Master's thesis

NTNU
Norwegian University of Science and Technology
Faculty of Information Technology and Electrical Engineering
Department of Electric Power Engineering

Steinvoll, Simon Bjerkan

Renewable district heating using borehole heat exchange unit with CO2 heat pump

Master's thesis in Energy and the Environment
Supervisor: Novakovic, Vojislav
Co-supervisor: Dai, Yanjun
July 2022

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Simon Bjerkan Steinvoll

Spring 2022

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Department of Energy and Process Engineering

Preface

This master's thesis is written in the spring semester of 2022. The thesis is the second phase of the work conducted in relation with a pre-project completed during the autumn semester of 2021. The project work combined with this master's thesis is a major part of the final year at the study program Energy and Environmental Engineering at the Norwegian University of Science and Technology (NTNU) in Trondheim, Norway.

The aim of the master's thesis is to contribute to ChiNoZEN, a cooperation project between among others, NTNU and Shanghai Jiao Tong University (SJTU), by researching a heat supply system for district heating consisting of a deep borehole heat exchanger in combination with a CO2 heat pump.

I would like to thank my supervisors, Prof. Vojislav Novakovic and Prof. Yanjun Dai. They have helped me throughout the semester with any questions I had and for general motivation. I also want to thank Prof. Trygve Eikevik and Dr. Jørn Stene for help regarding the CO2 heat pump part of the system, and Dr. Trond Slagstad for help regarding the borehole heat exchanger. Finally I want to thank Mr. Wenjie Liu, Mr. Huang Guo Rui and Mr. Mr. Yao Jian for helpful feedback and discussions throughout the semester.

Through the work on this thesis I have evolved my research, analytical and problem solving skills. I have also gained knowledge and insight in fields that were somewhat new to me. The experience on managing this sub-project has been both tough and exciting and I hope that the reader will find it enjoyable or at least learn something new.

Finally I would like to mention that even though this semester did not go as planned in terms of going to Shanghai as an exchange student, due to the pandemic, it was still nice to have regular meetings with my Chinese colleagues. This has helped me both in an academical and a social way.

Simon Bjerkan Steinvoll

Harstad, July, 2022

Norwegian University of Science and Technology

Faculty of Engineering
Department of Energy and Process Engineering

EPT-M-2022

MASTER THESIS WORK

for

student Simon Bjerkan Steinvoll

Spring 2022

Renewable district heating using borehole heat exchange unit with CO_2 heat pump

Fornybar fjernvarme som bruker borehullsvarmeveksler og CO_2 varmepumpe

Background and objective

Geothermal energy deep in the earth is a sustainable heating source, and the soil-rock temperature can reach 80 C in the depth for 2500m. It is expected to develop a borehole heat exchange unit to extract the heat for district heating, together with CO_2 heat pump system. The hydrodynamic and the heat transfer performances will be investigated, and the operation parameters will be optimized.

The master thesis assignment is related to the ongoing research project between Norway and China with the title: “Key technologies and demonstration of combined cooling, heating and power generation for low-carbon neighbourhoods/buildings with clean energy – ChiNoZEN”. The master thesis assignment is also a part of the Joint Research Centre in Sustainable Energy between NTNU and Shanghai Jiao Tong University (SJTU).

The aim of the master thesis assignment is to contribute to development of the mathematical model of the proposed system and to investigate the performance of such system under Shanghai and Trondheim climate conditions. A major part of the work should be performed as the Master thesis that is planned to be conducted at SJTU during the spring semester. If Covid situation does not allow it, some test data on bore hole performance will be provided by SJTU and the data will be used for supporting the master thesis work in Trondheim.

The following tasks are to be considered:

1. Simulation analysis of the performance of the proposed combined system using the developed mathematical model and simulation tool.
2. Validation of the simulation results with test data from SJTU lab and improvement of the mathematical model. Sensitivity analysis of the combined system performance.
3. Investigation of the feasibility of the proposed combined system under the climate of Norway and northern part of China, as well as the analysis of energy contribution and economic payback.
4. Optimization of the system performance by controlling the operation and configuration parameters.
5. Make a draft proposal (6-8 pages) for a scientific paper based on the main results of the work performed in the master thesis.

6. Make proposal for further work on the same topic.

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The master thesis work comprises 30 ECTS credits.

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

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

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

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

<u>Submission deadline:</u> July 15th, 2022

☐ Work to be done in lab (Waterpower lab, Fluid's engineering lab, Thermal engineering lab)
☐ Field work

Department for Energy and Process Engineering, February *2022*

Vojislav Novakovic
Supervisor

Co-Supervisor(s):
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Abstract

China and Norway desire to have a leading role within renewable energy technology and therefore researches ways to develop improved and more environmentally friendly systems that can reduce electricity and fossil fuel usage for heating purposes. Geothermal energy is a renewable energy source that has not yet been utilised extensively. Deep borehole heat exchangers can use high temperatures in the bedrock that are available for big scale heating systems. In combination with heat pumps it is achievable to get stable heating systems that can cover the heating and domestic hot water demand for multiple households or districts.

The objective of this Master's thesis is to contribute to the development of a district heating system that utilises heat from geothermal borehole heat exchange units in combination with CO_2 heat pumps. The chosen method to work on this system is by simulation. The performance and feasibility of the system should be investigated for Chinese and Norwegian climatic and geological conditions. Both costs and practical considerations are used for an analysis that evaluates how the system can be realised in China and Norway. For the simulation, TRNSYS will be used to build the model and to analyse operational results. Complications with the implementation of the deep boreholes lead to an evaluation on whether the procedure for this project was optimal. Due to these complications, several of the research goals were not completed. It is still my hope that the steps that have been taken with the simulation model can be of value for the further work with creating a model that functions optimally. And also that this thesis can be a contribution in the study of the feasibility of this energy system.

Key terms: Renewable energy, geothermal energy, CO_2 heat pump, TRNSYS, feasibility analysis.

Sammendrag

Kina og Norge ønsker å være ledende innenfor fornybar energi-teknologi og forsker derfor på måter hvor de kan utvikle bedre og mer miljøvennlige systemer som kan redusere bruken av strøm og fossile brensler for oppvarmingsformål. Geotermisk energi er en fornybar energikilde som enda ikke er benyttet i stor grad. Dype borehulls varmevekslere kan bruke høye temperaturer i berggrunnen som er tilgjengelig for storskala varmesystemer. I kombinasjon med varmepumper kan man oppnå et stabile varmesystem som kan dekke oppvarmings- og varmtvannsbehovet for mange husholdninger eller en hel bydel.

Målet med denne masteroppgaven er å bidra til utviklingen av et fjernvarme-anlegg som benytter varme fra geotermiske borehulls varmevekslere i kombinasjon med CO_2 varmepumper. Metoden valgt for å jobbe med systemet er simulering. Videre skal ytelsen og gjennomførbarheten av systemet undersøkes for kinesiske og norske klimatiske og geologiske forhold. Her blir både kostnader og andre praktiske hensyn tatt med i en analyse som vurderer hvordan systemet kan realiseres i Kina og Norge. For simuleringen blir dataprogrammet TRNSYS benyttet for å bygge modellen og for å få driftsresultater. Komplikasjoner med implementeringen av de dype borehullene inn i denne simuleringsmodellen fører til en vurdering av om fremgangsmetoden for dette prosjektet var optimal. På grunn av disse komplikasjonene blir flere av forskningsmålene for studiet ikke gjennomført. Det er likevel mitt håp at stegene som har blitt tatt med simuleringsmodellen kan ha verdi for det videre arbeidet med å lage en modell som fungerer optimalt. Likeså at denne oppgaven kan være et bidrag i studiet av gjennomførbarheten av dette energisystemet.

Nøkkelord: Fornybar energi, Geotermisk energi, CO_2 varmepumpe, TRNSYS, gjennomførbarhetsanalyse.

Contents

List of Abbreviations

Abbreviation	Description
C_3H_8	Propane
CO_2	Carbon dioxide
CHP	Combined heating and power
COP	Coefficient of performance [-]
cp	Specific heat capacity [$\frac{J}{kg*K}$]
Δ	Difference in
(D)BHE	(Deep) Borehole heat exchanger
DH	District Heating
gc	Gas cooler
GWP	Global Warming Potential
h	Enthalpy [kJ/kg]
HP	Heat pump
K	Kelvin
KPI	Key Performance Indicator
LMTD	Logarithmic mean temperature difference [Kelvin]
$\dot{m}$	Mass flow rate [$\frac{kg}{s}$]
NH3	Ammonia
ODP	Ozone Depletion Potential
P	Pressure [bar]
PV/T	Photovoltaic/Thermal
T_{in}	Inlet temperature [°C]
T_{out}	Outlet temperature [°C]
T_r	Return temperature [°C]
T_s	Supply temperature [°C]
ZEB	Zero Emission/Energy Building
ZEN	Zero Emission/Energy Neighbourhood

List of Figures

List of Tables

1 Chapter 1 - Introduction

As global energy usage keeps on rising, the search for new and sustainable sources of energy gets more and more pressing (EIA, 2019). By becoming more energy efficient, that can reduce thermal demands and make the transition to renewable energy sources a lot simpler (Florence, 2019). Geothermal energy is a renewable source where heating, cooling and in some cases also electricity can be harnessed virtually all over the world. But even though it is a great renewable source for energy in principle, it has been left behind by both solar and wind as an energy producing technology. The reason for this is mainly due to the high investment costs and the difficulty of obtaining the energy at great depths (Li, 2013). Figure 1 gives an indication on how the situation is regarding these three technologies on a global scale.

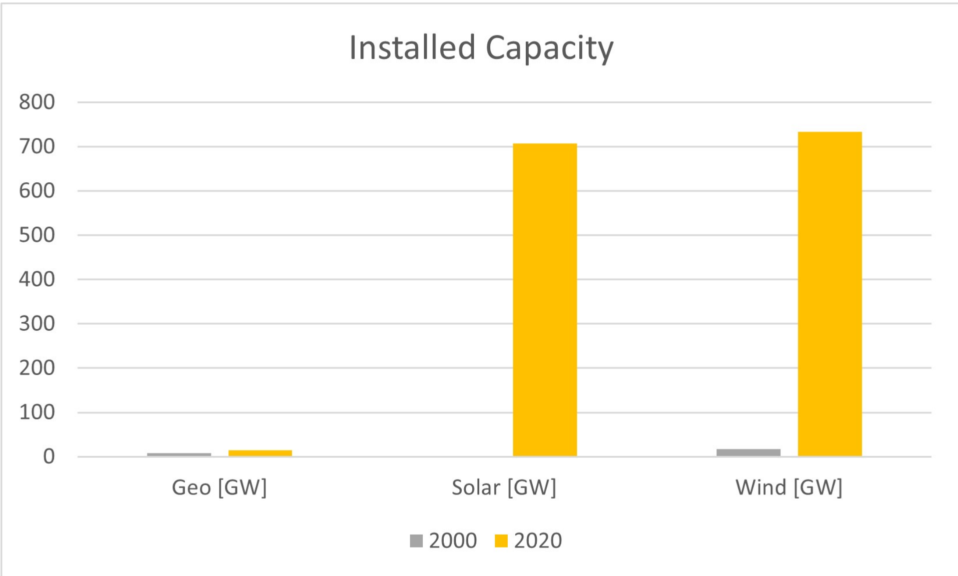

Figure 1: Installed capacity for geothermal, solar (PV) and wind energy (OurWorldinData, 2021).

