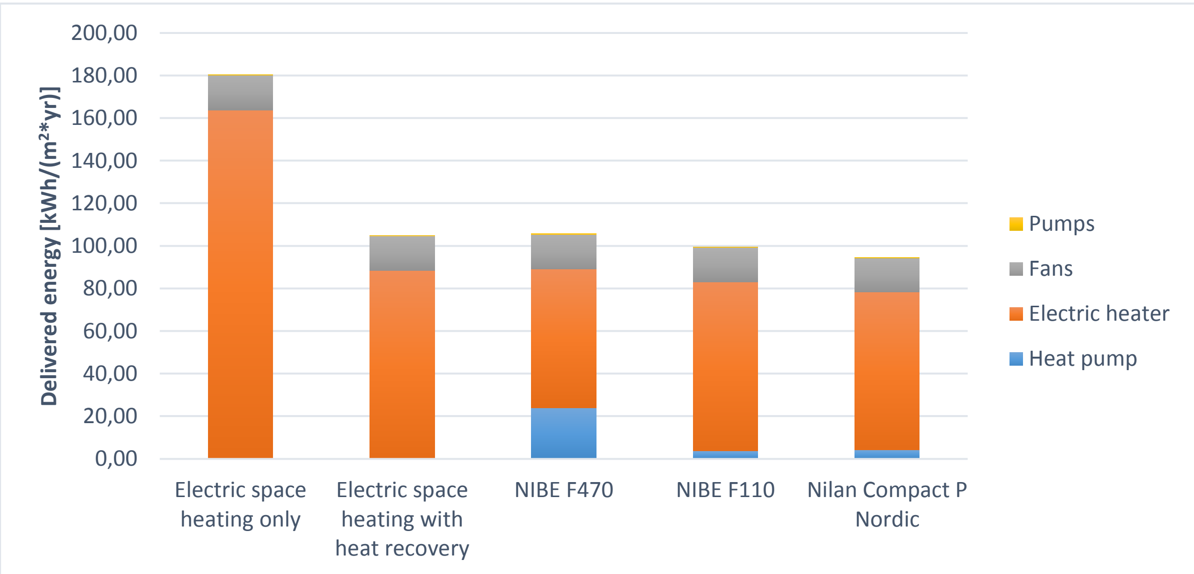

Figure 5.5: Net energy delivered for heating and ventilation in Kautokeino

Figure 5.4 shows that the heat pumps do bring down the net delivered energy, but that the two products with passive heat recovery (NIBE F110 and Nilan Compact P Nordic) achieves the best results in the end. Delivered energy ends up lower for NIBE F470, which only has active heat recovery, than the case with passive heat recovery and electric heaters in Trondheim.

Figure 5.5 shows that in the much colder climate of Kautokeino, that the heat pumps units is not able to keep up with the increased demand. The cold climate means that more heat is removed from the exhaust air by passive heat recovery, which reduces the performances of the heat pumps NIBE F110 and Nilan Compact P Nordic. NIBE F110 and Nilan Compact P Nordic still have the lowest energy delivered. Delivered energy for NIBE F470 in Kautokeino slightly higher than the model with electric heaters and passive heat recovery.

Table 5.1 shows the percentage of the heat demand that is covered by the heat pump units. NIBE F470 covers a larger percentage than the two other units do, since it delivers heating both for DHW and space heating. NIBE F110 delivers heating only for DHW, and the unit from Nilan supplies heat to DHW and ventilation air. The number in the parenthesis for NIBE F110 is the percentage of the DHW heat demand that is covered the heat pump unit.

Table 5.2 shows the reduction in delivered energy for ventilation and heating of the systems compared to the reference system.

Table 5.1: Heat demand covered by the three heat pump units for the building in Trondheim and Kautokeino

	Heat demand covered by heat pump units	
	Trondheim	Kautokeino
NIBE F470	89,64%	60,73%
NIBE F110	59,40% (85,60%)*	13,25% (40,72%)*
Nilan Compact P Nordic	57,23%	16,04%

*The number in parenthesis is the portion of the DHW heat demand that is covered by the heat pump unit

Table 5.2: Reduction in delivered energy for ventilation and heating compared to the reference system with no heat recovery

	Reduction in delivered energy compared to reference system with no heat recovery	
	Trondheim	Kautokeino
Reference system with only electric heating	0,00%	0,00%
Passive heat recovery combined with electric heating	46,84%	41,97%
NIBE F470	57,94%	41,37%
NIBE F110	62,12%	44,91%
Nilan Compact P Nordic	62,24%	47,58%

5.3 Impact from preventing frost formation

The simulation results that is presented in the previous chapter had the discharge air restricted to not fall below 5 °C. This is a restriction to prevent frost formation on the heat exchangers, and 5 °C is the recommended value for residential houses according to NS 3031.

It is possible to install some sort of frost protection system such that the discharge air temperature can be lower. The most usual methods for frost protection is by-pass, preheating of the air and periodic stoppage of the supply air [50].

Figure 5.6 and 5.7 shows the net energy delivered for the heating and ventilation in the case if the minimum discharge air is five °C, 0 °C or is not restricted at all. The building is still placed in Trondheim and Kautokeino respectfully.

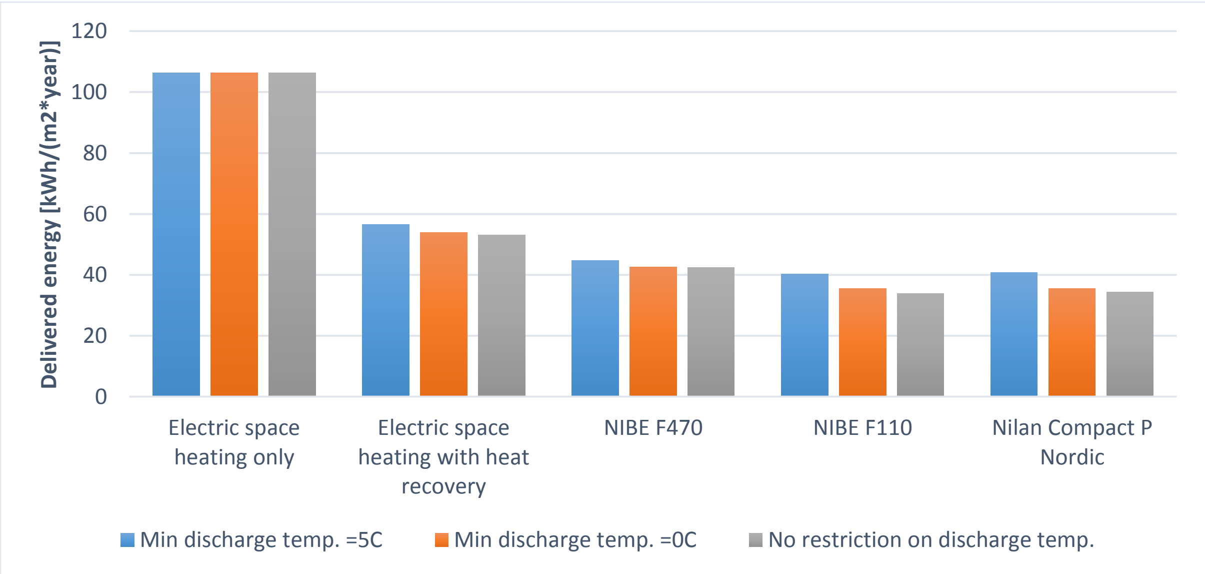

Figure 5.6: Delivered energy for heating and ventilation with different limits to the discharge air temperature in Trondheim

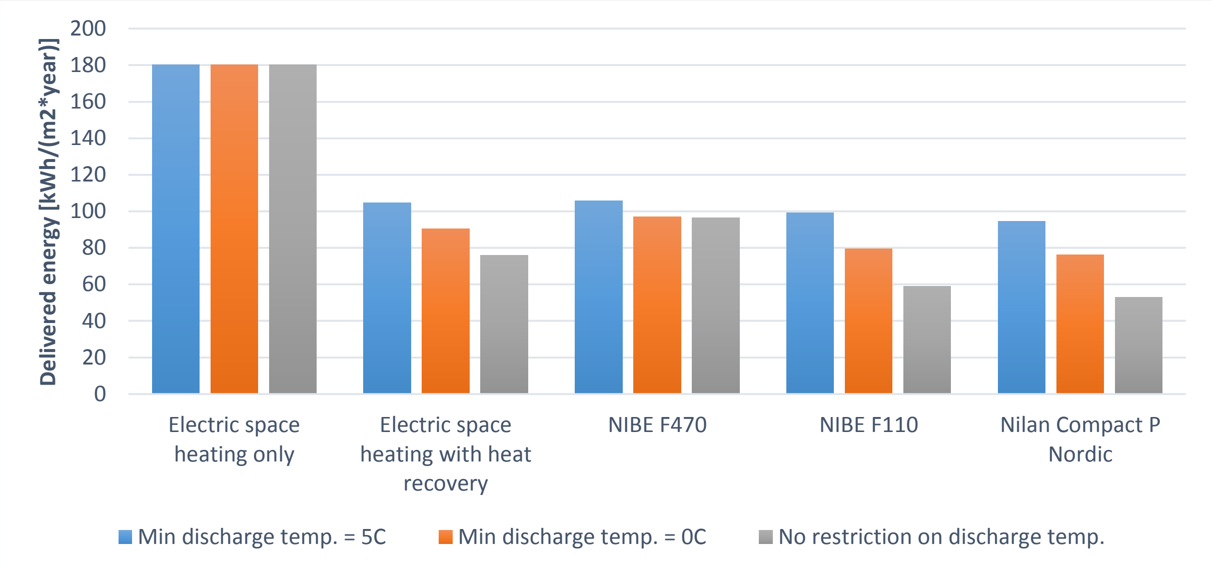

Figure 5.7: Delivered energy for heating and ventilation with different limits to the discharge air temperature in Kautokeino

In Trondheim, NIBE F470 is not affected by the restrictions to the discharge air temperature in the simulations. Not enough heat will be removed from the exhaust air by the evaporator of NIBE F470 alone for it to be any danger of frost formation. There is a small difference between the three cases in Kautokeino.

Changing the restriction have a very small impact on the case with only passive heat recovery in Trondheim. In Kautokeino however, there is a sizable reduction to delivered energy when the restriction is lowered or removed.

In the case of NIBE F110 and Nilan, the figures show that the effectiveness of the system can be made better by changing the restrictions to minimum temperature of the discharge air. Especially in Kautokeino, measures to increase the utilization of the heat pump units should be investigated.

5.4 The heat pump model in IDA ICE

This chapter will experiment with different parameters in IDA ICE and look at the performance of the heat pump model. The experimentation is done with the EAHP model based on NIBE F470, which delivers heating to both space heating and DHW. A figure of the plant in IDA ICE can be found in the appendix A.4.2.

5.4.1 Total heating capacity

In the tutorial for the ESBO plant in IDA ICE, it was recommended for most users to only change the total heating capacity for the heat pump. Figure 5.8 shows delivered energy for heating and ventilation when the heat pump heating capacity changes.

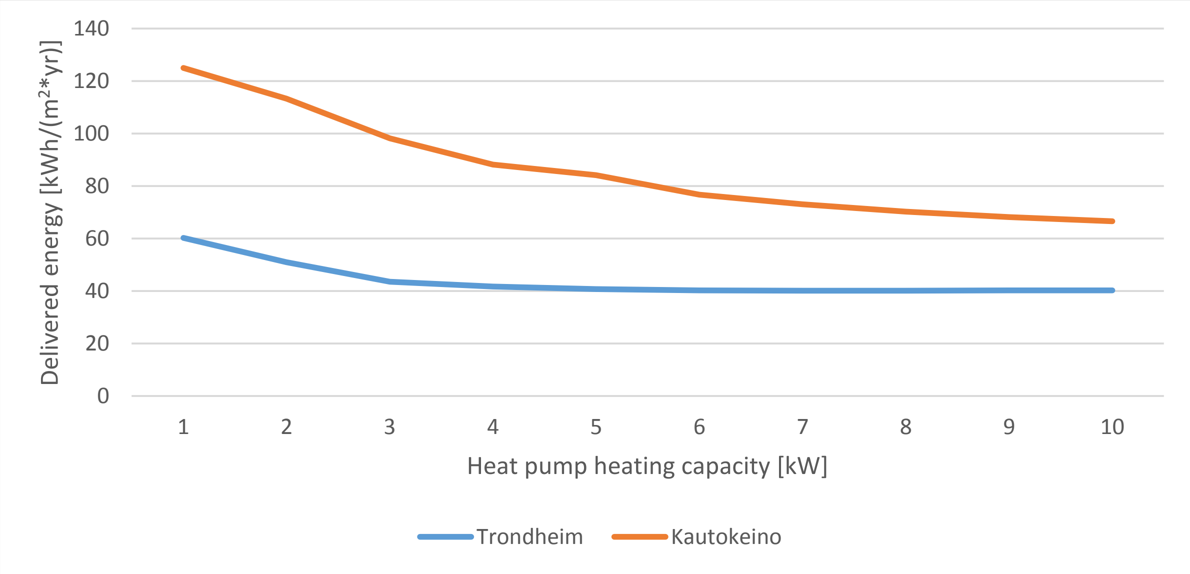

Figure 5.8: Delivered energy simulated for heat pumps with different heating capacity

The figure shows that for Trondheim that a larger heat pump result in less energy required for heat pumps with capacities up to about 3 kW. Heat pumps larger than 3 kW require about the same amount of energy to keep a comfortable indoor temperature. In Kautokeino, the required energy decrease with increased heat pump capacity for the entire simulated range. The curve is steeper for heat pumps smaller than 4 kW.