The Chinese energy sector is constantly growing as the country transitions from coal to renewable energy sources (Xin, Last updated 12.07.2022). They are on the top of the rankings when it comes to renewable energy growth. New targets set this year, looks to develop a modern energy system that will provide energy security and replace coal with renewable energy sources over time. (Xinhua, 2022)

In Norway, most of the electricity comes from renewable energy sources, and they have been for decades. During the last couple of years, the price for electricity has increased a lot in southern Norway due to power lines connected with the rest of Europe that is currently in an energy crisis and also that the water reservoirs for hydropower have been emptier than usual. This has lead to there being a vast difference in electricity prices when comparing the north to the south, reaching close to 100 times as much in the south. (**?**)

For both countries, geothermal energy can be a solution, to reduce the amount of coal used for electricity production, and to reduce the dependency on hydropower for dry years. (TWI, 2022)

1.1 Project background

This thesis is completed as the second and final part of the last year at the Norwegian University of Science and Technology (NTNU). The first part was a pre-project completed in the fall semester of 2021. The pre-project included a literature review, the selection of simulation software and initial work on the simulation model. The thesis is also part of the research project ChiNoZEN. The project name stands for China+Norway+ZEN (Zero emission/energy neighbourhood). It is a very big cooperation project where among others, Chinese and Norwegian engineers from SJTU (Shanghai Jiao Tong University) and NTNU (Norwegian University of Science and Technology) are involved. The collective goal is to work together and create a self-sustaining low-carbon ZEN with clean energy by developing solutions for power, heating and cooling demands for Norwegian and Chinese climate conditions.

The ChiNoZEN project in total focuses on a lot of different aspects of the energy system. This thesis focuses primarily on the heating demand and supply. The cooling and electricity demand is something to consider of course, but will not be handled in detail. The aim is to investigate a combined hybrid system with Deep borehole heat exchangers (DBHEs) in combination with a CO_2 heat pump (HP) system to cover the heating demands of the neighbourhood. This includes investigation of the hydrodynamic and heat transfer performances as well as working on optimising the operation parameters of the complete system.

1.2 Research goals

The aim of this master's thesis is contribute to the development of a simulation model for a district heating system with CO_2 heat pumps in combination with deep borehole heat exchangers as the heat source. Additional goals after developing the model is to verify the model, optimize the operation of it and conduct experiments in order to find the best option for the locations that are considered. The aim will be reached by achieving these research goals:

- 1) Identify a method of constructing the load model for the energy system.
- 2) Find or create a functioning CO_2 heat pump component that can be connected with the load model.
- 3) Add the borehole heat exchanger (BHE) component as the source of the heat pump.
- 4) Analyse and verify the energy system by comparing its structure and behaviour with data from similar systems in operation. This can include a sensitivity analysis and/or comparison to identify similarities and differences.
- 5) Performance analysis with some chosen parameters, KPIs, in order to identify ways of improving the simulation model. This includes some form of hydrodynamic and

heat transfer performance analysis, as well as investigating operation parameters to understand how the system can be optimized.

1.3 Outline of thesis

This dissertation consists of 7 chapters. Chapter One gives an introduction to the thesis with some background history for geothermal energy systems in a global context. Chapter one also presents the research goals, outline and limitations of the thesis. Chapter Two includes information on the subsystems that the complete energy system consists of. Chapter Three presents the scientific methodology of the work that has been done. Chapter Four presents the simulation software. Chapter Five describes the model development phase including verification/validation of the model, and optimisation. Chapter 6 Discusses the results from the model development and Chapter 7 gives a conclusion as well as some suggestions for further work.

1.4 Limitations and challenges

As mentioned, this thesis mostly looks at the heating demand for the neighbourhood. The ChiNoZEN project will in total look at heating, cooling and electricity demands for a neighbourhood or district in Norway (Trondheim) and China (Lanzhou). This means that other projects than the one in this thesis will have to cover methods for providing the required cooling and electricity.

By using a simulation software to analyze the performance of the system, it can be hard to know whether the results are reliable. Comparing the results to similar project systems can give an indication on how it performs, but to be able to properly analyze and optimize a system like this, it has to be built in real life. Since we can not know exactly how the system differs from a real one, the output data and results will lack a bit of reliability, even though the parameters and data put into the simulation are exactly the same as the real life ones. Some dimensions and values will likely be unknown, and therefore only follow default values already existing in the simulation software, which could be based on another type of system or for other conditions.

By not having a real-life system to compare results with, the reliability is a bit weaker than desired. Nevertheless, the simulation model can still represent the thermal process for the combined energy system and provide indications on which operation parameters that will be preferred by analysing a simulation model that is as detailed as possible.

2 Chapter 2 - Background

In this chapter, the different subsystems of the complete energy system are presented. This includes a historical perspective on the different technologies from where it started to where it is today. This will include development and challenges when considering established energy sources and how they are adjusted to fit into the modern world that aims to reduce CO2 emissions as much as possible in addition to become more energy efficient. For all subsystems investigated in this thesis, namely the district heating plant, the heat pump system and the borehole heat exchanger, they will all be investigated in this thesis, and the focus will be directed to the heating capability and performance with regard to the climate and geological conditions of Trondheim in Norway and Lanzhou in China. There are cooling equivalents to each of these systems: District cooling plants, heat pumps in reverse work as refrigerators where the working fluid absorbs heat from one source and ejects it to another, and it is possible to eject heat to the ground via borehole heat exchangers as a way to store heat or as a way to keep the thermal balance in the bedrock.

2.1 District heating

District heating is a heating system used in several cities around the world to cover heating demands of residential, non-residential and industrial buildings (Werner, 2017). It consists of a district heating plant where hot water flows in pipes to where the demand is. The heat can come from various sources: fossil fuels, waste heat as a bi-product from processes, renewable sources or recovered heat (Statkraft, 2021).

In Norway, electricity is one of the main sources for heating of buildings, so district heating can be a way to limit the load on the electricity grid (Norway, 2021*a*). By utilizing renewable energy sources to supply the district heating network, the global challenge of transitioning from fossil fuels can be smoother. Most district heating plants now rely on a lot of different sources of energy both for cooling and heating purposes. Modern district heating plants in Norway use heat pumps where they extract heat both from rivers and some shallow borehole heat exchangers in addition to using biofuel, electrical boilers, and oil and gas boilers to cover top load during critical operation periods (Lande, 2022). Figure 2 shows the distribution of heat types from district heating plants in Norway.

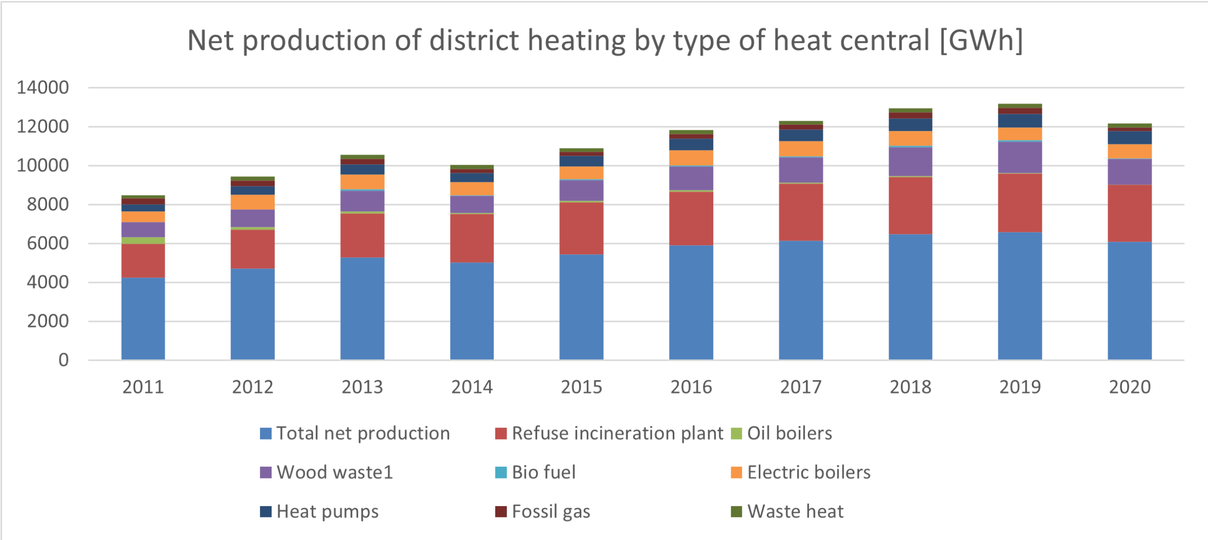

Figure 2: Net production of district heating by type of energy source (Norway, 2021*b*).

The figure shows that the total net production has increased by approx. 4000 GWh during the last decade. The rise in net production is mostly due to an increase for bio fuel and also the refuse incineration plants, which is incineration of different types of waste. The share of production from wood waste and heat pumps has also increased, while the net production from oil boilers is decreasing.

In China, district heating is mainly present in the northern part of the country (Chang Su, 2018). In total, only 15% of the heat demand of buildings is covered by district heating, but this is expected to grow (Abergel, 2021). Through government programs such as the "Clean Winter Heating Programme" China aims to cover 100% of the heating demand by clean energy in a relatively short time. Reducing pollution and prioritising renewable energy is part of the plan.

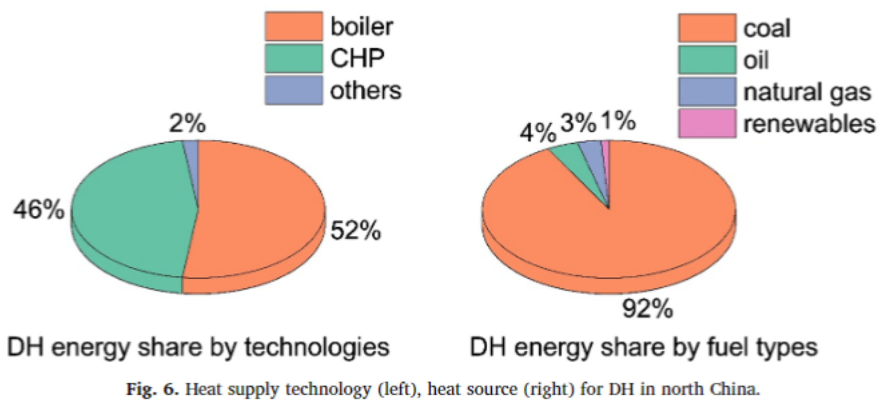

Figure 3: District heating energy share by technologies and fuel types in northern China (Chang Su, 2018).

As Figure 3 shows, the main energy source for district heating plants in northern China is coal.

2.1.1 Low temperature district heating

Since the first district heating plants, the heat delivery system has gone through different stages, or generations as it is usually called. An overview of the generations are presented in the project report called "Annex TS2: Implementation of Low-Temperature District Heating Systems" (Werner, 2021). The first generation, started in the United States in the last part of the 1800s, was based on using steam technology. Since the 1920s when Europe started using DH, the second generation was started, where high temperature water replaced steam to achieve a higher efficiency. The third generation used lower network supply temperatures below 100°C. The current transition is between the third and the fourth generation. The fourth generation of DH plants focuses on utilizing more renewable energy sources, by matching the supply and the demand more accurately. The temperature can be reduced to 45°C-60°C. In these low temperature DH systems, heat losses can be reduced significantly by being well designed and are mainly designed for low energy or refurbished buildings (Brand, 2014). The challenge with using low temperature is the risk of bacterial growth (mainly Legionella) , but this issue can be handled by reducing the volume between the tap and domestic hot water system (Lund et al., 2014). Low temperature district heating requires a conversion of current design systems. By conducting this, the total system can achieve better efficiencies than hot temperature district heating, by reducing the heat losses. The technology is there, but current solutions require financial support like motivation tariffs to make them financially attractive.

2.2 Heat pump system

To reduce the power demand for heating and cooling in buildings, the use of heat pumps has increased. They are flexible units used in residential buildings, nonresidential buildings and in industry. Depending on performance, they can reduce the power required to operate various heating or cooling devices up to 80% or even higher. Heat pumps can also be used in combination with geothermal energy systems to boost the temperature of the water from the ground up to a sufficient level before delivering it to the consumer.
An important remark is that the current equations are for a very basic heat pump cycle with only the components shown in Figure 4.

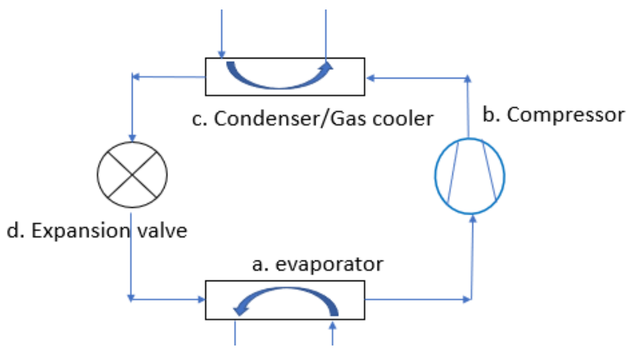

Figure 4: Basic heat pump cycle with evaporator (a), compressor (b), expansion valve (c) and condenser/gas cooler (d)

Figure 4 shows a basic heat pump cycle with the main components. Whether component

c. is called a condenser or gas cooler is based on the working fluid and the operation mode of the cycle.

Equation 1 shows the equation for the heat load, $\dot{Q}$, done by the heat exchanger. This can be used for the evaporator, gas cooler and for the simulated district heating load. U is the overall heat transfer coefficient for the heat exchanger, A is the surface area of the heat exchanger and LMTD is the logarithmic mean temperature difference between the two streams in the heat exchanger (EnggCyclopedia, 2021).

$$\dot{Q} = U * A * LMTD \tag{1}$$

The $\dot{Q}$, energy transferred per unit of time can also be expressed like in equation 2.

$$\dot{Q} = \dot{m} * cp * \Delta t \tag{2}$$

This equation is more used when analysing the particular fluids, like CO_2 or water.

$$LMTD = \frac{\Delta 1 - \Delta 2}{ln\frac{\delta 1}{\delta 2}} \tag{3}$$

To aid equation 3, Figure 5 shows how the difference in temperature is found for LMTD-calculations. The red line marks the hot fluid and the blue line marks the cold fluid. The difference in temperature on the left hand side is called Δ1 and the difference in temperature on the right hand side is called Δ2.

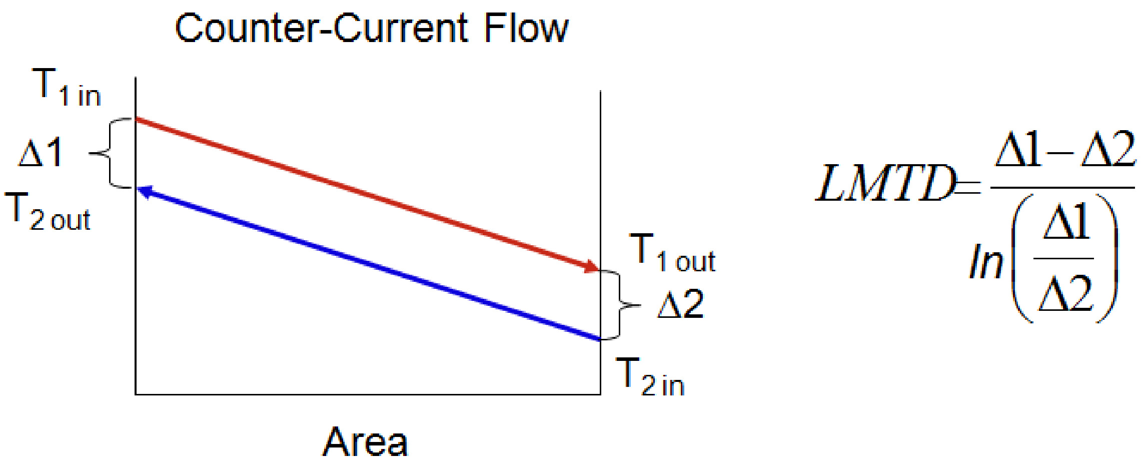

Figure 5: Graph showing how to find Δ 1 and Δ 2 for LMTD-calculations (Joe Polito, 2021).

To be able to calculate the Coefficient of performance (COP) of the heat pump cycle, the state points with temperature (t), pressure (p) and enthalpy (h) needs to be defined (Onaka, 2008). When the working fluid is known, these values can be found in tables or by using a pH-diagram. An example of how a pH-diagram for a simple CO_2 one stage plant could look like is presented in Figure 6. This is a cutout from the free-to-download software used for calculations on CO2 heat pump cycles (IPU, 2022).

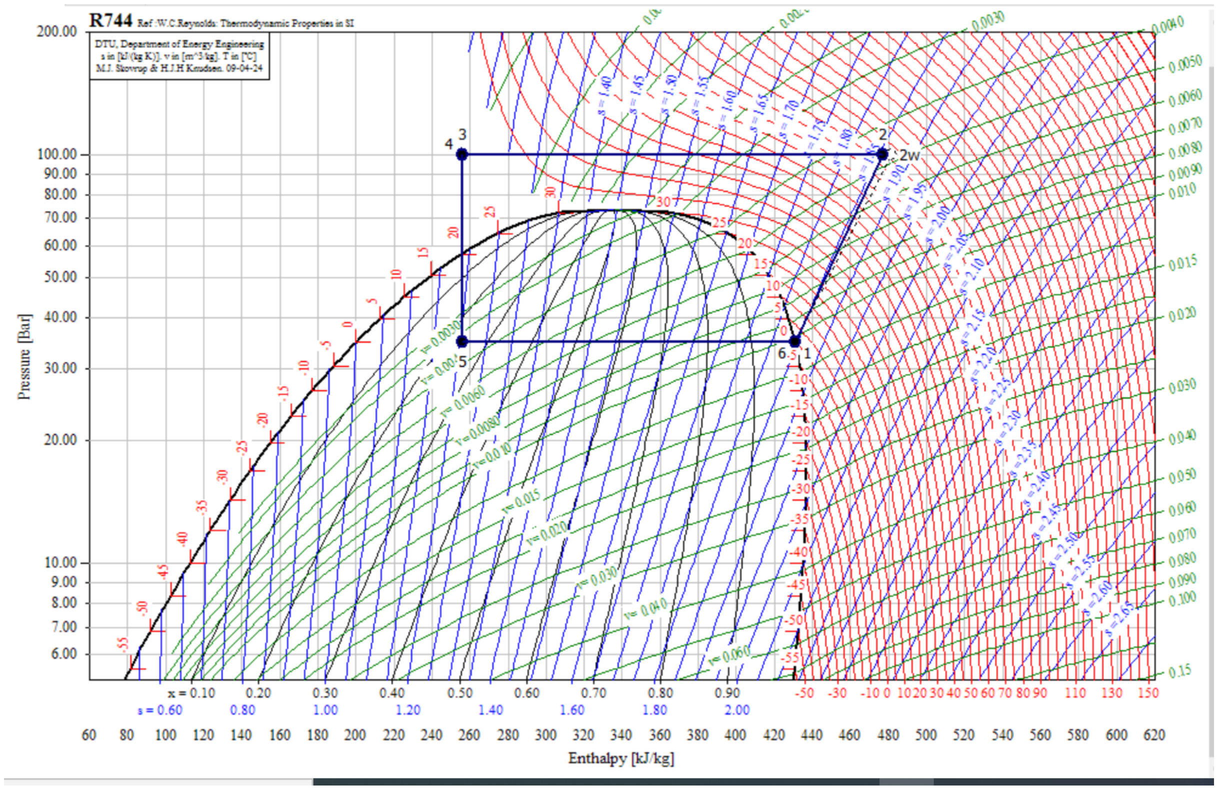

Figure 6: Example of a one stage CO_2 cycle in a pH-diagram. Image cut from "Simple One stage CO_2 cycle program.

$$\Delta h_{is} = h_{2,is} - h1 \tag{4}$$

The Δh_{is} is the difference in enthalpy between point 2_{is} (for an isentropic compression) and the enthalpy in point 1. In the next step, Δh_{is} is used to calculate the specific work necessary to operate a motor for the compressor, shown in Eq. 5.

$$w = \frac{\Delta h_{is}}{\eta_{is}} \tag{5}$$

In the equation above, the η_{is} represents the isentropic efficiency in the compressor. It compares real specific work to the isentropic specific (ideal) work done by the compressor (*Isentropic Efficiency – Turbine/Compressor/Nozzle*, n.d.).
The enthalpy of point 2 can then be calculated using equation 6.

$$h2 = h1 + w * (1 - h_l) \tag{6}$$

In this equation $h2$ is found by adding the enthalpy in point 1 and adding it to the specific work with the heat loss (hl) substracted.

The enthalpy of point 3, $h3$, is found by first deciding on what the outlet temperature from the gas cooler should be. Then just follow along the pressure line from point 2 towards the left side where it matches this temperature. For simple heat pump cycles it is normal to assume that there is no enthalpy loss through the expansion valve. Therefore $h3 = h4$. The mass flow rate of the refrigerant (CO_2 in this case) can now be calculated from equation

7.

$$\dot{m} = \frac{\dot{Q}}{\dot{q}} = \frac{Q}{h2 - h3} \tag{7}$$

This mass flow rate can be used to reach the target of any heat pump analysis, which is finding the efficiency of the cycle, COP. First of, the work can be calculated by using equation 8. Note the difference between w, which is the specific work with unit kJ/kg, and W, which is the work in terms of energy units per unit of time,

$$\dot{W} = \dot{m} * w \tag{8}$$

The COP is then calculated by using equation 9.

$$COP = \frac{\dot{Q}_{Heating}}{W} \tag{9}$$

In addition to this performance analysis, evaluating some dimensions within the system can also be helpful to understand more about the components and their requirements. One of these parameters is the required suction volume for the compressor, V_s. Equation 10 shows that the suction volume consists of the factors: mass flow, volume at state point 1 and λ, which is the volumetric efficiency of the compressor.

$$V_s = \frac{m * v_1}{\lambda} \tag{10}$$

2.2.1 Heat pump configuration

When investigating heat pump systems in relation to residential heating, different heat pump configurations are considered and investigated. This could include variants of the gas cooler split into several units in series where the different gas cooler units serve different purposes. The first gas cooler unit is for preheating of tap water, then a middle one for space heating and a final one for reheating of the tap water. Another option is to add a compressor to increase the maximum mass flow rate and thereby widen the operation possibilities. A third option that is very common in CO_2 heat pump cycles is to add an internal heat exchanger to aid the efficiency of the system.

2.2.2 Working fluids

When designing an energy system that includes a heat pump, the working fluid of the heat pump is a crucial decision for the operation and how the heat pump is going to be used. The environmental aspect is something that historically has gotten a lot of attention and made the industry move away from certain types of working fluid. Ozone Depletion Potential (ODP) and the Global Warming Potential (GWP) are characteristics that determine how environmentally friendly the working fluid is. In addition, some physical and thermodynamic properties will affect the operation of the heat pump such as the process losses, pressure levels, pressure ratio, evaporator temperature, pipe temperature and volumetric heat capacity. All of these parameters for the heat pump will affect either the energy usage, the costs or the life time.

Emissions related to the working fluids in heat pumps have been a topic of discussion in recent decades due to the increasing awareness of global warming and the potential harmfulness they bring. Natural working fluids have much lower global warming potential (GWP) values compared to synthetic ones and are much preferred in that regard. It is therefore highly relevant to look at ways to implement heat pumps that use natural fluids in modern energy supply systems, like carbon dioxide (CO_2), propane (C_3H_8) and ammonia (NH_3).