A factor that is not taken care of in the model made in IDA ICE is the minimum heating capacity of the heat pump. Larger heat pump will also have a higher minimum heating capacity. Minimum part load for the heat pump were investigated in IDA ICE, but changing parameters to adjust minimum part load only resulted in error messages. Nevertheless, a 10 kW heat pump would probably be too large for the demand of a small house and not perform as well as the figure shows. A larger heat pump will also have a much higher investment cost.

5.4.2 Compressor type

There are three standard types of compressors to choose from in the heat pump menu. The three are reciprocating, screw and turbo. Reciprocating compressors are the one that fits a residential unit best, while screw and turbo compressors are more used in larger units [51]. In all simulations, the reciprocating compressor has been chosen.

Table 5.3 shows delivered energy for heating and ventilation simulated with the model for NIBE F470 with the different types of compressors chosen. The amount of energy in the case of screw or reciprocating compressor is very close. The data shows that the heat pump is more utilized when the reciprocating compressor is chosen and the screw compressor is less utilized but have higher COP.

Table 5.3: Delivered energy from IDA ICE EAHP model with different types of compressors

	Trondheim [kWh/(m²*year)]	Kautokeino [kWh/(m²*year)]
Reciprocating	44,71	105,69
Screw	44,06	105,58
Turbo	46,61	107,63

5.5 Comparison with matlab model

This chapter compares the heat pump model in IDA ICE with the matlab model made by Atle Solberg [22]. The matlab model can simulate for different heat pump installation with the option of outside air and/or exhaust air as heat source. Here the focus have been on exhaust air heat pump with and without passive heat recovery.

The compressor volume is the parameter used to sets the size of the heat pump in matlab, while the heating capacity is the parameter in IDA ICE. Maximum compressor volume for the matlab model were investigated by Atle, and was found to be optimal at 0,75 – 1,0 m^3/h [22]. 0,75 m^3/h is used here since the house simulated for here is smaller. The maximum heating output from the matlab simulation is then used in IDA ICE to make a comparison.

The plant in model used in IDA ICE is shown in appendix A.4.5. It is the same plant used for NIBE F470, which can deliver heating for both DHW and the zones. The matlab model do not have frost protection, so the discharge air can have very low temperatures. IDA ICE simulations is done both with and without frost protection.

Figure 5.9 shows delivered energy for heating and ventilation for the three cases: matlab model, IDA ICE model with frost protection and without frost protection.

From figure 5.9 one can see that the model in IDA ICE have lower delivered energy in Trondheim. The main reason for this seems to be the heat pump performance. The average COP registered for the heat pump in IDA ICE around 4,0 for all the simulations. In matlab, the average COP is under 2 for simulation with passive heat recovery, and around 2,5 for simulations with only EAHP.

The COPs is about the same in Kautokeino, but with frost protection, the heat pump in IDA ICE will be turned off for long periods. Therefore, the model in matlab has less delivered energy than the IDA ICE model with frost protection.

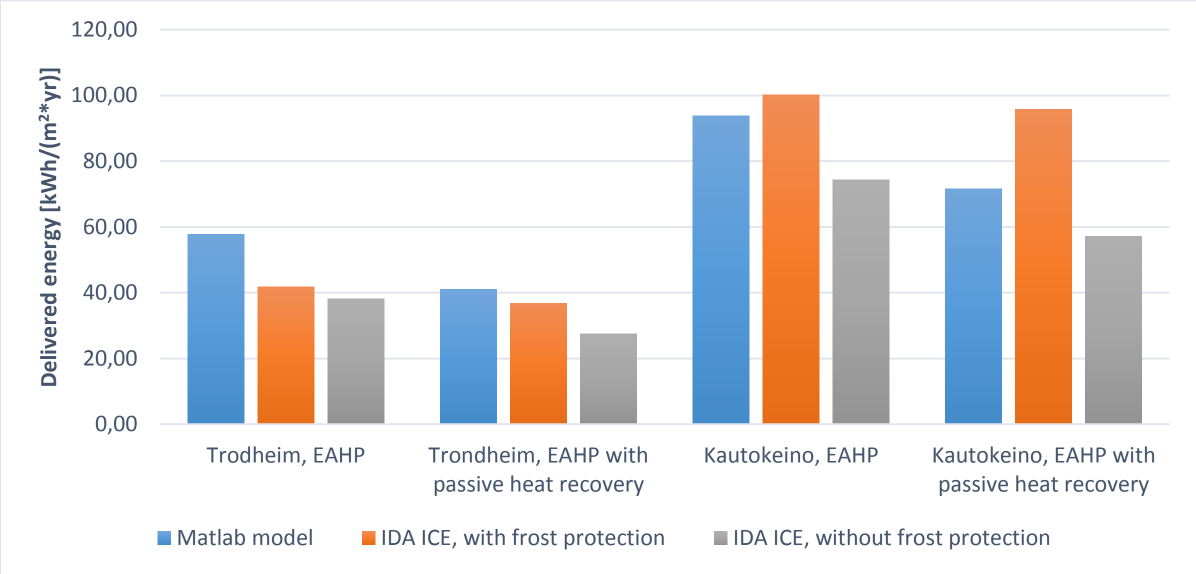

Figure 5.9: Delivered energy for heating and ventilation using matlab mode and IDA ICE model with and without frost protection.

5.6 Outdoor air as additional heat source

Simulating with outdoor air as an additional heat source was done with different limits to the outdoor air temperature and different flow rates for the outdoor air. In the end, several simulations were carried out, with different amount of outdoor air that was mixed with the exhaust air.

The minimum temperature of the discharge air was still set to 5 ^{o}C for frost protection. And as long as the minimum outdoor temperature for the outside air fan to operate was above that limit the addition of the outside air reduced the delivered energy to the heat pump and the electric heater.

However, the reduction was always low. Moreover, the added energy to run the outdoor air fan was larger than the reduction from the heating units, so the net energy delivered was larger with outdoor air as an additional heat source.

Chapter 6: Life cycle costing (LCC) comparison

This chapter present a LCC comparison between different EAHP solutions based on commercial products and simulation in IDA ICE. The different solutions include:

- A reference system with only electric heating
- Passive heat recovery combined with electric heating
- Products from NIBE:
  - F470
  - F110
- Products from Nilan
  - Compact P Nordic

6.1 LCCWeb

The calculations of the life cycle costs for the different heating options is done in a calculation tool called LCCWeb. LCCWeb is a free tool that one can gain access too through the website www.lccweb.no. Statsbygg owns the program, and Statsbygg, and Forsvarsbygg developed it with assistance from Norconsult. The calculations follow the Norwegian standard NS3454 ("Livssykluskostnad for byggverk – prinsipper og structurer") that had its last update in 2013, but the program has not been updated since 2011 [53] [54]. The program still works fine for the analysis in this paper, despite it not following the most resent standards. Note that LCCWeb is only available in Norwegian.

6.1.1 The programs structure

One can log into the website when one have received a user and access code via e-mail, a new user can create up to ten projects. A project have different levels:

Project → Phase → Functional part → Alternative → Main post → Costing level

One can have multiple phases for a project and multiple functional parts for each phase, and so on. This paper looks at different alternatives for the house used in the simulations.

The functional part contains important factors that is used in the calculation for all the alternatives:

- Gross floor area
- Operating time
- Salvage value or cost, given in percentage
- Real interest rate
- Whether or not taxes are already included in the cost

There are more options that can be set by the functional part, but those mentioned are the ones important for this analysis. The different alternatives branches off from the functional part levels.

The program allows for very detailed specifications when it comes to the cost. Different types of costs can be put into the different main posts. The costing levels specify how detailed the specification of the costs. It is important to set the costing level one wants to use as active, or else the program will not count the input of that post when it sums up the costs. Figure 6.1 shows how the program looks. The menu for navigating through the different levels are highlighted by the red square.

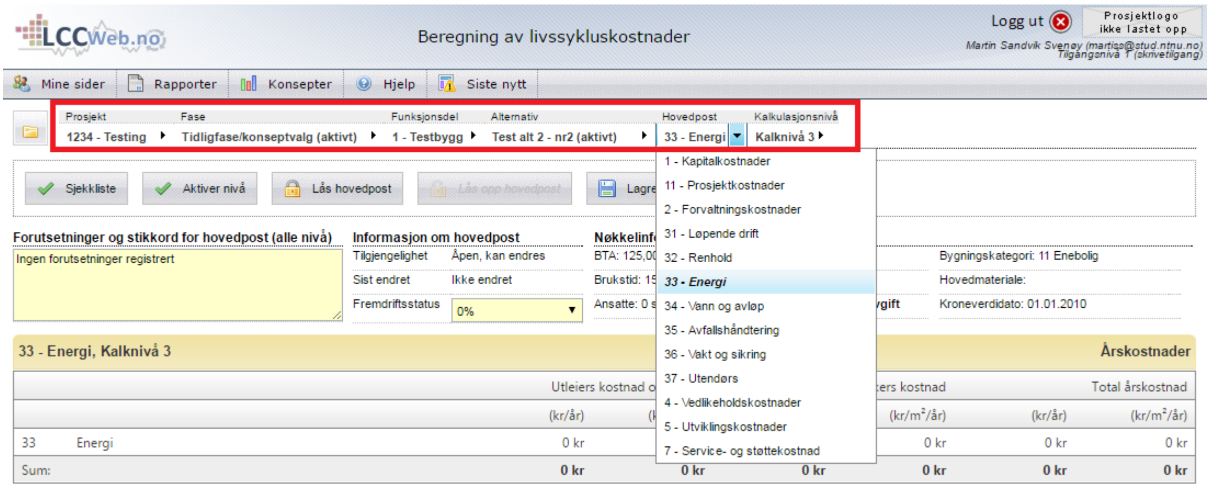

Figure 6.1: A picture of how LCCWeb looks [53]

6.2 Inputs to the LCC-analysis

The investment and energy cost is used to compare the different heating solutions. The results from chapter 5.2 is used for input in LCCWeb. Both climates Trondheim and Kautokeino is being investigated. Price per kWh is gathered from Trønderenergi, which is the company responsible for the electric network in Trondheim. At the current date (10.06.2016) the price for electricity was 35,94 øre/kWh, and the grid tariff was 41,875 øre/kwh [55] [56].

Calculations are based on the discount rate from Husbanken, which is 6,25% [57].

All of the heat pump units comes with a tank for hot water storage inside the units. The alternatives that is electrical heating systems with and without passive heat recovery should also include a tank for hot water storage. The price is based on the tank Super “S 200 Boligbreder” from Oso Hotwater, which costs 5725 NOK [58].

6.2.1 Heat pump units

The price and lifetime of the heat pump units are based on information from ABK and Nilan Norge. The expected lifetime of all the units is between 15 and 20 years [59][60]. 15 years lifetime was used for all the products, but an increase or decrease of lifetime is investigated in chapter 6.4.1.

ABK is the main importer of NIBE products in Norway, as is Nilan Norge for products made by Nilan. A summary of the different prices is shown in table 6.1.