2.2.3 CO2 as working fluid

CO_2 as a working fluid for heat pumps was rediscovered in the 80s by Gustav Lorentzen, working at NTNU. It can be a very efficient working fluid if used properly. The advantages of CO_2 often include the environmental aspect with 0 GWP and 0 ODP. It stands out due to a very high critical pressure and low critical temperature which leads it to often operate in the trans-critical phase (Stene, 2007). The most important thing when using CO_2 as a working fluid is to get a big temperature interval for the water that it is heated. If this is achieved, the COP is often high.The correlation between temperature and enthalpy has a curved graph, and becomes more and more linear as we move from 75 bar up to 120 bar and in the upper layer it is close to being a straight line. (Stene, 2016)

2.3 Geothermal heat systems

Large buildings and neighbourhoods in arctic climates as in Norway and northern China mostly require heating to achieve a satisfying indoor temperature. Modern buildings with strict standards make the buildings less dependant on heating supply since infiltration and heat losses are diminished. They do however, due to their compact structure often require a cooling supply during warm periods. Energy consumption for space cooling has increased significantly during the last 30 years, both for residential and non-residential buildings. By utilizing geothermal energy systems to cover the demands of the building, both the heating and cooling demands can be attended to by extracting heat during the winter and injecting excess heat during summer. The ground can in these cases be used as a way of storing energy, either for shorter periods (e.g. day/night) or longer periods (e.g. seasonal). By utilizing the ground to cover several building demands, the pay-back-time of the energy system can be severely reduced. (Gotaas, 2011)

2.3.1 Geothermal energy potential

Deep geothermal systems for heating are already established in many countries (Brun, 2010). The heat source, hot soil/bedrock, comes partly from stored solar heat and partly from radiation created inside the core of the earth (Andrew Turgeon, 2021). As the depth increases from the surface of the earth down to the core, the temperature rises. This change in temperature by unit of length is called the geothermal gradient. A typical geothermal gradient used for the global average is 25°C per kilometer (Andrew Turgeon, 2021), but this will vary with the local geological conditions. Since the amount of geothermal heat available is heavily dependent on the placement, it is vital to look at local conditions when establishing a geothermal energy system (Havellen, 2012).

In Norway there is only one case of a completed deep geothermal energy system as of now deeper than 1000 meters (Karoline H. Kvalsvik, 2019). At the main airport for Oslo, two boreholes with 1500 meter depth are used to retrieve heat for de-icing of a test engine area, to avoid the use of heat pumps (Theloy, 2021). In addition to this, research projects such as the ChiNoZEN and NEXT-drill have been started in the last decade to "develop the technology and tools needed to produce geothermal heat from the earth." (Sintef, 2012). The Norwegian geothermal energy sector uses established knowledge from the petroleum sector. Both experience with drilling and the use of different materials for boreholes can contribute to reduced drilling costs and improve future geothermal energy projects (Randeberg, 2012).

When establishing large geothermal systems there is a need for detailed planning and test drilling to obtain detailed geophysical information of the local geological conditions (Atle Dagestad, 2021). The heat flow is relatively low in most parts of Norway. The geology situation in the Trondheim area is dominated by Cambro–Ordovician schists, greywackes and greenstones of the Upper Allochthon of the Caledonian orogen. Measurements from the LITO-project at the Geological Survey of Norway (NGU) showed that the thermal conductivity in the Norwegian bedrock is about 2.5-4 $\frac{W}{m*K}$, with typical values around 2.85 $\frac{W}{m*K}$. The heat production rates for these rocks is on average 1.5 $\frac{\mu W}{m^3}$, which is a relatively low yield (Slagstad, 2008). A deep borehole of approximately 1km depth at Løkken (about 50 km southwest of Trondheim) where the rocks are identical to those in Trondheim, yielded a topographically and palaeoclimatically corrected heat flow of 57 $\frac{mW}{m^2}$ (Slagstad, 2009). The borehole at Løkken also measured the thermal gradient to 16°C/km down to 1000 meters, but may increase to 18°C/km for the next 1000 meters, below a layer affected by the glacial periods. The rock type Caledonian nappes is the main one in Norway, also covering Trondheim. It normally has much lower heat production rate than the underlying Precambrian basement which has more granite in it. The Fredrikstad area is one of the most promising areas with regards to heat utilization in the rock. The local "Iddefjord" granite has a heat production rate of over 6 $\frac{\mu W}{m^3}$ (Slagstad, 2006). The palaeoclimatically corrected heat flow is 73 $\frac{mW}{m^2}$, the thermal gradient is approx. 18°C/km and the thermal conductivity is about 3 $\frac{W}{m*K}$.

The progress with deep geothermal energy systems in China is fairly similar to the Norwegian one, in that it is in a start-up phase. In fact, the geothermal energy sector is the only one where China does not score highest in the world by installed capacity of the five main renewable energy sources: Solar, wind, hydropower, bio and geothermal energy citepRen.en.. There is however some optimism in the future for Chinese deep geothermal energy utilization, with an intention of covering future demand and reducing emissions by replacing aged methods with new renewable sources (Jianchao Hou, 2018). Due to a high amount of abandoned oil and gas wells, the potential is there to utilize them for geothermal energy (Yong-Le Nian, 2018). As of now there are only 5 energy systems based on hot dry rock, but the future of deep geothermal energy systems are both promising and ambitious (Wang, 2020).

In northern China for the area surrounding Lanzhou, most of the bedrock consists of gravel down to about 1000 m, then follows a layer of argillaceous rocks for 1000-1500 meters and for deeper than that there is sandstone. A typical avg. value used for the heat flow in China's mainland bedrock is 79.5 $\frac{mW}{m2}$. Figure 7 shows a map of Lanzhou and the surrounding area. At some locations, test-drilling has been done to find the heat flow, thermal conductivity and temperature gradient. (Liu, 2022)

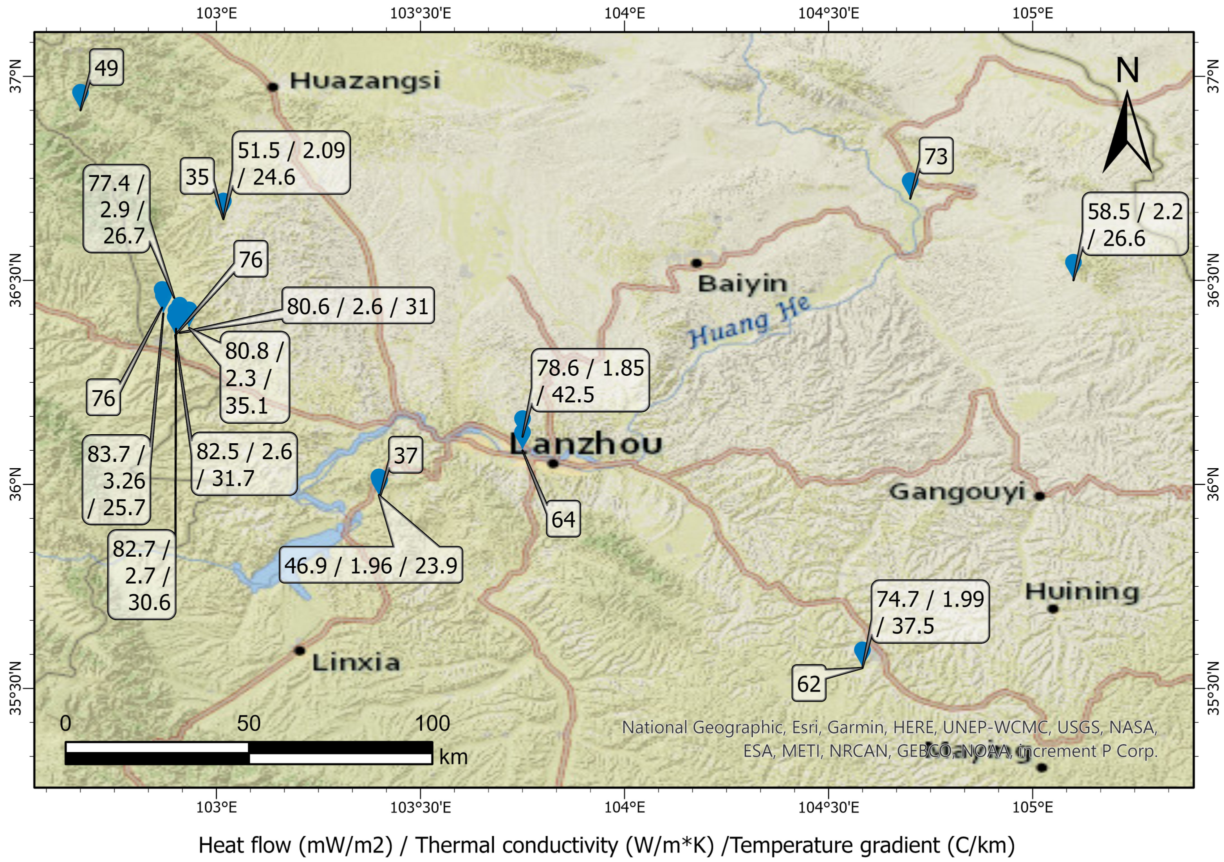

Figure 7: Heat flow, thermal conductivity and temperature gradient for areas in and around Lanzhou, northern China (Fuchs and Norden, 2021)

The most promising areas for Lanzhou shows a heat flow of 78,6 $\frac{mW}{m2}$, thermal conductivity of 1,85$\frac{W}{m*K}$ and temperature gradient of 42,5 $\frac{°C}{km}$.

2.3.2 Borehole heat exchangers

The application of deep borehole heat exchangers is a relatively recent phenomenon which started in the US. and Europe (Thomas Kohl, 2002, Lydia Dijkshoorn, 2013). Since the late 80s and early 90s, interest for the technology has initiated projects in numerous locations around the world (Morita, 1994, Morita Koji, 1992). Initially, they were implemented by using previously used oil wells because the drilling and construction work already was done. Based on results from several of these systems it has become clear that they show sufficient prerequisites for delivering heat to modern district heating networks due to low emissions, a high energy efficiency and relatively easy implementation compared to other geothermal energy systems (Zhang, 2021).

MD-BHE systems do however also come with some challenges. One of them is that there typically are big differences in operation and design conditions which leads to varying results. Another issue is that while regulating the operation conditions of the system, there is a deficiency on the theoretical understanding of the correlation between parameters. (Zhang, 2021)

It can be both interesting and useful to study cases like these when the aim is to create something similar. Both the decisions that are made during design of the systems or models, and the results they achieve. However, one detail makes certain projects hard to utilize in transient systems, and that is the lack of accurate models for heat transfer and energy conversion in variable state cases. The system should be designed and operated for heating demands that will vary with time due to fluctuating climate conditions and change between operating modes. Models like these are based on mathematical equations based on thermodynamic properties of components and the structure of the system.

One study, (Zhang, 2021), establishes a complete dynamic heat transfer model for a middle-deep geothermal heat pump system and verifies the model by comparing simulation results with results attained through real life testing made on the system. After getting the confirmation on the usability of the model, testing and altering of different parameters to optimize the system can begin. The objective was to find optimal parameters that gives the best COP (and energy conversion) as possible for the system. Other factors, such as the economic aspect and the practical aspect also have to be taken into account, to make the adjustments realistic. As an example of this type of optimization, the circulation rate was one of the parameters investigated. By trying different circulation rates for different depths it was discovered that the optimal circulation rate at 2000 meter depth was at 6.7 $\frac{kg}{s}$ and that by increasing the depth by 1000 meters to 3000 meters, the optimal flow rate increased to 9.9 $\frac{kg}{s}$.

Systems for geothermal energy for buildings and neighbourhoods are typically separated into two categories, open and closed systems.