Table 6.1: Summary of price for exhaust heat pump units [61][60]

Product	**Suggested retail price**
NIBE F470	65 000 NOK
NIBE F110	32 000 NOK
Nilan Compact P Nordic	78 500 NOK

In Norway, one can get support from the government owned organization Enova to invest in energy efficient solutions. Exhaust air heat pump is one of the possible solutions that are supported by Enova. Since all three units have energy meters installed, 25% percent of the cost up to 20 000 NOK can be refunded [62]. The costs for the units with subsidy from Enova included is shown in table 6.2.

Table 6.2: Exhaust heat pump cost with subsidy from Enova included [62]

Product	**Suggested retail price**
NIBE F470	48 750 NOK
NIBE F110	24 000 NOK
Nilan Copact P Nordic	58 875 NOK

Note that Enova can also support retrofitting balanced ventilation and installing waterborne heating in an existing building [63]. For simulations done in this report, it is assumed that the building is new.

6.2.2 Ventilation

In this analysis, it is assumed that the work to install a ventilation system is the same for all solutions. For the case with NIBE F470 and Nilan Compact P Nordic, the heat recovery unit is replace with the heat pump unit. NIBE F110 is installed as an addition to the ventilation heat-recovery unit. In addition, since the IDA ICE model only have one exhaust duct, the option for a kitchen hood must be included in all the options with heat recovery. A kitchen hood removes grease and other particles from the air with a filtration system in order to prevent it to spread further into the ventilation system. The alternative is to have an own ventilation duct for the kitchen.

The data are mainly gathered from the ventilation entrepreneur Økovent. The sum of the different components adds up to about the same values given by manufactures System air and Flexit [64][65]. Table 6.3 shows the prices used for the simulation.

Table 6.3: Prices for ventilation that is used for the LCC comparison [66]

	Suggested retail price
Heat recovery unit (incl. fans)	25 000 NOK
Ducts	18 000 NOK
Installation work	18 000 NOK
Kitchen hood	3 500 NOK

6.2.3 Hydronic- and electric heating installations

NIBE F470 require a hydronic heating system, which will increase the initial cost for this system. As mentioned in chapter 3.3, there is a positive trend for installing of hydronic heating in Norwegian households. It is often coupled with district heating, which is a system that is not investigated in this analysis.

Only the case with the EAHP F470 uses hydronic space heating and the else uses an electrical heating installation. The price for installing either a hydronic- or electric heating system in a building is summed up in table 6.4. The data is gathered from a study done by Cowi in 2012, and the numbers have been confirmed to still be valid [67]. From the study, the average value is multiplied with the house floor area, which is shown in the rightmost column in table 6.4. This study focuses on buildings built after the passive house standard.

Table 6.4: Costs for hydronic and electrical heating systems [30]

Water borne heating	Price from report,	Middle value	Total cost
TEK 10	447-541 NOK/ m^2	494 NOK/ m^2	56 316 NOK
Passive house	351-423 NOK/ m^2	387 NOK/ m^2	44 118 NOK
Electrical heating			
TEK 10	160-196 NOK/ m^2	178 NOK/ m^2	20 292 NOK
Passive house	102-124 NOK/ m^2	113 NOK/ m^2	12 882 NOK

6.3 LCC – Results

From the operating cost and investment cost, LCCWeb calculates the total annual cost for the systems. Figure 6.2 and 6.3 shows the total annual cost for the five systems that is simulated for a building in Trondheim and Kautokeino respectfully.

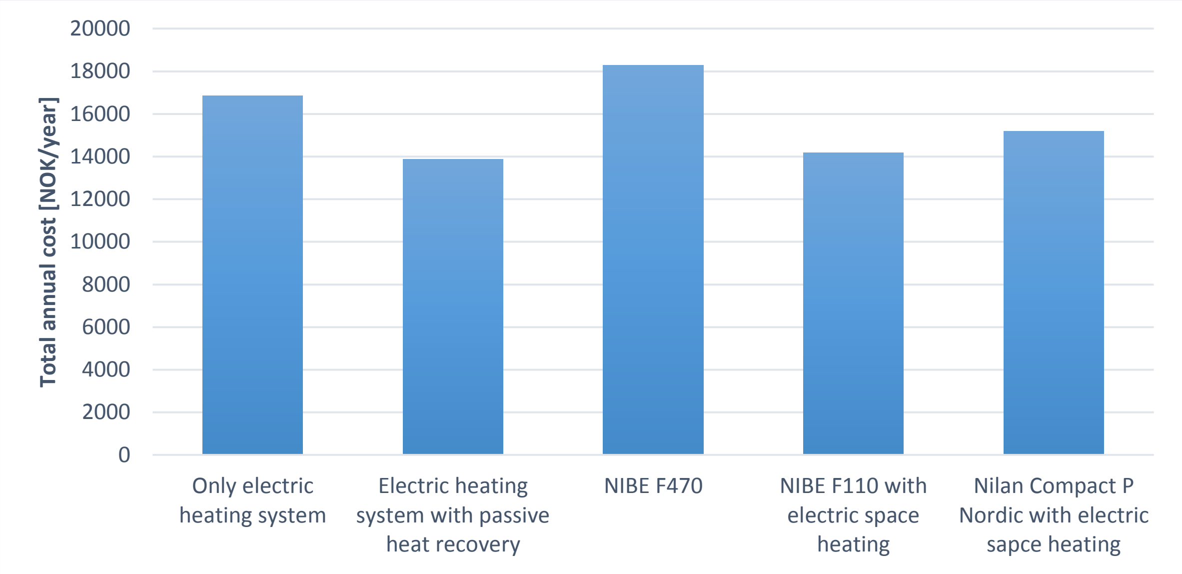

Figure 6.2: Total annual cost for heating and ventilation for different system for a building in Trondheim

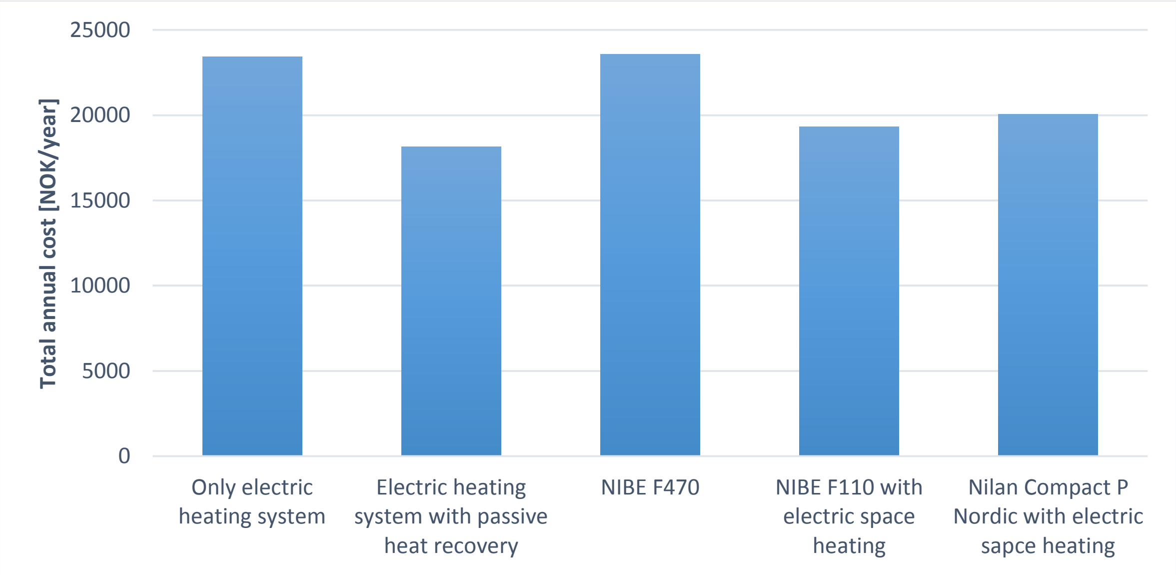

Figure 6.3: Total annual cost for heating and ventilation for different system for a building in Kautokeino

The average cost with the five solutions is 15673 NOK/year in Trondheim and 20908 NOK/year in Kautokeino. For both climates the order from cheapest to most expensive is:

- Electric heating with passive heat recovery
- NIBE F110 with electric space heating
- Nilan Compact P Nordic with electric space heating
- Only electric heating
- NIBE F470

Table 6.5 shows the total annual costs compared to the reference system without any heat recovery.

Table 6.5: Total annual cost compared to the reference system with no heat recovery

	Total annual cost compared to reference system with no heat recovery	
	Trondheim	Kautokeino
Reference system with only electric heating	100,00%	100,00%
Passive heat recovery combined with electric heating	82,27%	77,50%
NIBE F470	106,86%	100,01%
NIBE F110	84,31%	83,05%
Nilan Compact P Nordic	90,70%	85,64%

6.4 LCC – sensitivity analysis

This part look at some of the parameters that were specifically used in the LCC-comparison. First parameter to be investigated is the products lifetime and the second is the discount rate.

6.4.1 Product lifetime

The analysis in chapter 6.3 uses 15 years as the lifetime for the installation, which is on the low end of the value given by NIBE and Nilan. Both NIBE and Nilan said that the typical lifetime for their product is 15-20 years [59][60]. Figure 6.4 and 6.5 shows the total annual cost for the five solutions with different value for lifetime used in the calculations. The building is paced in Trondheim in figure 6.4 and Kautokeino in figure 6.5.

The figures shows that the annual cost becomes lower with the increasing lifetime. And that the change is largest for NIBE F470 because of the large investment cost. When 25 years lifetime is used in the calculations, NIBE F110 with electric space heating becomes the cheapest option in Trondheim. NIBE F470 becomes a cheaper solution than only electric heating in both Trondheim and Kautokeino when 25 years lifetime is used in the calculation.

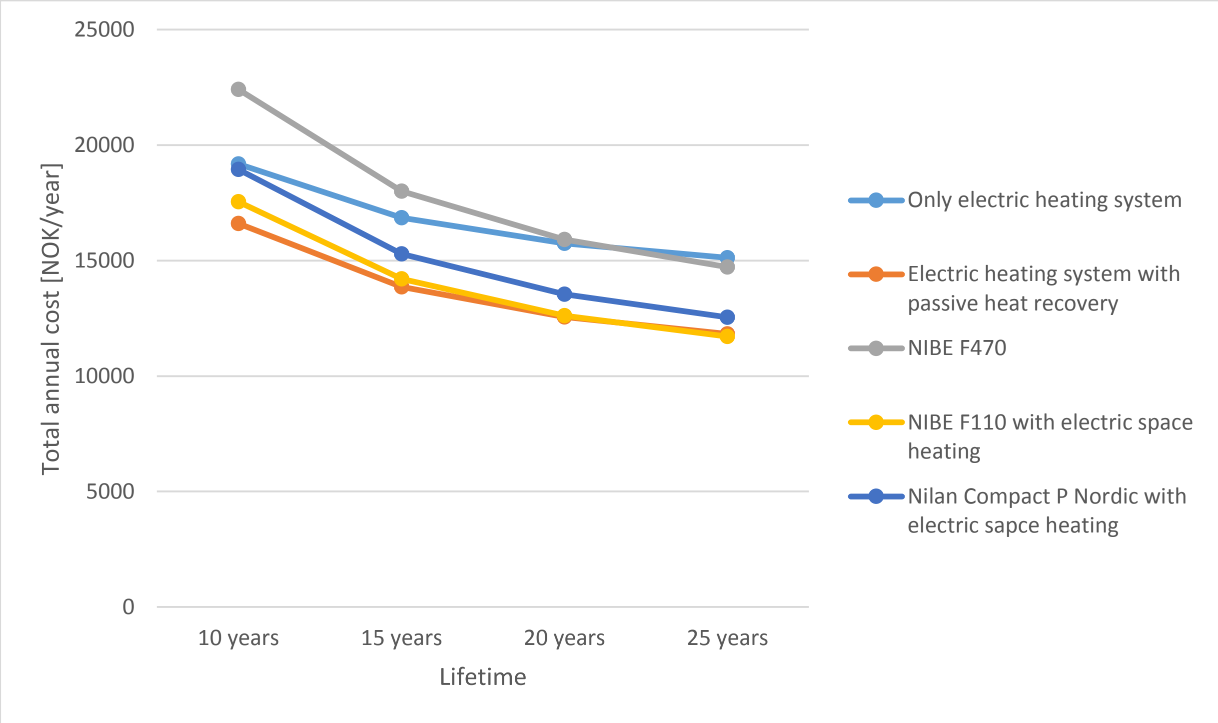

Figure 6.4: Total annual cost for heating and ventilation calculated with different lifetime in Trondheim

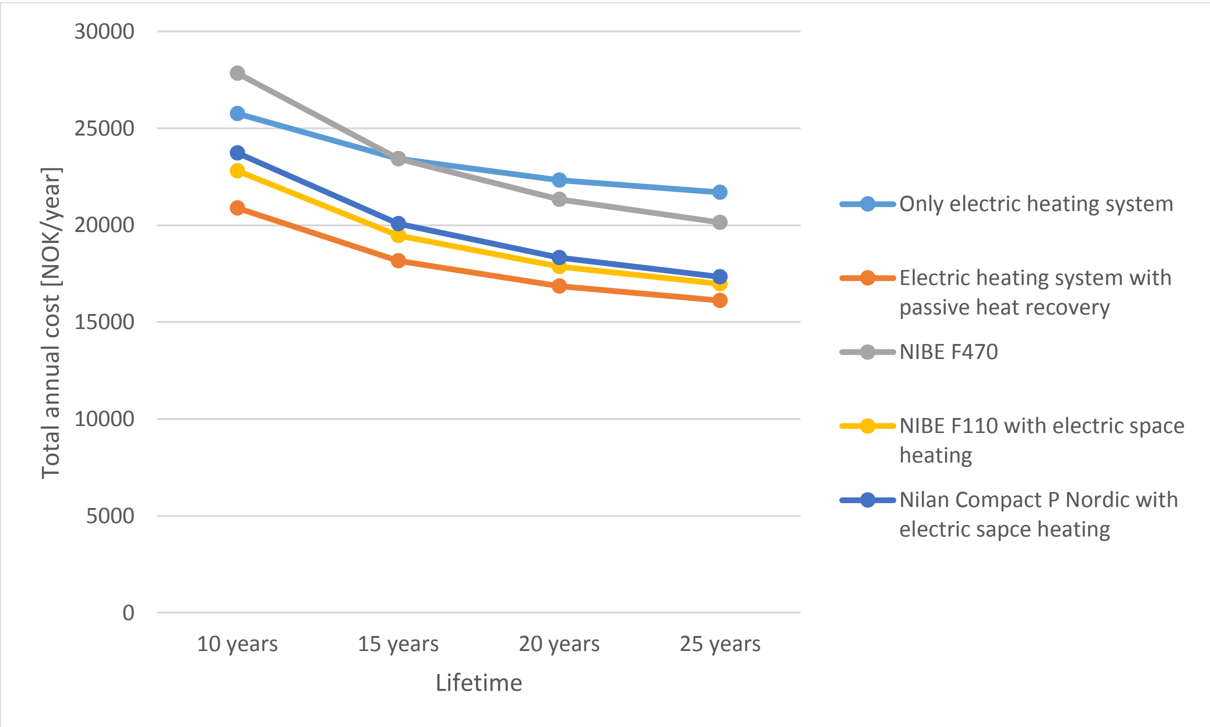

Figure 6.5: Total annual cost for heating and ventilation calculated with different lifetime in Kautokeino

6.4.2 Discount rate

In the calculations the rate were set to 6,25%, which is the discount rate that are used by Husbanken. It has stayed at that level since 2011. It is correct to use the discount rate for calculations, as it is set to account for changes in the market. Today one can get a rate that is bound for 20 years at about 2,57% at Husbanken [68]. Table 6.6 shows a comparison of the result with a rate at 2,57% against a rate at 6,25%.

The change in interest rate yields about the same results as the change in lifetime to 25 years. It affects the solution with the largest investment cost the most. NIBE F470 becomes cheaper than electric heating in Trondheim and Kautokeino, and NIBE F110 is the cheapest option with the lowered interest rate in Trondheim.

Table 6.6: Comparison of total annual cost by using different interest rates in the calculations

Trondheim	**6,25% [NOK/year]**	**2,57% [NOK/year]**	Deviation [NOK/year]
Only electric heating system	16856	15189	-1667
Electric heating system with passive heat recovery	13868	11906	-1962
NIBE F470	18012	14851	-3161
NIBE F110 with electric space heating	14212	11818	-2394
Nilan Compact P Nordic with electric sapce heating	15288	12662	-2626
Kautokeino			
Only electric heating system	23432	21765	-1667
Electric heating system with passive heat recovery	18160	16198	-1962
NIBE F470	23434	20373	-3161
NIBE F110 with electric space heating	19461	17067	-2394
Nilan Compact P Nordic with electric sapce heating	20068	17442	-2626

6.4.3 The Enova grant

The grant from Enova is an initiative that support investment into energy efficient solutions in Norway. It is not guaranteed that it will be so forever and one may not get similar support in other countries. Table 6.7 shows the difference in annual cost for the three heat pump solutions. The lifetime is set to 15 years.

Table 6.7: Enova grant, annual value

	Enova grant, annual value [NOK/year]
NIBE F470	1703
NIBE F110 with electric space heating	839
Nilan Compact P Nordic with electric space heating	2058

Nilan Compact P Nordic is the most expensive heat pump unit, which relate to the largest grant from Enova. Comparing total annual cost, the unit from Nilan will be more expensive than using only electric heaters for a building in Trondheim.

Chapter 7:
Discussion

The discussion in this chapter will center on modeling in IDA ICE, the results regarding the commercial products, and strengths and weaknesses in the simulations. Future trends in the field and the application of exhaust heat pumps in modern buildings will also be discussed.

7.1 Modeling in IDA ICE

7.1.1 Building model

IDA ICE have many tools to create a realistic model of a house for simulation. As a result, the building will behave very close to what is expected during simulation. The house meets the requirements for a passive house located in Trondheim. Because of ventilation, the indoor air quality is good with CO_2 concentration well beneath TEK 10 recommendation in all simulations [07].

Simulation results show that the indoor temperature is for some periods above the setpoint. The period were this could occur differs between the two climates. Temperatures above the setpoint can occur in Trondheim between April and September, and between late May and August in Kautokeino. There is high outdoor temperatures and high solar gains during the summer in Norway. Kautokeino is further north than the polar circle and will have the sun up for the entire 24 hours of the day during the summer. Automatic window shading reduces solar gains and will have an impact for the indoor temperature. Such systems are not normal in small residential houses however. Occupants in the building will normally control the window shading and opening in order to fit their comfort levels. The indoor temperature can be expected to go higher than simulated when the occupants are not at home.

The hydronic heating system for the building in the simulation is set to have a supply temperature of 45 ^oC and a return temperature of 35 ^oC. Average values during the simulation period is 40 ^oC supply and 25 ^oC return for the building in both Trondheim and Kautokeino. Since the temperature levels in the heating system is about the same for both climates, one can assume that it is not the heating demand that cause the temperature to drop below the set value. It is possible that there is configurations in the model that can change this. The default value for the heating system for a model in IDA ICE is 50 ^oC supply and 20 ^oC return, which is not the temperature levels shown by the results either.

7.1.2 Heating plant

The overall customization of the plant in IDA ICE is one of the program’s strong points. In the schematics for the plant in IDA ICE, one can have heating units and hot water storage tanks mimic how heating is supplied in accordance with commercial solutions.

The water used for space heating and DHW comes out of the same hot water tank in some simulations. This is the way that the hot water tank is set up for heat pump simulations, where the heat pump is used for heating DHW and the zones. It is not possible to use a double-mantled water tank, as NIBE F470 is shown to use [25]. Double-mantled tanks is a common method for combining hydronic space heating and DHW in one compact unit. The low return temperature from the space heating that was mentioned above, will affect the temperature at the bottom of the hot water tank. The temperature at the bottom of the tank is the inlet temperature to the heat pump, resulting in a large temperature difference between the inlet and the outlet for the water in the heat pump.

PI-controllers and temperature sensors is used to control the heat pump and the electric peak-load heater. The temperature sensors measures temperature of the water in the hot water storage tank. Both the heat pump and the electric heater have water pumped from the bottom of the tank and back into the top. It is how a heat pump normally heats water, but the electric heating element is normally place inside the hot water tank.

The heat pump parameters were set according to the heat pumps from NIBE and Nilan in the main simulation. There are some limitations to IDA ICE’s heat pump model however. On can for example not set which working fluid the heat pump uses. And it does not look like IDA ICE’s heat pump model account for overheat since the only temperature outputs is condensation and evaporation temperatures. However, the heat pump seem to respond as one would expect, for example when the heat source is very limited such as it is for the simulations of NIBE F110 and Nilan Compact P Nordic in Kautokeino.

Some of the parameters in the heat pump menu were tested in chapter 5.4. One of the parameters that was not presented there was the LMTD for the condenser and evaporator. They were tested, but the testing gave little response in the result. This is caused by that the heat pump operated with the condensation temperature and evaporation temperature well inside the allowed range. Changing the LMTD for the condenser or the evaporator did little to the performance of the heat pump unless the condensation- or evaporation temperature reached their limits.

7.2 Exhaust heat pump products

All three products that were simulated are compact units that is a good fit for supplying modern buildings with heating. There are many options when designing a heating system for a house, and if the design is good and tailored for local climate, one will probably be happy with the result.

NIBE F470 represent the complete solution that can supply both heating for DHW and the building space. The simulations show that delivered energy for heating and ventilation is lower for NIBE F470 than only passive heat recovery in Trondheim, but not in Kautokeino. The two other products, being hybrid systems, have a lower energy demand than the F470 in both climates. NIBE F470 is the most expensive system because of the energy demand, price of the unit and that it requires a hydronic heating system.

A positive with the F470 that is not explored further in this paper, is that after its lifetime, one have more choice for replacement since the building has hydronic heating. Given that, the hydronic heating system has a longer lifetime. A negative to the F470 is that it is more vulnerable to malfunctions, since it covers the entire heating demand. However, the additional heating output of the electric heater has a high capacity and can supply heating if the heat pump side of the unit malfunctions.

NIBE F110 is a unit that supplies heating for DHW only. The combination of NIBE F110, passive heat recovery and electric space heating is the cheapest option of the three units. The system with electric space heating with passive heat recovery was the cheapest of the five options. The system with the F110 had the second lowest energy demand in both climates.

Results from the simulations in Kautokeino showed that the heat pump in the F110 unit was not utilized very much. In addition, the difference of delivered energy for F110 and the system with passive heat recovery and electric heaters is very small. Frost protection in the simulations were done by setting the minimum discharge temperature to 5 °C. When that limit were reduced, one could see that there was potential in the unit. NIBE F110 can work with outside air down to -10 °C as a heat source, and it would probably give better result for the climate in Kautokeino.

The simulations in IDA ICE show that the EAHP Compact P Nordic from Nilan in combination with electric space heating had the lowest energy demand. However, because the unit is the most expensive, its total cost was the third cheapest of the five systems analyzed. The heat pump in the product from Nilan has the same problem that NIBE F110 has in the simulation in Kautokeino.

Nilan Compact P Nordic supplies heating for DHW and heating of ventilation air. Simulating for the climate in Kautokeino with frost protection, the electric heater in the Compact P Nordic unit was dimensioned too small for some periods. In order for the system to supply heating for DHW and the supply air, one needed to increase the maximum effect of the electric heater in the Compact unit.

7.3 Exhaust air heat pumps in modern buildings

The exhaust air heat pump can work very well in Norway and will most likely have good results in modern ventilated buildings with DHW being a large part of the heat demand. The simulations have shown that passive heat recovery is both very energy efficient and efficient in the sense of economics. Combining passive heat recovery and EAHP in the cold climate of northern Norway should however be done differently than in the simulations. Hybrid systems can possibly be even more attractive for climates warmer than Norway.

Combining the exhaust air with another heat source is not fully investigated in this paper. Especially for larger buildings (>200 m^2) can utilize the combination of heat sources very well. Nilan has some products that combines either heat from outdoor air or the ground with exhaust air.

A model was worked on for this report that used a mix of outdoor air and exhaust air as a heat source for a heat pump. The results from simulations showed that the effect the additional heat source had on the heat pump did not outweigh the energy needed to run the fan to supply outdoor air into the system. Another way to introduce outside air as an additional heat source is to set up a separate heat pump with outdoor air as heat source.

Heat pumps that uses CO_2 as working fluid is a hot topic in new research, and the way that modern buildings are going will benefit CO_2 heat pumps. CO_2 heat pumps are still young on the market, so there a few products on the market today. Splitting up the heating unit of the heat pump, by including a de-superheater and internal heat exchanger, is also a very interesting method of supplying heat that is not investigated in this paper. This is also relevant for CO_2 heat pumps by using a tripartite gas cooler.