2.3.3 Open system

The open systems use underground water reservoirs directly. One pipeline goes down to the particular area and extracts heated water, and the other one is used for injection of water. The groundwater functions as a large water tank which is both naturally insulated and exchanges heat with the bedrock around it. This provides a highly efficient system. The open system has an economic advantage in that it requires less material for piping, and the drilling process is less comprehensive. The main disadvantage is that it requires a certain location with an available water reservoir. This limits the placement of the energy system. The left side of Figure 8 shows a principle sketch of an open loop system. This particular one is for a residential building, but it can also be scaled up to provide heating and/or cooling for several buildings. (Geothermal, 2021, AltaVista, 2015)

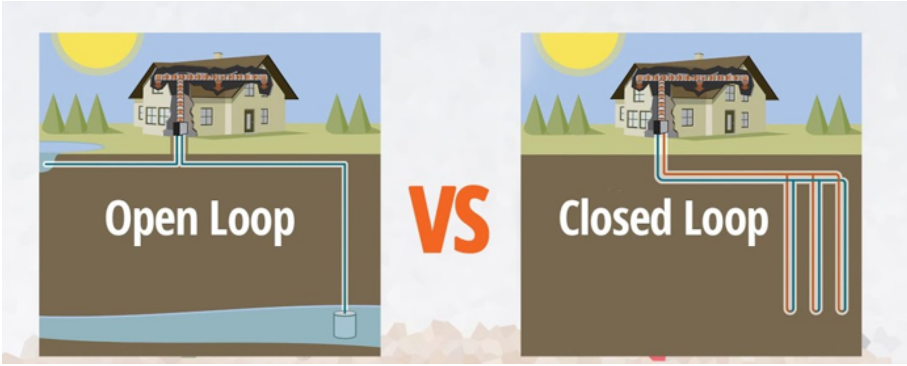

Figure 8: Image showing the principle difference between closed and open loop system for geothermal energy (WebReps, 2017).

2.3.4 Closed system

As the right hand side of Figure 8 shows, closed systems are connected pipes with a heat transfer fluid inside. Usually this is water or a water based solution that gathers heat by circulating through the bedrock with a higher temperature than the fluid. These types of systems are less affected by potentially damaging mineral content in the bedrock water. This leads to a higher durability and stability for the system. Even if it initially costs more, the high durability makes the system cheaper in operation due to less demand for maintenance. (Geothermal, 2021, AltaVista, 2015)

For both cases there is a need for drilling into the ground. In Norway, there are lots of companies that have experience with drilling, both vertically directional drilling and branch drilling. This experience stems from the petroleum industry. It is therefore a certain expectancy put on the Norwegian industry to research and develop this technology further. (Gotaas, 2011)

2.3.5 Pipe type

Deep borehole heat exchangers (DBHEs) are based on different pipe designs. The different designs are usually divided into either U-pipes or Concentric pipes (Georgios Florides, 2007). A third option, the doublet design is investigated into (Hu, 2021), but it will not be further assessed in this report. As shown in 9 each design type has several subversions.

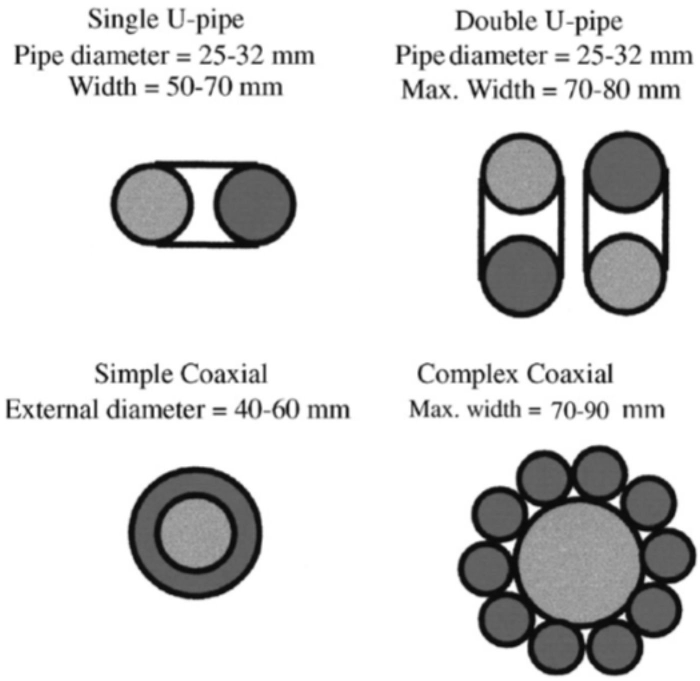

Figure 9: Different pipe structures for borehole heat exchangers (Georgios Florides, 2007).

2.3.6 Challenges with geothermal energy systems

Geothermal energy is often mentioned as a promising renewable energy source for the future. There are however some issues with the technology that should be evaluated. The main challenge, and the reason it is not as widespread as it could be, is the huge investment costs of the systems. This leads to a long pay-back-time for the system leaves the return of investment uncertain. The technology is there, it is just too expensive to make it an attractive alternative to other energy sources. Another issue is the instability in the surface of the earth's crust in particular areas. This has led to cases where constructing geothermal energy systems has caused earthquakes that damaged both buildings and the drilling equipment. Another issue that brings several small challenges is that the placement of the geothermal system can be hard. The searching and locating of a good place can be costly and could lead to high heat losses while distributing the heat from the system. (Bhatta, 2021)

2.4 Economic evaluation and feasibility analysis on hybrid borehole heat exchanger and CO_2 heat pump

2.4.1 Price

The price of a system like this will vary with location, drilling technique, size and many other factors. A typical price for an industrial CO_2 HP for 600 kW rating is approximately 155-160.000 Euro (Frost, 2022). For a 1.5 MW heat pump with NH_3 as working fluid, it is estimated to be around 730 000 Euro (Lande, 2022).

In China, the price of electricity varies in different cities. In Lanzhou, the price of electricity is about 0.51 RMB per kWh. This equates to 0,076 Euro per kWh. In Norway, as mentioned, this varies based on where in the country you are from 0,0029 Euro (northern Norway) to approximately 0,29 Euro per kWh.

2.4.2 geological conditions

Based on the litterature review completed for Trondheim and Lanzho it seems like the temperature gradient might be 2-3 times as good for Lanzhou, but this will be highly dependant on specific location.
In 2012 Norconsult wrote a report on the potential of geothermal energy (Norconsult, 2021). They estimated that a deep geothermal energy system for heat production at least should be 4-5 MW and deliver 25-40 GWh per year, based on the economic perspective and delivery to a district heating plant (Havellen, 2012). These figures fit well with the article, (Liu, 2021), that states that the required heating power for a typical Chinese residential district is about 2,5-5,0 MW, and will require several DBHEs to cover the demand.

The report also claims that the temperature difference for deep energy systems should be at least 25°C. To be able to compete with current heat deliverance systems, the current market and technology for deep geothermal energy systems have to achieve a 70% cost reduction and preferably some sort of ban on waste incineration which is the main barrier to achieve a successful geothermal energy system that can deliver reliable heat to district heating plants/networks. The main conclusion on the financial aspect of DBHEs is that the technology has to be developed further before it can be considered an attractive energy source.

3 Chapter 3 - Methodology

To contribute to the development of the energy system and the investigation of the performance, simulation is chosen as an ideal method for creating and analysing a model that represents the energy system. This chapter will present the methods used in order to achieve the research goals of the thesis.

3.1 TRNSYS course phase

During the preliminary work done in the autumn semester of 2021, some essential decisions were made that formed the base of the master's thesis project. Most of the work during this phase was related to research and acquiring knowledge about the technologies. From this research, TRNSYS was chosen as the Simulation Software and a system configuration with the BHE as a direct heat source for the CO_2 HP was established. Also, two different courses for TRNSYS were identified as a way to gain knowledge about the software.

The two courses found in the pre-project are both online video-based courses intended to give a basic understanding of the different subprograms for TRNSYS, namely Simulation Studio, TRNBuild and SketchUp. The first course, called "Learn TRNSYS", is provided through the Udemy website. The course creator is an engineer that works with in-person and online training courses for TRNSYS. The other course is a self-paced training course provided by the creators of TRNSYS. Both of them introduce and demonstrate how the simulation software works and give examples on how to design systems for various purposes.

3.2 Model development

When the courses are completed and necessary knowledge and experience from using TRNSYS is obtained, it is time to start developing the energy system model. Since the purpose of the energy system is to supply heat for a neighbourhood, the first thing to design is the load model. The model should be designed either as a very large building or several smaller ones to accurately represent the heating demand of a ZEN. Since the model is created from scratch with few preconditions, the model development process is fairly experimental and open. The focus of this thesis is not on the load model, and it can therefore be simplified as much as possible as long as it works individually and together with the energy supply system. The load model is created by first designing a building in SketchUp, then importing it to TRNBuild where specifications on the building are implemented. When the building model is properly set up, it can be imported into the Simulation Studio. From then on, the building component functions as a load component with demands that must be met in order to achieve its set temperatures.

After completing the load model, the HP model is next in line. The HP model should be sized to cover the demands of the load model by itself. The heat pump component requires a data file input in order to function. This data file assembly has to follow the code syntax of the heat pump component and might be challenging to complete. A control system can help to manage the operation. Since the BHE is the novel aspect of the energy supply system, it is important that the model (HP and load model) works prior to the BHE being added to the system in order to analyse how the BHE affects the system.

3.3 Validation

After the BHE component is connected to the HP component as a heat source, it is time to verify the simulation model. The initial plan is to perform measurements and operation analysis by plotting several parameters throughout the system for the simulation period of one year. Flow rates, temperatures, heat transfer rates and COP can be compared with similar projects in order to find out if the results are reasonable. Since it is not based on a real life system as of the time this thesis is written, the results are hard to verify. Therefore, a lot of different projects with varying conditions will be used for validation purposes. If possible, some test data from a laboratory at SJTU will be used for comparisons as well. In addition to comparing different results, a sensitivity analysis for different parameters will also be performed. This is a method where chosen variables are analysed in detail as other variables are increased/decreased in order to see how much it affects the chosen variables.

3.4 Optimisation

When the simulation model is validated, the next step is to optimise the model performance. This can be done in two main ways, either by trying different parameters to identify which ones that improve the performance or it can be done by modifying the operation of the system. The BHE could for example be operated continuously at a relatively low rate, or at maximum capacity during certain times of the day/week/month/year.

3.5 Feasibility study

When the simulation model is both validated and optimised, an investigation of the feasibility of this system should be completed, both for Norwegian and Northern Chinese climate. A study like this can aid in uncovering the price and economic payback of this system. Based on the different climatic and geological conditions, the operation of the system and therefore the energy contribution from the BHE could be different as well.

3.6 Scientific paper draft proposal

After completing all the previous phases for the energy system, it is time to gather some of the main findings from the work and structuring it like a scientific paper. The aim of this exercise is to practice presenting results with a different approach as well as being able to show the essence of the work that has been completed in this project.

3.7 Further work

Finally, the last objective is to reflect upon the work that was done during this project, and think about ways to continue contributing to the development of the system. This could include considering the use of different simulation software, a different system configuration, adding more and/or different components or adjusting the control system.

4 Chapter 4 - Simulation software

In most high investment projects with a risk regarding how successful they will be, it is normal to simulate the system as accurately as possible to predict how the project will do before starting to do anything in real life. For geothermal energy systems usually a test drilling will be completed on the considered location to test geological conditions prior to the actual drilling process starts (Bailey, 2012). Based on the results of this test drilling, certain parameters can be entered into a simulation program to run tests on how the completed system would do. The results from the simulation will vary based on how much that is already known about the system. Given a certain system with details about materials, dimensions, operation, location, and other relevant information, the uncertainties of the results are reduced and the simulation software can provide realistic results that help make decisions about the real life system. On the other hand, if the system that is simulated only has a few given parameters, all the other necessary parameters can be provided as default values already existing in the program or from assumptions made about the system. An example of this could be that the pipe type is unknown. In this case it is not clear if the simulation should use a U-pipe or a Coaxial pipe type. This leads to uncertainties regarding every parameter that are related to the pipe such as materials, length of the pipe, flow rate and diameter just to mention some of them. And with a lot of uncertain parameters in total, the results will become less and less reliable until the results of the simulation can not be trusted at all. It is therefore important not just to simulate the system, but to verify it and make sure that it truly is a reflection of the real life system.