Research are done in the field every day. New technologies for EAHP and new products on the market will make the units both cheaper to make and more robust. The sensitivity analysis in LCCWeb shows that longer lifetime can change the order of most cost efficient system.

Chapter 8: Conclusion

The focus of the report were to compare energy efficiency of different heat recovery solutions in a residential building. Simulations were carried out in IDA ICE for five systems in order to investigate their performances:

- A reference system with only electric heating
- Passive heat recovery combined with electric heating
- Products from NIBE:
    - F470
    - F110, with electric heaters for space heating
- Products from Nilan
    - Compact P Nordic, with electric heaters for space heating

The systems were compared for two climates, Trondheim and Kautokeino.

Delivered energy for heating and ventilation from the simulation results was used in a LCC comparison between the different solutions. Investment costs for the different products, ventilation and heating systems were investigated for this analysis. Here is a list of the most important conclusions from this report:

- The hybrid heat-recovery solution with Compact P Nordic from Nilan is the most energy efficient system. Second most efficient were the system with F110 from NIBE, which was also set up as a hybrid heat-recovery solution.

- NIBE F470 is more energy efficient than a system with only passive heat-recovery in Trondheim, but not in Kautokeino.

- The results from the Life Cycle Costing comparison show that the cheapest solution is to use passive heat recovery with electric heaters for space heating. A system with F110 from NIBE is the second cheapest solution.

- Simulation without any limitations to the discharge air temperature will have very low discharge air temperatures over long periods, especially in Kautokeino. Actual frost formation cannot be simulated in IDA ICE. But simulations without the limit shows a sizable increase in the efficiency of the hybrid heat recovery system.

- The expected lifetime of the heating system will affect the life cycle cost. It can be expected that in the future heat pumps will be more robust and have a longer lifetime. Exhaust air heat pumps are expensive units compared to a passive heat recovery unit and can end up costing less than the alternative with a longer lifetime.

- Adding outdoor air as an additional heat source for the heat pump by mixing it with the exhaust ventilation air, after eventual passive heat recovery, turned out not to be an efficient solution. Simulation results showed that the extra effect from the heat pump would not make the system efficient enough to make up for the energy required to run the fan supplying outdoor air.

- In order to have a heating system that is both energy efficient and have reasonable costs, the most important is to design the system according to the buildings demand and the local climate. Having a larger heat pump than what is needed will cost more, and the heat pump will be less efficient or turned off when the heating demand is lower than design conditions. Simulation tools such as IDA ICE can be used to indicate which systems that will have good results.

Chapter 9: Suggestion for further work

Energy efficiency in highly insulated buildings is a large field and this report has focused on a part of that subject being heat recover a heat exchanger and/or a heat pump. Further work can go in several directions.

Further work could look into other system solutions and compare to the systems that were analyzed here. There is district-heating plants in all the major cities in Norway that could be a system to pair with passive heat recovery. Other heat pump systems with a different heat source could also be compared.

The exhaust heat pump model could also be further expanded to work with additional heat source such as outside air, solar heating and heat from the ground. Mixing of outside air and exhaust air were tried out in this report, but were less efficient than other solutions. One could have a separate heat pump unit that uses outdoor air as a heat source. Nilan have heat pumps that utilize additional heat sources, one should investigate how they functions.

This report only looked at a single residential house for four people. A block of flats or a large office building will have a very different heating demand. Using EAHP for other buildings could be interesting, especially buildings with a larger relative DHW demand.

The matlab script for the CO_2 heat pump should be improved. Implementing a control system could open up opportunities for the model to operate without some of the assumptions that the model has. Investigations into how a CO_2 heat pump is actually controlled should be done. The heat pump model could also be modified to use other types of working fluids.

Both energy efficiency and costs were investigated in this report. Environmental impact is also an aspect that could be investigated with a life cycle assessment (LCA).

Bibliography

[01] Norwegian Building Authority. 2015. "Norwegian building code (TEK 10), Chapter 14: Energy."

[02] Statistics Norway. 2014. *Energy consumption in households, 2012.* July 14. Accessed Febuary 19, 2016. https://www.ssb.no/en/energi-og-industri/statistikker/husenergi.

[03] Norwegian Building Authority. 2015. *Nye energikrav fra 1.1.2016.* December 21. Accessed February 19, 2016. https://www.dibk.no/no/Om_oss/Arkiv/Nyhetsarkiv/nye-energikrav-fra-1.1.2016/.

[04] Enova. n.d. *Dagens standard of fremtidens boliger.* Accessed May 17, 2016. http://www.enova.no/radgivning/privat/energismarte-rad-for-din-bolig/fremtidens-bolig/nullhus-plusshus-og-passivhus/174/0/.

[05] Standards Norway. 2013. "Norsk Standard NS 3700: 2013."

[06] Norwegian Building Authority. 2007. "Veiledning til Tekninsk Forskrift til Plan- og Byggningsloven 1997 (TEK 07)."

[07] Norwegian Building Authority. 2016. *Byggteknisk forskrift (TEK 10).* January 01. Accessed May 17, 2016. http://dibk.no/no/byggeregler/tek/3/14/14-2/.

[08] Mathisen, Hans Martin. 2014. "Ventilation and heat recovery, Lecture TEP4235 autum 2015."

[09] Maria Justo Alonso, Peng Liu, Hans M. Mathisen, Gaoming Ge, Carey Simonson. 2014. "Review of heat/energy recovery exchangers for use in ZEBs in cold climate countries."

[10] Mats Fehrm, Wilhelm Reiners, Matthias Ungemach. 2001. "Exhaust air heat recovery in buildings."

[11] Alo Mikola, Teet-Andrus Kõiv. 2014. "The Efficiency Analysis of the Exhaust."

[12] Jørn Stene. 2015. "Ammonia (R717) as working fluid in heat pumps, Lecture TEP16."

[13] Gian Vincenzo Fracastoro, Matteo Serraino. 2010. "Energy analyses of buildings equipped with exhaust air heat pumps (EAHP)."

[14] Wikipedia. 2015. *Legionella.* 9 27. Accessed 11 12, 2015. https://en.wikipedia.org/wiki/Legionella.

[15] Jørn Stene. 2004. "Residential CO2 heat pump system for combined space heating and hot water heating."

[16] Jørn Stene. 2014. "Working Fluids (Refrigerants) for The Heat Pump Cycle, Lecture TEP4260."

[17] Stene, Jørn. 2015. "Carbon Dioxide(R744) as a Working Fluid in Heat Pumps, Lecture TEP16."

[18] International Institute of Refrigeration. 2016. *EU F-Gas Regulation phase-down: BRA stresses the vital part of reclaimed/recycled HFCs.* May 03. Accessed May 17, 2016. http://www.iifiir.org/clientbookline/service/reference.asp?output=PORTAL&INSTANCE=EXPLOITATION&DOCBASE=IFD_REFDOC_EN&DOCID=IFD_REFDOC_0017684&PORTAL_ID=erm_portal_news.xml.

[19] International Institute of Refrigeration. 2016. *Paris Agreement signed and the OEWG37 makes headway.* April 26. Accessed May 17, 2016.

http://www.iifiir.org/clientBookline/service/reference.asp?INSTANCE=EXPLOITATION&OUTPUT=PORTAL&DOCID=IFD_REFDOC_0017519&DOCBASE=IFD_REFDOC_EN&SETLANGUAGE=EN.

[20] Wikipedia. 2016. *Paris Agreement.* May 14. Accessed May 17, 2016. https://en.wikipedia.org/wiki/Paris_Agreement.

[21] Jørn Stene. 2014. "Arbeidsmedier (kuldemedier) for varmepumpeprosessen, Lecture TEP4260."

[22] Atle Solberg. 2015. "Heat recovery in combination with different heat pump solutions for energy supply."

[23] NIBE. n.d. *Avtrekksvarmepumpe | NIBE F470 | NIBE.* Accessed May 18, 2016. http://www.nibe.no/produkter/avtrekksvarmepumper/nibe-f470/.

[24] NIBE. n.d. "Frånluftsvärmepump NIBE F470, Produktbrosjyre."

[25] NIBE. n.d. "Installatørhåndbok NIBE F470 avtrekksvarmepumpe."

[26] NIBE. n.d. *Avtekksvarmepumpe | NIBE F110 | NIBE.* Accessed May 18, 2016. http://www.nibe.no/produkter/avtrekksvarmepumper/nibe-f110/.

[27] NIBE. n.d. "Installatørhåndbok NIBE F110 varmepumpe."

[28] Nilan. n.d. *How our Compact P solution work.* Accessed May 18, 2016. http://www.nilan.dk/Default.aspx?ID=2525.

[29] Nilan. n.d. "Produktdata Compact P Nordic serien by Nilan."

[30] COWI. 2012. "Faktastudie - kostnader for elektrisk og vassboren oppvarming."

[31] Ole Smedegård. 2012. "Analyse av forenkla vassborne varmedistribusjonssystem for større bygningar."

[32] Statistics Norway. 2015. *Boforhold, levekårsundersøkelsen, 2015.* November 25. Accessed May 18, 2016. https://www.ssb.no/bygg-bolig-og-eiendom/statistikker/bo/hvert-3-aar/2015-11-25.

[33] International Institute of Refrigeration. n.d. *What's in Fridoc?* Accessed May 18, 2016. http://www.iifiir.org/medias/medias.aspx?INSTANCE=exploitation&PORTAL_ID=portal_model_instance__fridoc_decouvrir_en.xml&SYNCMENU=DECOUVRIR_FRIDOC&SETLANGUAGE=EN.

[34] International Institute of Refrigeration. n.d. *A cool offer at the IIR.* Accessed May 18, 2016. http://www.iifiir.org/clientBookline/service/reference.asp?INSTANCE=EXPLOITATION&OUTPUT=PORTAL&DOCID=IFD_REFDOC_0011474&DOCBASE=IFD_REFDOC_EN&SETLANGUAGE=EN.

[35] Long Ni, Jiankai Dong, Yang Yao, Chao Shen, Dehu Qv, Xuedan Zhang. 2015. "A review of heat pump systems for heating and cooling of buildings in China in the last decade."

[36] M. Shan, T. Yu, X. Yang. 2015. "Assessment of an integrated active solar and air-source heat pump water heating system operated within a passive house in a cold climate zone."

[37] Standards Norway. 2014. "Norsk Standard NS 3031: 2014."

[38] Haitao Hu, Trygve Magne Eikevik, Petter Neksa, Armin Hafner, Guoliang Ding, Qingnan Huang, Jingjing Ye a. 2015. "Performance analysis of an R744 ground source heat pump system with air-cooled and water-cooled gas coolers."

[39] Jian-Fei Zhang, Yan Qin, Chi-Chuan Wang. 2015. "Review on CO2 heat pump water heater for residential use in Japan."

[40] European Commission. 2016. *EU legislation to control F-gases - European Commission.* May 13. Accessed May 18, 2016. http://ec.europa.eu/clima/policies/f-gas/legislation/index_en.htm.

[41] F.Z. Zhang, P.X. Jiang, Y.H. Zhu, S.S. Sun. 2014. "System optimization of CO2 heat pump water heater based on economy."

[42] Nicolandrea Calabrese, Rita Mastrullo, Alfonso William Mauro, Paola Rovella. 2014. "Performance analysis of a rooftop, air-to-air heat pump working with."

[43] Nils Eivind Eriksen. 2014. "Study of Refrigerants for Heat Pumps in Colder Climates."

[44] M. Pitarch, E. Navarro-Peris, J. Gonzalves, JM. Corberan. 2014. "Analysis and optimization of different two stage transcritical carbon dioxide cycles for heating applications."

[45] Silvia Minetto, Luca Cecchinato, Riccardo Brignoli, Sergio Marinetti, Antonio Rossetti. 2015. "Water-side reversible CO2 heat pump for residential application."

[46] Lixing Zheng, Jianqiang Deng, Yang He, Peixue Jiang. 2015. "Dynamic model of a transcritical CO2 ejector expansion refrigeration system."

[47] EQUA Simulation AB. 2015. *History - EQUA- Building and Tunnel simulations.* Accessed 06 07, 2016. http://www.equa.se/en/about-us/history.

[48] Anders Kirkhus, SINTEF Byggforsk. 2012. "Yttervegger i passivhus - BYGNINGSFYSIKK.NO." November 21. Accessed June 07, 2016. http://www.bygningsfysikk.no/NorskBygningsfysikkdag2012/06_Kirkhus.pdf.

[49] EQUA Simulation Technology Group. 2013. "IDA Early Stage Building Optimization (ESBO) User guide." October. Accessed June 07, 2016. http://www.equaonline.com/esbo/IDAESBOUserguide.pdf.

[50] SINTEF Byggforsk. 2002. "552.340 Varmegjenvinnere i ventilasjonsanlegg." Accessed June 17, 2016. https://bks.byggforsk.no/DocumentView.aspx?documentId=537&sectionId=2.

[51] Jørn Stene. 2014. "Komponenter for varmepumpeaggregater, lecture TEP 4260."

[52] NIBE. n.d. *Om NIBE | NIBE.* Accessed June 22, 2016. http://www.nibe.no/om-nibe/.

[53] Forsvarsbygg, Statsbygg. 2011. *LCCWeb.* August 12. Accessed June 22, 2016. http://www.lccweb.no/.

[54] Standard Online AS. 2015. *NS 3454 Livssykluskostnader for byggverk.* June 07. Accessed June 22, 2016. http://www.standard.no/no/nyheter/nyhetsarkiv/bygg-anlegg-og-eiendom/2013/ns-3454-livssykluskostnader-for-byggverk/?gclid=CIaw1ojP6MwCFYcocgodeQcGjQ.

[55] Trønderenergi. n.d. *Garantipris - TrønderEnergi.* Accessed June 22, 2016. https://tronderenergi.no/produkter/garantipris.

[56] Trønderenergi. n.d. *Priser fra 1. Jan 2016 - TrønderEnergi.* Accessed June 22, 2016. https://tronderenerginett.no/nettleie/privat/priser-fra-1.jan-2016.

[57] Husbanken. 2016. *Kalkulasjonsrenten Husbanken.* January 06. Accessed June 22, 2016. http://www.husbanken.no/rente/kalkulasjonsrenten/.

[58] Comfort. n.d. *Super S 200 Boligbreder.* Accessed June 22, 2016. http://www.comfort.no/varme-og-inneklima/varmtvannsbereder/boligbereder/super-s-200-boligbereder.

[59] Christian O. Arnsen, ABK. 2016. "Conversation over phone." March 01.

[60] Per Erik Hansen, Nilan Norge. 2016. "Conversation over phone." March 02.

[61] Norconsult. 2015. "Energikonsept boligblokk, Kringstadvegen 1."

[62] Enova. n.d. *Tilskudd for avtrekksvarmepumpe.* Accessed June 22, 2016. http://www.enova.no/finansiering/privat/enovatilskuddet-/avtrekksvarmepumpe/tilskudd-for-avtrekksvarmepumpe/907/1972/.

[63] Enova. n.d. *Våre tilbud - Enova.* Accessed June 22, 2016. http://www.enova.no/finansiering/privat/slik-stotter-vi-deg/vare-tilbud/904/0/.

[64] Joakim Miksand, System air. 2016. "Conversation by phone." April 01.

[65] Jon Dehli, Flexit. 2016. "Converation by phone." April 01.

[66] Sturla Nergård, Økovent. 2016. "Converation by phone." April 01.

[67] Ole Smedegård. 2016. "Conversation by phone." March 01.

[68] Husbanken. n.d. *Renter - Husbanken.* Accessed June 22, 2016. http://www.husbanken.no/rente/.

[Fig01] Wikimedia Commons. 2007. *File: Rotary-heat-exchanger.svg.* November 11. Accessed May 17, 2016. https://commons.wikimedia.org/wiki/File:Rotary-heat-exchanger.svg.

[Fig02] Wikimedia Commons. 2012. *File: Heat exchanger.svg.* June 30. Accessed May 17, 2016. https://commons.wikimedia.org/wiki/File:Heat_exchanger.svg.

[Fig03] Jørn Stene. 2014. "Heat Pumps in Passive house Buildings - Residential Buildings, Lecture TEP16."

[Fig04] Jørn Stene. 2014. "Termodynamikk for varmepumpeprosessen, Lecture TEP4260."

[Fig05] Jørn Stene. 2015. "Carbon Dioxide(R744) as a Working Fluid in Heat Pumps, Lecture TEP16."

[Fig06] Jørn Stene. 2004. "Residential CO2 heat pump system for combined space heating and hot water heating."

Appendix

A.1 Product comparison

Table A:1.1: Product comparison [25][27][29]

	Nibe, F470	**Nibe, F110**	**Nilan, Compact P Nordic**
Dimensions			
Width/Depth/Height [mm]	600/616/2270	600/605/2110	900/610/2000
Ventialasion duct diameter [mm]	125	160	160
Capacity			
Heat pump heating capacity [kW]	1,9 – 2,2**	1,08 or 1,32***	3,2
Max additional electric heating [kW]	10,0	1,3	1,5
DHW tank volume [liter]	170	265	175
Space heating tank volume [liter]	70	-	-
Refrigeration circuit			
Refrigerant	R290 (propane)	R134a	R134a

*Indoor installation and then outdoor installation
**Dependent on air flow, varies from 110 m^3/h to 200 m^3/h
***Dependent on heat source, 1,08 when use outside air, 1,32 if use exhaust air

A.2 Window shading control

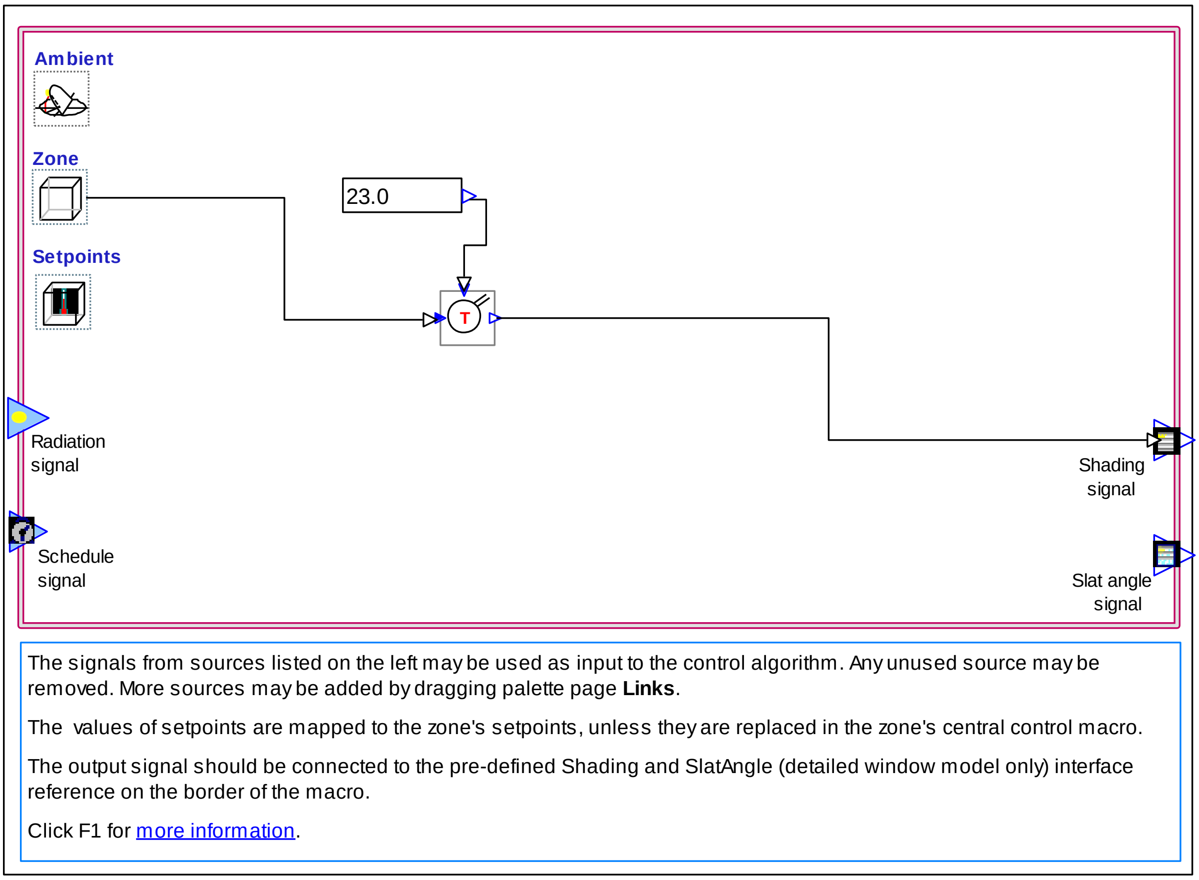

Figure A.2.1: Macro to control window shading [22]

A.3 Response from EQUA about building an exhaust air heat pump in IDA ICE

Jörgen Eriksson posted an answer.

Answered by Jörgen Eriksson:

Use ESBO plant to simulate Exhaust air heat pump.

Make sure you have radiators or similar for zone heating, ideal heaters will not work now! Instruction

1. Change to ESBO plant by click on replace on general tab: Replace>>Plant>>ESBO-Plant. Replace is located just below the HVAC Systems.
2. Open ESBO-Plant and drag a "Brine to water heat pump". Remove the chiller by clicking on the trash bin of the "generic electric chiller". Set the volume of the cold tank to 20 liters, as volume of the pipes on the cold side.
3. Double click on the heat pump component to open it and select heat pump model in the database or ad values as preferred.
4. Set the warm tank to preferred volume.
5. Use the standard AHU, set the efficiencies of the Heat exchange and heating coil to 0 Disconnect the cooling coil from supply side and place it in the exhaust air stream.

To flip the cooling coil, "right click>>Properties>>Symmetry>>FLIP". Disconnect the set point of the coil and a constant to set the preferred leaving temperature. Open the coil and eventually change the efficiency and the temperature rise.

1. Open the plant, build model (in the upper right corner of the plant form)
2. Open the schematic view of the plant. At the "Brine" area set the constant to 3 (instead of 7) and open the pump and set the parameter MFNOM=1 (or what is needed)

Open the component "Coldrecovery" located just left of the warm tank below the heat pump. Set MNOM=1(or what is needed) and Tmin=-50 deg

Open the cold tank and set the parameter UAHX[1:1]=10000.(heat exchanger)

1. Before simulate log "plant details" (simulation tab). Look at Base heating to check the performance of the heat pump.

If you want to have an outdoor air unit, in point 2 above, drag an Ambient heat exchanger into the plant and size it. It will automatically work together with the heat pump but perhaps you have change some small details to make it work as you like.

In reply to maria alonso's question: Exhaust Air heat pump

We are simulating an exhaust air heat pump for cold climate to produce both domestic hot water and space heating Does someone have a piece of advice /experience which can help us?. We would also like to get advice about how to mix teh exhaust air and outdoors air as heat source Thanks!

======= Full thread summary =======

Question : Exhaust Air heat pump

Asked by maria alonso:

We are simulating an exhaust air heat pump for cold climate to produce both domestic hot water and space heating Does someone have a piece of advice /experience which can help us?. We would also like to get advice about how to mix teh exhaust air and outdoors air as heat source Thanks!

Please note - you can easily change how often you receive these notifications or unsubscribe. Thank you for your interest in our forum!