4.1 TRNSYS

After a broad review of available simulation software for energy systems, three were chosen based on their features and usability. Three different simulation software, Energy Plus, IDA ICE and TRNSYS were evaluated further by looking at user-friendliness, options for energy sources, implementation readiness and how available the software is. One common feature of these three programs is that they are regularly updated and well established for building simulation models. They all have different advantages and disadvantages, and the one that was chosen was TRNSYS. TRNSYS (Transient System simulation tool) is a simulation software that can be used to simulate complex and varied transient systems. TRNSYS can simulate systems in different modes by using control devices, use real-life weather data and plot results to use for further analysis. As this master's thesis assignment is based on a novel hybrid energy supply system including a geothermal heating system with varying results based on its geological placement, construction method and operation parameters as well as a CO_2 heat pump system, it is important that the simulation tool is flexible and easy to handle in regards to energy supply design. Based on the evaluation, TRNSYS seemed like the optimal option of the ones considered. TRNSYS also has its own sub-program meant for setting up a building for in-depth analysis of indoor air quality, building materials, gains/losses, angles related to solar, windows with shadow options and much more. This is a great advantage when considering that not only the energy supply system is dynamic, but also that the building and its needs in terms of heating, cooling and electricity will vary based on the time of day, month of the year and weather conditions. In my thesis this will apply to the heating needs for a ZEN neighbourhood.

Another requirement for the simulation software was that it should not be based on black box models where the components are represented by boxes in which the only thing that can be analysed is the input and the output with a limited understanding of what happens within the different processes. Initially, all variables and processes should be available for analysis, to completely understand the mathematical models that the system is based on. (Simulatelive, 2020)

4.2 SketchUp

One of the many available subprograms for TRNSYS is called TRNSYS3D which is a plugin for a drawing program called SketchUp. TRNSYS3D makes it possible to construct a building with everything related to the geometry of the building, and then import it to TRNBuild. TRNSYS provides two main options on how to set up the building. An alternative method to drawing the building in SketchUp is a fast-track solution built into the Simulation Studio in TRNSYS. By using this method, in theory the same building can be constructed as SketchUp would give you, but without the proper visual understanding of the building, which was considered important at the time. This step-by-step guide requires the same input as the building imported from SketchUp to TRNBuild. Based on the desire to understand each subsystem and its influence on the complete model throughout the model development process, the traditional route from SketchUp to the Simulation Studio via TRNBuild was chosen.

4.3 TRNBuild

After designing the structure of the building in SketchUp, the building file can be imported to TRNBuild as an idf-file. Then Norwegian Standards (NS) for modern buildings can be used to set the building up like a passive house. As the name implies, passive houses use passive measures in order to reduce the general energy demand. There is not a real definition regarding size for small houses, but in Norway about 80% of residential houses are between 60 and 250 m^2 (Bakken, 2010). Mostly these measures are related to keeping the building envelope air tight and well insulated. NS3700 is a standard designed for passive and low energy houses and can be used to meet the criteria for Zero emission/energy buildings. The standard sets requirements for the simulation, U-values, leakage number and heat recovery system among others. The U-values of a passive house are presented in table 1.

G/l category	Operation time	heat gain	net power demand	annual energy demand
People	24/7/52	1.50 $\frac{w}{m^2}$	-	-
Lighting	16/7/52	1.95 $\frac{w}{m^2}$	1.95 $\frac{w}{m^2}$	11.4 $\frac{kWh}{m^2*year}$
Technical equipment	16/7/52	1.80 $\frac{w}{m^2}$	3.00 $\frac{w}{m^2}$	17.5 $\frac{kWh}{m^2*year}$
Domestic hot water	16/7/52	0.00	5.10 $\frac{w}{m^2}$	29.8 $\frac{kWh}{m^2*year}$

Table 2: Standardized gains and losses from NS3700:2013

External wall	0.10-0.12
Roof	0.08-0.09
Floor	0.08
Window and door	0.80

Table 1: U-values requirements for passive house given by the NS3700:2013 building standard. (Sørensen, 2020)

Internal loads will also affect heating and cooling demands. NS3700 also includes specifications on how the internal loads affect the building through schedules and hourly values that ensures more realistic simulations. TEK17, another Norwegian standard for buildings have a requirement for window per wall rate given by equation **??** (Tek17, 2021). It is important to note that the "greater than" sign should be "greater than or equal".

$$Ag > 0.07 * \frac{A_{BRA}}{LT} \tag{11}$$

Table **??** presents the heat gain and net power demand for people, lighting, technical equipment and domestic hot water.

4.4 Simulation Studio

The Simulation Studio is the main part of TRNSYS. Here, all components are chosen from component libraries and placed in a model-building area where the components are modified and connected to each other. Then, various components for analysis can be added in order to plot certain variables over a user-defined time interval.

4.5 Main components - Simulation Studio

This sub-chapter serves as a brief description of the main components (called types in TRNSYS) used and some of their mathematical references provided by the TRNSYS software.

4.5.1 Type 15-6, Weather data

This component is used to read and simulate real-life weather conditions for the system. The component can handle weather data files in several different formats such as International Weather for Energy Calculations (IWEC), Typical Meterological Year, version 1, 2 and 3., Canadian Weather for Energy Calculations (CWEC), German TRY 2004 and

TRY 2010. The weather data can be used for solar components, radiation dependent components and for temperature dependent components, such as load components.

4.5.2 Type 927, Water-Water heat pump

The water-to-water HP component is part of an additional component library called "Geothermal Heat Pump (GHP) Components". It models a single-stage HP cycle. It requires an input data file with information on the boundary conditions for inlet temperatures and mass flow rates for source and load side. It then interpolates within the map of known performance conditions to determine the correlating heating or cooling capacity and power draw. In addition to the equations presented in the Background chapter, the heat pump component relies on equation 12, 13 and 14.

$$\dot{Q}_{absorbed} = \dot{Cap}_{heating} - \dot{P}_{heating} \tag{12}$$

The amount of heat energy absorbed is equal to the heating capacity minus the power required for the compressor.

$$T_{source,Out} = T_{source,In} - \frac{\dot{Q}_{absorbed}}{\dot{m}_{source} * cp_{source}} \tag{13}$$

The outlet temperature on the source side is equal to the inlet temperature minus a term consisting of the absorbed heat energy divided by the mass flow rate times the specific heat of the fluid that flows on the source side.

$$T_{load,Out} = T_{load,In} - \frac{\dot{Cap}_{heating}}{\dot{m}_{load} * cp_{load}} \tag{14}$$

The outlet temperature on the load side is equal to the inlet temperature minus a term consisting of the heating capacity divided by the mass flow rate times the specific heat of the fluid that flows on the load side.

4.5.3 Type 557, Ground Heat Exchanger

This component is also a part of the "Geothermal Heat Pump (GHP) Components" library. The component models a vertical heat exchanger, either U-tube or coaxial that thermally interacts with the ground. A fluid flows through the heat exchanger and either absorbs or ejects heat when interacting with the surrounding bedrock, depending on the temperatures. A complete description of the mathematical model for the component is available in the TRNSYS documentation (Pahud et al., 1996). The mathematical model of this component is from the 80's and focuses a lot on the heat storage ability of the borehole heat exchanger.

4.5.4 Type 56, Multi-zone Building

TRNSYS has a component in the "Loads and structures" called type 56 that can be modelled to represent a Multi-zoned building. This can include current building standards for Norway and China. The weather data file used in combination with the building component will aid to better represent the difference in weather conditions for the two cities

(Trondheim and Lanzhou). Type 56 is one of the most complex and diverse components in TRNSYS with TRNBuild as a sub-program where specifications for the building are modified. In the Simulation Studio, where all the components are connected and the actual simulation process is completed, Type 56 functions as any other component with inlets/outputs.

Two alternatives to the Multi-zone building component (Type56) are Type 88 and Type 682. Type 88 is used to model a lumped capacity single zone structure. It does not consider solar gains and assumes an overall U value for the entire structure. It serves as a quick way to add a heating and/or cooling load to a simulation system. The other alternative considered, type 682, takes a user-defined load that either represents heating (negative load) or cooling (positive load) and connects it with a fluid flow. The load(s) can be gathered either from measurements on a building, in real life or through other simulation software, or even TRNSYS. It then calculates the outlet fluid conditions after interacting with the load. One limitation for this type is that it ignores boiling and freezing effects. For systems where the only thing needed in regards to load is the actual heating/cooling load, this type should be able to do the job. The load can be set as a constant or as a variable.

4.6 Secondary components

4.6.1 Type 110, variable speed pump.

Type 110 is an alternative to Type 114 that only functions at a constant speed. For Type 110, the mass flow is maintained between no flow up to a user-defined rated flow. The mass flow rate is based on a control signal and follows it linearly. The power drawn is set as a parameter for the heat pump and can be modeled using equations with variables or just be set as a constant. The pump does not consider start or stop characteristics or pressure drops. In addition to flow rate and power drawn, heat losses are set as user-defined values for each variable speed pump. (TRNSYS, 2021)

Outlet temperature and outlet mass flow from the pump can be calculated using the following equations:

$$To = Ti + \frac{P * f_{par}}{\dot{m} * Cp} \tag{15}$$

In this case To is the outlet temperature, Ti is the inlet temperature, P is the power consumption of the pump, $\dot{m}$ is the mass flow rate of the pump, c_p is the specific heat capacity of the fluid $[\frac{J}{kg*K}]$ and f_{par} is a user-defined fraction of how much of the power used that gets converted into thermal energy for the fluid.

$$m_o = \lambda * m_{max} \tag{16}$$

Here m_o is the outlet mass flow, m_{max} is the maximum mass flow capacity of the pump and λ is the user-defined variable control function between 0 and 1.

4.6.2 Type 31, pipe

The pipe component, type 31, is used to model the fluid flow's thermal behaviour. The component has user-defined parameters such as the inside diameter, length of the pipe and the loss coefficient of the pipe. The loss coefficient determines heat loss to the environment. This component is often used when dealing with hydronic systems to accurately include heat losses. As presented in Schmidt (2020), there is another similar component called type 604 that accounts for the thermal capacity of the borehole. In the study, that particular type was unavailable and type 31 was used instead since it is available in the standard library. When used for this purpose, modifications are needed. This component is often used for systems with fluid mass flow to and from buildings and geothermal components. The reason is that the component carries out internal calculations throughout the simulation for the energy of the fluid at the inlet and the outlet, as well as internal energy losses. These calculations are primarily based on inlet temperature and inlet mass flow rate. Without the pipe component(s), convergence issues for the fluid flow typically occurs due to large variations in the energy flow between the components.

4.6.3 Type 166, Simple room thermostat

Type 166 models a simple room thermostat. It takes in a temperature from a room and then outputs a control signal to another component, in most cases a pump (either circulation or heat). Heating and cooling setpoints need to be specified to let the component know when to send an on/off signal. Temperature dead bands can be set up to contribute to less variations between on and off.
Alternative control components include more complex thermostats that can add stages of heating and cooling with separate temperature limits. These can include auxiliary heaters to ensure that the target temperature is reached.

4.6.4 Type 65, Online graphical plotter

The online graphical plotter is used to present results with graphs. It can display several variables simultaneously and while the simulation is running. If desired, it can also generate an output data file for more detailed analysis.

4.6.5 Type 55, Periodic Integrator

Type 55 is used to integrate particular values over a user-specified time range. This can be used to study important statistics for simulations such as count, average, integral, minimum and maximum to name a few.

4.6.6 Type 77, Soil Temperature Profile

Type 77 can be used to model the vertical temperature distribution. The component reads temperature information such as the average soil temperature, amplitude of the temperature as well as some general information on the soil like thermal conductivity, density and specific heat. The dynamic temperature will follow the ambient air temperature over the year and can be used as the temperature on top of the storage volume for the vertical borehole heat exchanger.