Sincerely,
The EQUA Team

A.4 IDA ICE plants and AHU

A.4.1 AHU for an exhaust heat pump

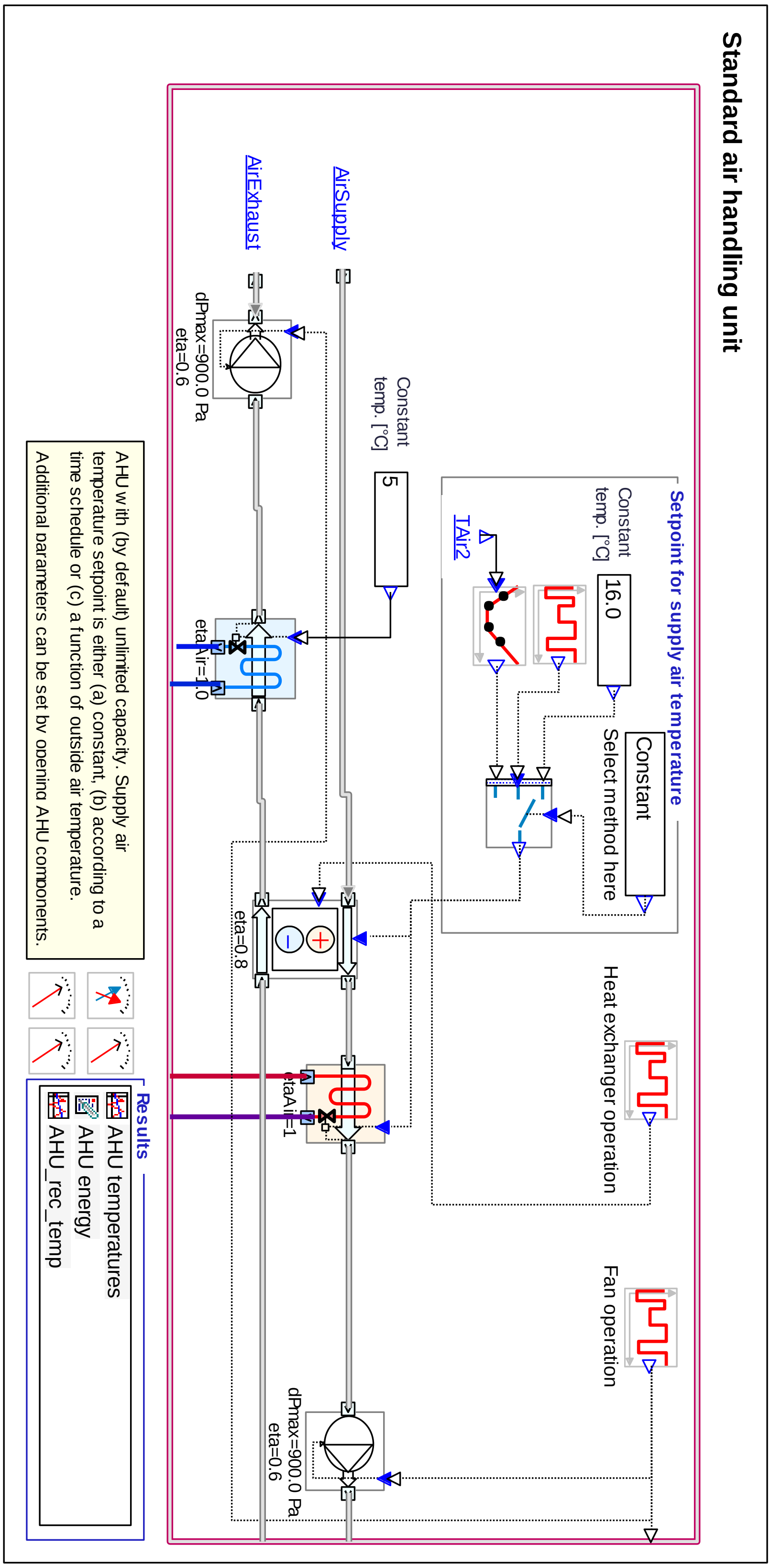

Figure A.4.1; Air handling unit for an exhaust heat pump

A.4.2 NIBE F470 Plant

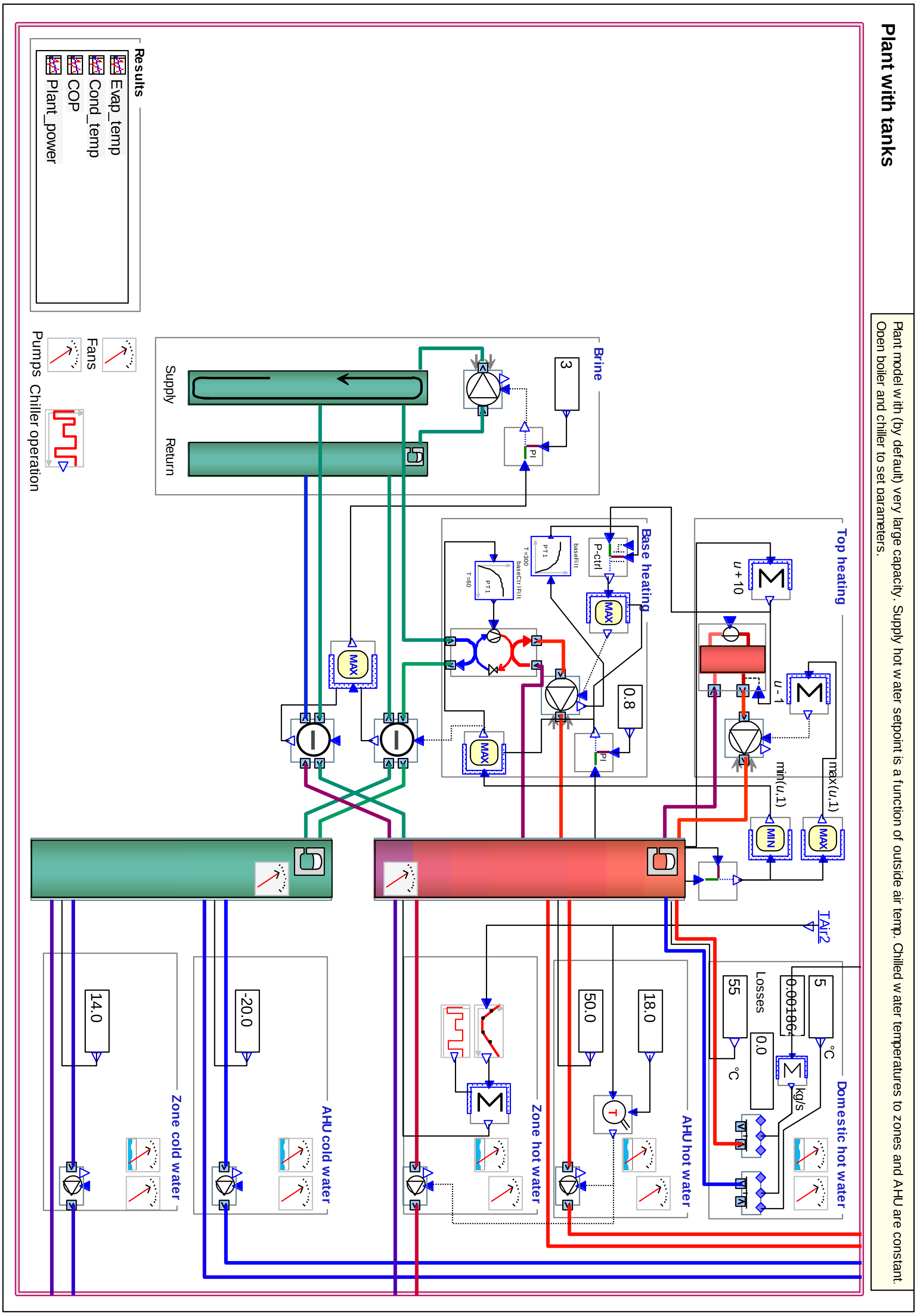

Figure A:4.2: NIBE F470 plant

A.4.3 NIBE F110 and Nilan Compact P Nordic Plant

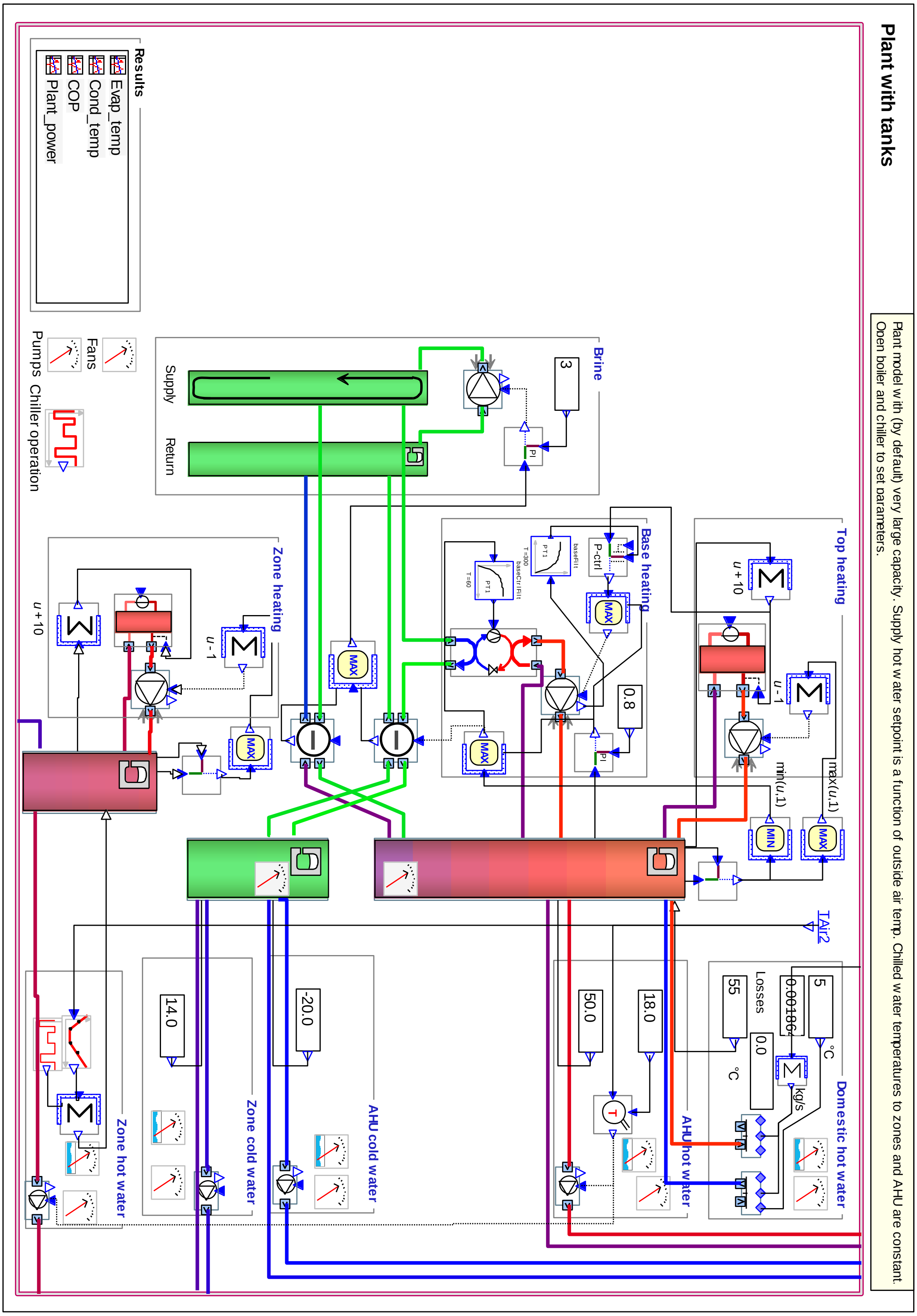

Figure A.4.3: NIBE F110 and Nilan Compact P Nordic plant

A.4.4 AHU with outdoor air as an additional heat source

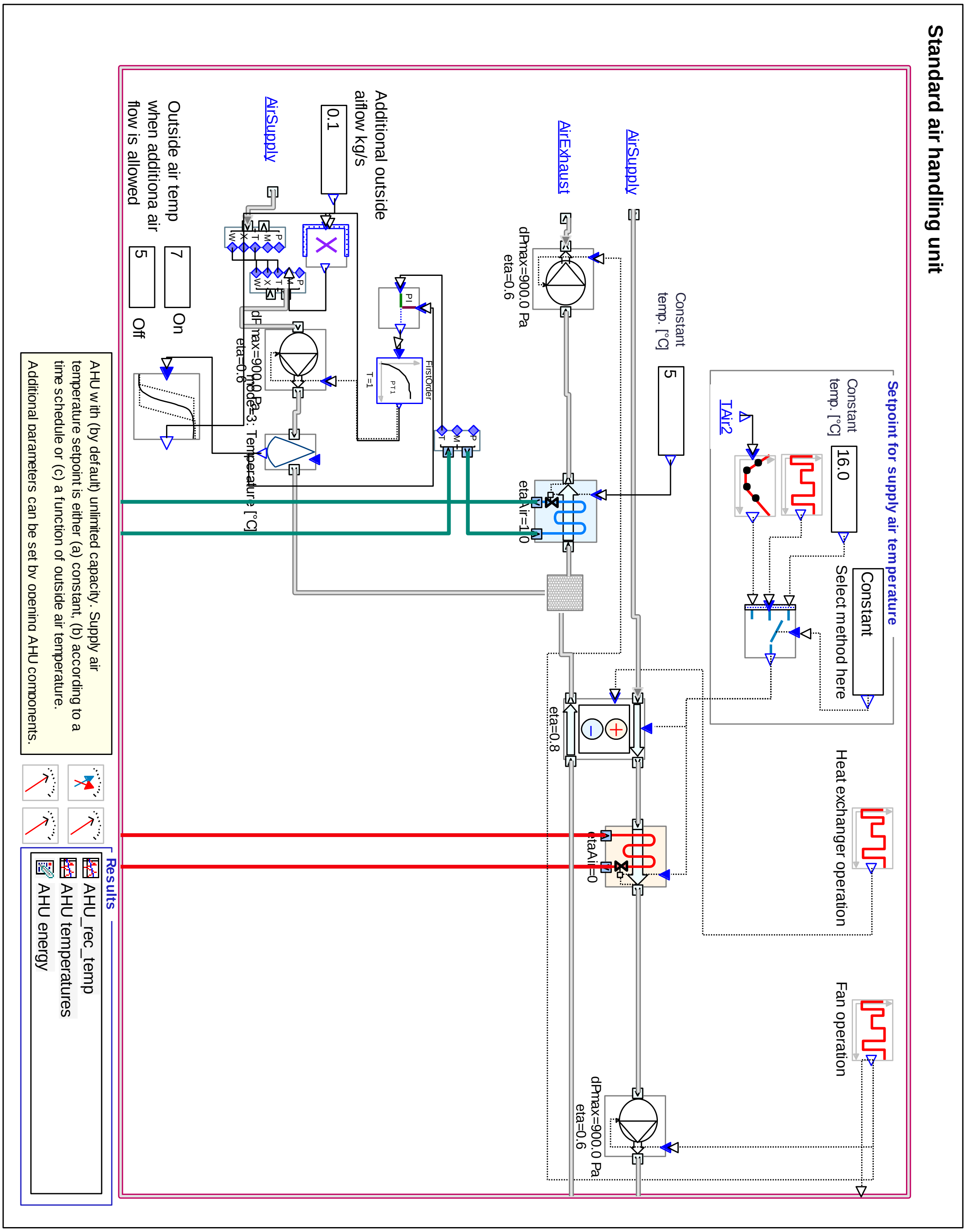

Figure A.4.4: AHU with outdoor air as an additional heat source

A.4.5 Plant that is used to make input for matlab model

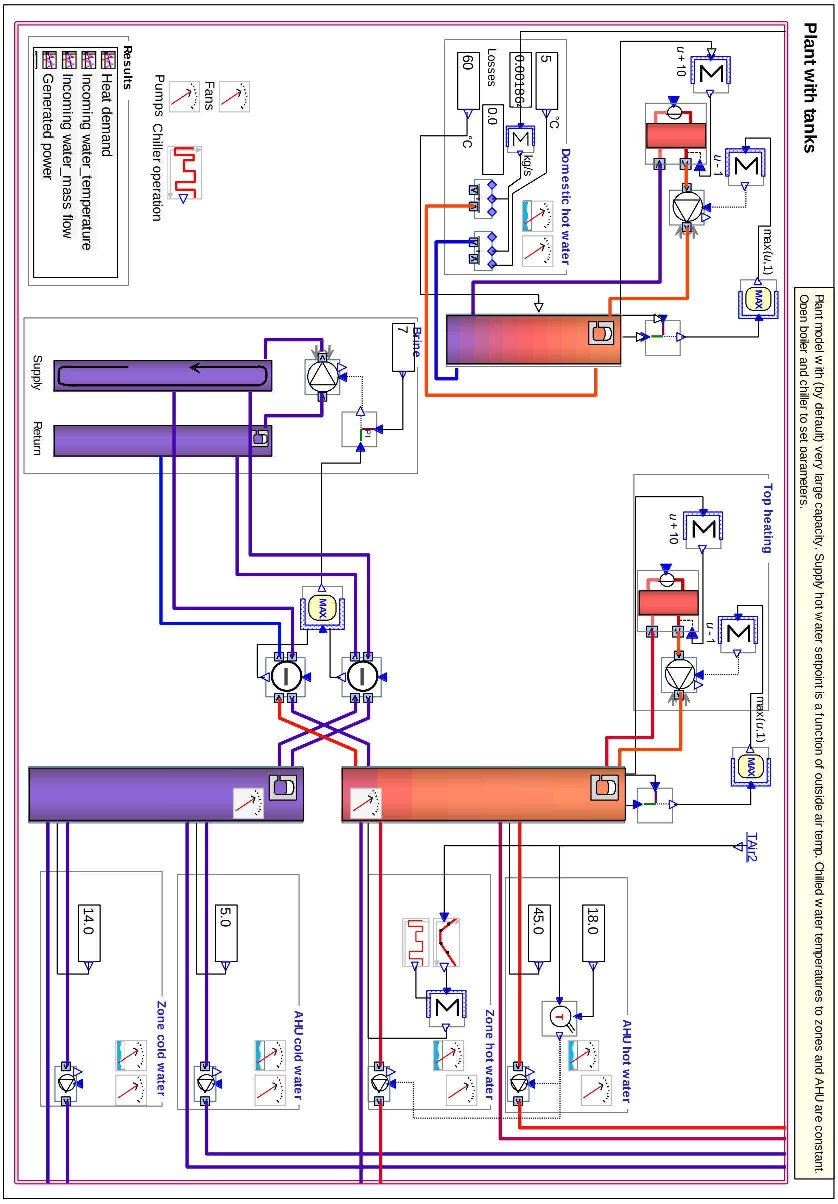

Figure A.4.5: Plant that is used to make input for matlab model

B.2 A guide to Heat pump Matlab script

main.m

- Main file
- **Line 0-53:** Takes input from Excel files in the folder “input”. Sets up parameters used in calculations
    - **Using:** *parameters.m, constants.m, preallocation.m*
- **Line 55-84:** Checking for error in input
- **Line 86-88:** Calculate temperature of water entering gas cooler
- **Line 90-95:** If the choice to use outside air as an heat source, the temperature of outdoor air after being drawn thorough the fan and the fan power usage is calculated
- **Line 97-107:** Fix parameters (Temperature and flow of the air that goes into the evaporator) in the case that outdoor air is chosen to be the only heat source for the heat pump. Also, set some of the activation factors so the rest of the script will work.
- **Line 145-403:** This loop runs through every time-step
    - **Line 148-152:** Guesses an initial value for the discharge air temperature, and sets parameters so the iteration can start
    - **Line 154-208:** Calculates heat pump circuit states by iterating the discharge air temperature until the calculated values fit the heat pump unit defined in parameters.m. In the case that both outside air and exhaust air is chosen as heat source, this calculation only uses the exhaust air.
        - **Line 156-163:** Heating input and output, and key heat pump parameters for the input values at given time step and guessed discharge air temperature. Uses the function themodynamics.m
        - **Line 165-186:** Rough assumptions made for the discharge temperature. This temperature is adjusted in the while loop by the following method:
            - **Higher if:**
                - CO_2 discharge temperature (after comp.) is too high **or** compressor volume to high **or** heat delivered is too high, **while** the compressor volume is above minimum.
            - **Lower if:**
                - Both compressor volume is to small and CO_2 discharge temperature is at accepted level
                - If it fails both of the two test mentioned it is also lowered
        - **Line 189-191:** The test ends if change in discharge temperature is lower than a specified minimum
        - **Line 193-203:** Turns off the heat pump if the heat demand is too low for heat to be recovered
    - **Line 210-217:** If heat delivered from gas cooler is too high after iterations, parameters are adjusted. Q_gas-cooler, Q_evaporator, compressor- and fan work are scaled down to only cover the demand, other parameters stay the same
    - **Line 220-232:** If compressor volume is below minimum, the heat pump turns off.
    - **Line 237-323 : If both outside air and exhaust air as heat source**
    - **Line 237-323:** Does the same as line 148-232, but the air going into the evaporator is now a mix of both outside air and exhaust air. The size of the flow of outside air is defined in parameters.m

  - **Line 328-353**: Compare the results with and without outside air used as additional heat source at every time step
  - **Line 357-369:** Check if COP is less than 1 (can happen in case of outside air only sometimes) and turn off HP if it is less than 1.
  - **Line 371-375:** If HP has been turned off at some point, here some factors that verify that is set.
  - **Line 379-397:** Calculates heat recovery and possible heat recovery. Happens as long as exhaust air is warmer than outside air
  - **Line 399-401:** Clean command window and print a progress report before calculations for the next hour is calculated.
  - Back to **line 145.**
- **Line 405-408:** Correct fan power parameters if outside air is the only heat source