4.6.7 Type 25c, Printer

Type 25c is a printer component used to get user-defined values printed in a data file. The component does not handle units and variables can be printed for different time steps, based on what details the user provides in the parameter settings of the component. The component also provides information about the simulation such as the name of the file and the total time of the simulation run.

5 Simulation Model development

Following the completion of the two TRNSYS courses, now it was time to create the simulation model. This part started with the load model building, and moved on with the HP model. During the final step of the system creation, there appeared some issues with the implementation of the borehole heat exchanger component which were deemed unsolvable during the thesis period. Between the load model and heat pump model design, the software was changed from TRNSYS17 to TRNSYS18 and some new opportunities arose that made the model work a bit better, but it still did not solve the main issues in order to make the complete model work as intended. TRNSYS18 made it easier to communicate and exchange files with others, since this is the most updated version, and the one most people use. It also has the advantage of being able to open and edit TRNSYS17 projects, but this does not work the other way around.

5.1 Load model development

The load model development was initially planned to be a minor part of the simulation model. But, after completing the courses, it became clear that the matching between demand and supply is crucial in order for the simulation to work, since both thermal and energy balance is a requirement in most TRNSYS components. Therefore it was not possible to use a small building for a small energy system and simply upscale everything. The initial lack of experience and knowledge with the software also caused errors because the different subprograms could not "cooperate" unless the different versions matched up. A trial-and-error phase for this lead to using the 2021 versions of SketchUp and TRNBuild with TRNSYS 18 for Simulation Studio.

5.1.1 SketchUp

The building was initially created with 1000 m^2 (25 m * 40 m) ground floor and height = 3 m. The window per wall rate followed the definition from the TEK17 standard, and with an assumed LT of 0,7 the total window area was 100 m^2. The building is shown in figures 10 and 11. One thing that is important to note is that TRNSYS only considers window area and cardinal direction with regards to thermal gain from the sun, so shape and placement on the wall is not important.

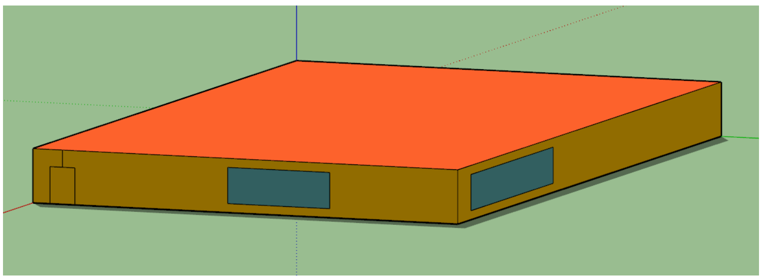

Figure 10: Building model in SketchUp shown from north-east.

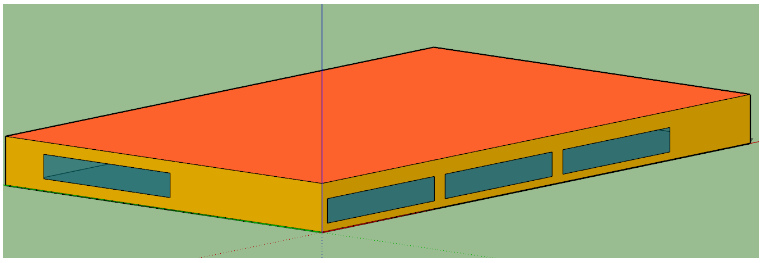

Figure 11: Building model in SketchUp shown from south-west.

SketchUp also provide a way of implementing shading for the building. Since the location and objects that can provide shading are not known at this stage, the shading option was neglected.

5.1.2 TRNBuild

After completing the building in SketchUp it was imported to TRNBuild as an idf-file. The building was now set up to fit the passive house standard. The infiltration rate was set to 0 and the ventilation was set to having 0.6 air change per hour with ambient temperature for the inlet air given by the weather data component. The temperatures for heating and cooling were set at 20 °C and 24 °C respectively. Since it is not defined in the standard, the 16 active hours of the day for "lighting", "technical equipment" and "domestic hot water" was set between 06:00 and 22:00. The thermal heat capacitance of the building, which is how much energy it takes to change the temperature 1 °C, is by default set equal to the thermal capacity of the air, 1,2 $\frac{kg}{m^3}$. For a more realistic simulation, the building needs typically has a higher thermal capacity to include furnishing. The rule of thumb for this value, which is something that the TRNSYS courses stated, is to multiply the thermal capacity by a value between 5-10. Based on this, the default value thermal capacity was multiplied by 7,5. The U-values for the walls/windows/door/floor and roof was adjusted to fit the NS3700 standard by adjusting the materials and thickness in each surface type.

This first setup of the building was done by using energy rate control. This is a way of modelling the building demand by adding a heating type (and cooling type) to analyse how much energy that is required to satisfy the set temperatures. This is not a realistic way to model the heating system, since the heating supply changes momentarily as the temperature goes below the set temperatures. The reason this method does not work when implementing other heat sources such as auxiliary heaters, heat pumps or other is that the simulation software is not able to realistically add heat and therefore switches from one value to another instantly which would not happen in real life. It does however serve as a good method to identify the demands and this can be used to properly size equipment for the energy supply system.

Temperature control is another way to manage the condition of the building in a more realistic way. For this method, delays and physical values such as the temperature will follow a more dynamic pattern. This makes it an improved way of analysing the temperature while constructing the rest of the system, to analyse changes and identify which parameters that affect the building load matching. After completing the load demand test, the TRNBuild

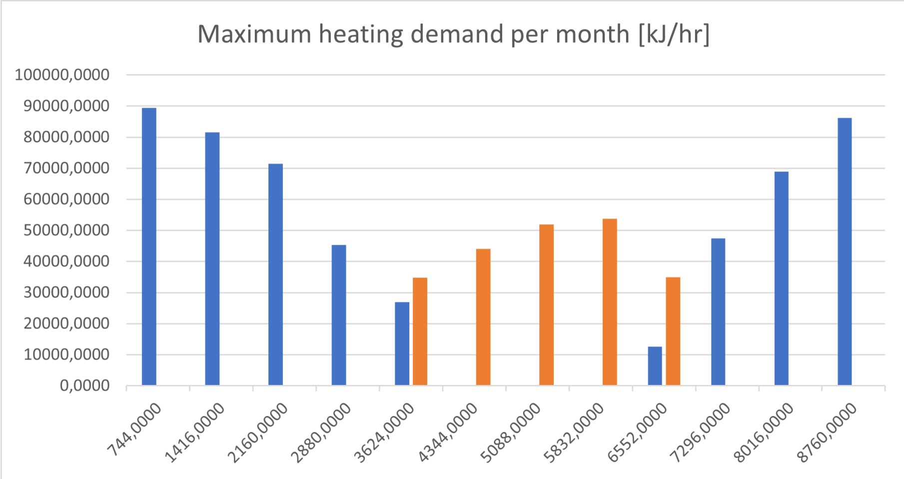

Figure 12: Maximum heating demand (blue) and cooling demand (orange) per month [kJ/hr] for Lanzhou. Time [h] marked for each month on the X-axis.

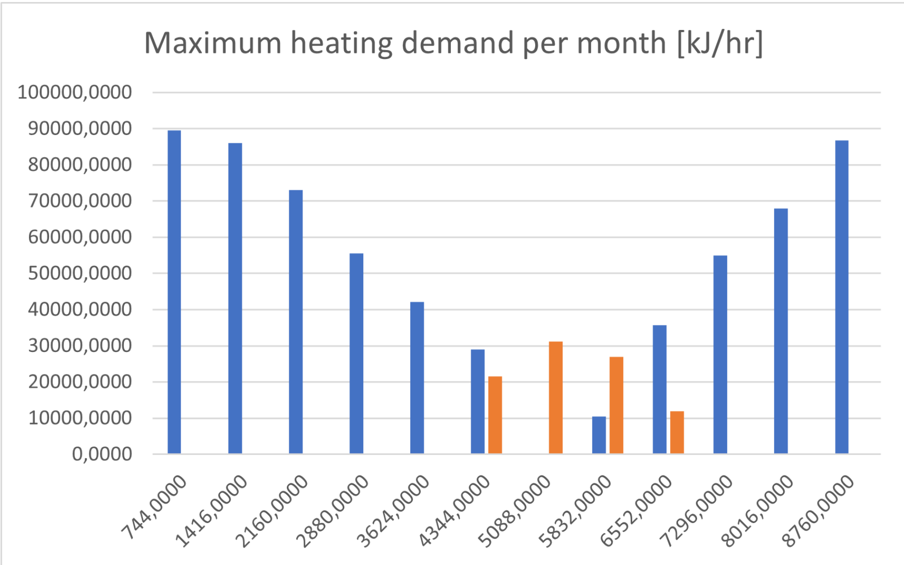

Figure 13: Maximum heating demand (blue) and cooling demand (orange) per month [kJ/hr] for Trondheim, Time [h] marked for each month on the X-axis

file was changed to this by removing the heating type that could provide unlimited heat and connecting it to a heat pump.

5.1.3 Simulation Studio

After completing the building setup in TRNBuild, it was imported into the Simulation Studio. By connecting the building component (Type56) with a periodic integrator (Type55) and a printer (Type25c), results reflecting the demands of the building over a year were produced. The graphs from this first building model test are presented in figure 12 and 13.
For both these graphs, the maximum heating demand for the whole year occurs in January, and converted from kJ/hr to kW the value is 24,9 kW. It should also be mentioned that the cooling demand was included as a way to compare the general temperature curves for

the locations. The graphs indicate that the climatic conditions are fairly similar in the two cities. Differences can be seen during the summer months in the middle of the graph, where there is a bit more more cooling demand for Lanzhou and more heating demand for Trondheim. It should also be noted that during the time of the simulation, since the building was managed with energy rate control, that the temperature flowed between the set point temperatures 20°C and 24°C.

Since the energy system should be able to supply heat for a neighbourhood (ZEN), the building needed to be scaled up somewhat. Since the correlation between heating demand and building size was unclear, a volume test was initiated as a trial. That meant looking at the volume for the first building and multiplying by the factor between 24,9 kW and the desired size of 4-5 MW, based on the economic review. The factor between 5 MW and 24,9 kW is approximately 200. So the next building should have a volume that was 200 times bigger than the first one, and hopefully the correlation between volume and heat demand was directly proportional. This meant a ground floor of 104 000m^2 and a doubling of the height to 6 meters. The reason why one building was used instead of 200, which was an option, was because the connection from the heat pump already seemed like a challenge when there was one building to handle. 200 connections between buildings to heat pumps would be extremely hard and time consuming to construct and analyse.

5.1.4 Volume test

The next step was to create a new building in SketchUp and repeat the steps from the first building. The volume test used to upscale the heating load demand did have some consequences with regards to the Norwegian standards. The internal gains, losses and window to wall ratio are intended for a small house, typically not more than 300m^2. In this case the floor area would extend to more than 300 times that size. The window to wall ratio would not be able to implement because the window area required would be bigger than the wall area, if the TEK17 specifications were followed. Instead, the same ratio as in the first building was followed which was approximately 25% of the wall was re-designated as window area. Also for the first simulations on the second building, testing the heating demand were surprising. The heating demand was completely covered by the internal gains. Therefore a decision to reduce the internal gains from people, lighting and technical equipment by 90%. By doing this, the heating demand appeared again while simulating. The decision to do all of these modifications did hurt the realistic appearance of the building simulation. The heating demands of this second building are presented in figures 14 and 15.