- **Line 411-422:** Summation of demand and consumption over the year
- **Line 425-431:** Calculates efficiencies of:
  - Heat pump recovery efficiency
  - Real heat pump recovery efficiency
  - Total heat recovery efficiency (HP + HW)
  - Real total heat recovery efficiency
- **Line 437-452:** Makes a save of the result by name defined in *parameters.m*
  - **Uses:** *clear_var.m* to delete less interesting variable before completing save

parameters.m

- Set parameters such as
  - Range
  - Name of output files
  - Min temp difference allowed
  - Compressor data
  - Evaporator data
  - Gas cooler data
  - Fans data

constants.m

- Heat capacity for air
- Kelvin-Celsius conversion
- Specific heating capacity for water

preallocations.m

- Reallocates values for more efficient memory use

thermodynamics.m

- Calculates heat rates supplied by the gas-cooler and absorbed by the evaporator, CO_2 discharge- and evaporator temperature, compressor work and CO_2 volume flow. Function inputs are:
    - Measured air handling unit air temperature at the inlet of the evaporator
    - Measured water temperature at the inlet of the gas-cooler
    - Measured air volume flow rate
    - The air discharge temperature that is guessed

- **Line 5-6:** Load constants and parameters
- **Line 8-10:** Calculate heat absorbed by the evaporator and LMTD from the measured exhaust air temperature and assumed air discharge temperature. Specific heating capacity for the air and evaporator UA-value is assumed constant and set in constants.m and parameters.m respectfully.
- **Line 12-40:** Calculates states in the heat pump process (temperature, pressure, enthalpy, entropy, specific volume) in the four points (before and after evaporator/gas-cooler).
    - 1. Outlet of evaporator and inlet if compressor:
        - Assume saturated vapor
        - Look up pressure, enthalpy, specific volume and entropy, using refpropm.m, based on temperature and saturation
    - 2.Outlet of compressor and inlet of gas cooler:
        - Uses eta_is.m to find the isentropic efficiency
        - With the isentropic efficiency (calculated from eta_is.m) and a percentage of heat loss (defined in parameters.m), the specific enthalpy at the compressor outlet is found
        - The temperature is found using refpropm.m and by assuming a constant gas cooler pressure
    - 3. Outlet of gas cooler and inlet of expansion valve:
        - Assume a given temperature difference between water and CO2 at gas cooler outlet.
        - Assumes a constant water outlet temperature
        - Assume no pressure loss
        - Find spec_enthalpy based on assumed temperature at gas cooler outlet and constant gas cooler pressure
    - 4. Between expansion valve and evaporator:
        - Assume constant specific enthalpy through expansion valve
        - Temperature and pressure is assumed constant in evaporator (temperature and pressure is the same as in state 1)
- **Line 43-48:** Calculates mass flow, CO_2 volume flow rate, heat supplied by the gas-cooler, compressor work (output parameters)
    - Uses eta_vol.m to calculate CO_2 volume flow rate

clear_var.m

- Deletes less important variable from workspace before saving the workspace

eta_is.m

- Calculates isentropic efficiency from compressor pressure ratio
- $\eta_{is} = \left(-0{,}0095 * \left(\frac{p_{gc}}{p_1}\right)^2 + 0{,}0584 * \frac{p_{gc}}{p_1} + 0{,}5712\right) * 0{,}95 + \frac{\eta_{is_{displacement}}}{100}$

eta_vol.m

- Calculates volumetric efficiency from compressor pressure ratio
- $\eta_{volumetric} = \left(-0{,}66 * \frac{p_{gc}}{p_1} + 1{,}012\right) * 0{,}95$

refprop.m

- REFPROP is a program that uses equations for the thermodynamic and transport properties to calculate the state points of fluids or mixtures [http://www.boulder.nist.gov/div838/theory/refprop/Frequently_asked_questions.htm#RefpropIsAProgram]. Refprop.m likes the program to matlab.
- This is file is downloaded from http://www.boulder.nist.gov/div838/theory/refprop/LINKING/Linking.htm

rp_proto.m and rp_proto64.m

- Is functions that help refprop.m work
- Tease files is downloaded from http://www.boulder.nist.gov/div838/theory/refprop/LINKING/Linking.htm

Refprop

http://refprop-mini.software.informer.com/9.1/

http://www.boulder.nist.gov/div838/theory/refprop/LINKING/Linking.htm