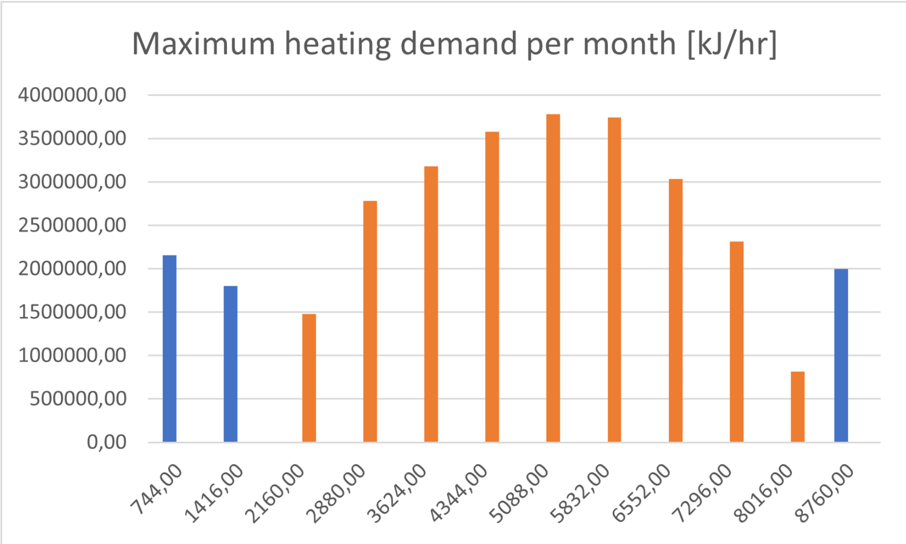

Figure 14: Maximum heating demand (blue) and cooling demand (orange) per month [kJ/hr] for Lanzhou. Time [h] marked for each month on the X-axis.

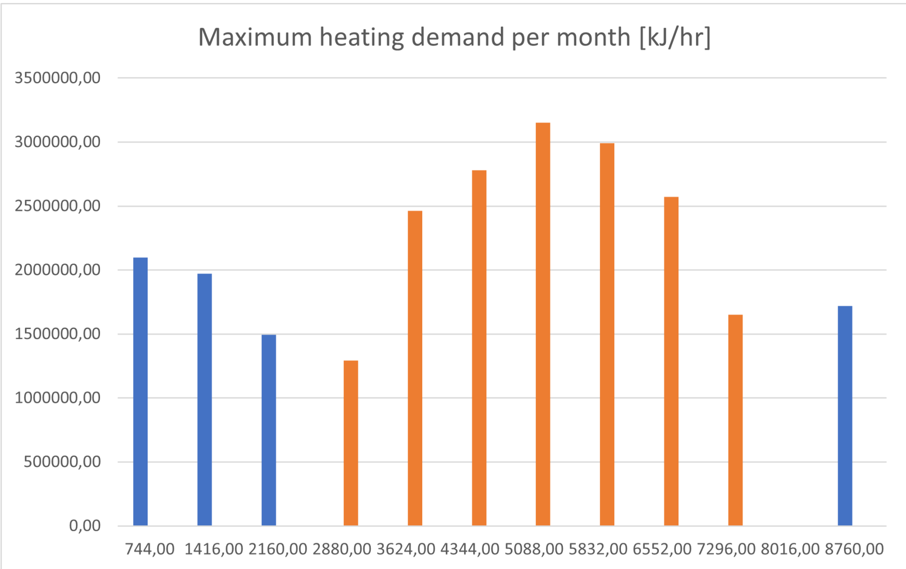

Figure 15: Maximum heating demand (blue) and cooling demand (orange) per month [kJ/hr] for Trondheim, Time [h] marked for each month on the X-axis

The converted values from kJ/hr to kW gave approximately 599 kW as the maximum heating demand for Lanzhou and 583 kW for Trondheim. The heating demand for this building varied a bit more for the two cities, Lanzhou and Trondheim. Based on this increase in difference in addition to all the modifications done in order to obtain realistic results for the second building, the aim of achieving a 5 MW heating demand was ended.

5.1.5 Adding waterborne system

Up to this point, the heat transfer from the heat type in the TRNBuild settings was based of an unlimited, unrealistic heat supply only meant for load demand testing. The next step was initiating a temperature rate control, where the heating was going to be supplied by an energy system consisting of, in the first phase, a heat pump. Since the chosen heat pump is water-to-water as normal district heating plants are, naturally the heating system within the building also needed to be waterborne. Both TRNSYS courses covered the use of heat pumps somewhat, but only as air-sourced heat pumps connected to the ventilation system, supplying heat through the air. The alternatives of connecting water to the building were either to use radiators to cover the space heating demand and a water tank to cover the DHW demand, or to add an active layer to one of the surfaces and eject heat to the building zone through circulating water within the active layer. The last of the two options were chosen because the alternative with radiators and water tank seemed a lot more complicated and it meant that the heating demand had to be split up into one for the DHW and one for space heating. Since the aim of this building initially was to simply represent the load of a neighbourhood, and the heating load demand already was in place as a combined value from the load model development, it was the logical way to go.

The active layer could be set up either as a radiant heating and cooling system for the ceiling or walls, as a capillary tube system or as a floor heating system. The latter was chosen based on having less requirements put on the input data, amount of active layers and on pipe sizes. The floor heating system that was chosen would need a higher temperature than usual systems. Typically, the temperature in floor heating systems are around 35°C, while for radiators it is approx. 70-90°C, so just based on the temperature level from the heat pump, it would suit a radiator system better (). To be able to connect the heat pump properly to the building, some inputs and outputs for waterborne heating were required, such as the temperature and the mass flow rate of the inlet and outlet water. The U-values for every surface needed to be kept the same as the load demand testing, so some modifications were also made to the construction layers in order to keep the thickness and U-values that it had prior to the active layer introduction. Table 3 shows the specifications needed to create the active layer. The values used for the pipe were default values.

Table 3: Active layer specifications

Layer parameter	**Value**	**Unit**
specific heat	4.19	$[\frac{J}{kg*K}]$
pipe spacing	0.2	[m]
outside pipe diameter	0.02	[m]
pipe wall thickness	0.002	[m]
pipe wall conductivity	1.26	$[\frac{W}{m*K}]$

5.2 Heat pump model development

The HP size in DH systems is normally affected by which alternative heat sources that are available and how much of the total energy and power demand that the HP should cover. In this case, the only source available is the heat pump. This means it needs to be sized to cover 100% of the heating demand during the coldest day. For every other day of the year, when the heating demand is smaller than the maximum, the heat pump will be operated on partial load, which is less than optimal because the COP therefore will be lower. An alternative to this is to have a secondary source to cover the peak hours when it is too cold for the heat pump to satisfy the required set temperatures. Since no secondary source is available, the heat pump is naturally oversized. Based on the second building load test, the heat pump should be sized to cover a maximum heating load of 599 kW, so a 600 kW HP should suffice.

5.2.1 Controlling the heat pump flow rate

There are multiple ways of controlling the operation of the system through temperature control of the circulation pumps and heat pump. From the very start the idea was to make this phase as simple and quick as possible. So the initial test simulations with the heat pump and the building were run with only minor adjustments to the heat pump component. But the results were unsatisfactory, and a lot of errors occurred because of the heat pump data file and its mismatch with what the heat pump was trying to supply. A simple thermostat (Type166) was introduced to manage the temperature from the heat pump in order to maintain the set temperature for the building. There were also a lot of errors when using a single speed pump (type114) due to operation issues, where the circulation pump turned off and on again between 0% and 100% mass flow rate which caused errors for the temperature and heat transfer rate. By changing it to a variable speed pump (type110), simulation results became much more dynamic and were able to vary more smoothly without any errors. The final modification done prior to working on the data file was to add pipes (Type31) for the inlet and outlet of the load side of the HP. This was a measure to reduce convergence issues.
Data file development
In the TRNSYS documentation for the T927 water-to-water heat pump it is stated that "Type927 is not a first principals model but relies instead upon catalog data readily available from heat pump manufacturers". This might be true given a general HP where any working fluid can be used. But this proved to be a harder task than expected, given that the heat pump needed to be of a certain size and it had to be for CO2. One catalog data had some of the data required, from Fenagy, a Danish heat pump manufacturer. The nominal conditions for this 600 kW heat pump are given in the list below:

- Supply temperature: 70°C
- Return temperature: 40°C
- CO_2 temperature out from gas cooler: 42°C
- CO_2 pressure at gas cooler: 110 bar
- Ambient air temperature: 5°C
- Relative humidity: 85%
- Evaporation temperature: -2°C

Using these nominal conditions with the Simple One Stage CO_2 software, some useful values for the heat pump data file are calculated, shown in the list below:

- Q_{gc}: 173.92 $[\frac{kJ}{kg}]$

- Q_e: 120.96 $[\frac{kJ}{kg}]$

- W: 58.84 $[\frac{kJ}{kg}]$

The internal heat exchanger is set to 0% since it can not be included in the TRNSYS simulation model. Some assumptions made in addition to the values calculated are the isentropic efficiency = 85%, heat loss factor for the compressor = 10% and 0K super heat before the compressor.

5.2.2 Heat pump and load model results

Figure 16 shows how the model looked like when the heat pump and all its control components were connected with the building component. It was during this time that the data file was developed.

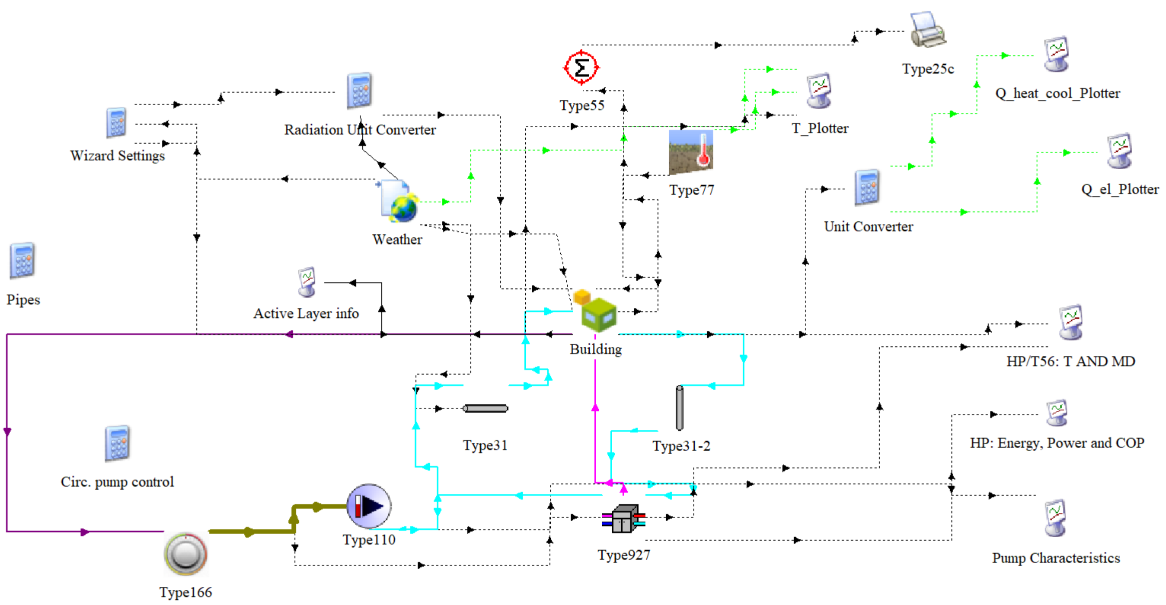

Figure 16: Simulation Studio image of the simulation model with the heat pump and building component.

The first data file were based on equations 1,2,3,6,7 and 8. After analysing the results of the simulation, it was clear that it was a bit too dependant on the nominal case, and the COP in practice was set as a constant throughout the simulation. The reason was that the power drawn and heat transfer from the gas cooler was set as proportional to each other, so the relationship between energy in and out of the HP system was constant. The results from this phase are shown in figures 18, 19, 17, 20 and 21.

Figure 17: Outlet temperature and outlet heat transfer from the circulation pump.

The red graph shows the temperature of the water going out of the circulation pump. The yellow graph is a user-defined constant set for the pump with no influence on the thermal process.

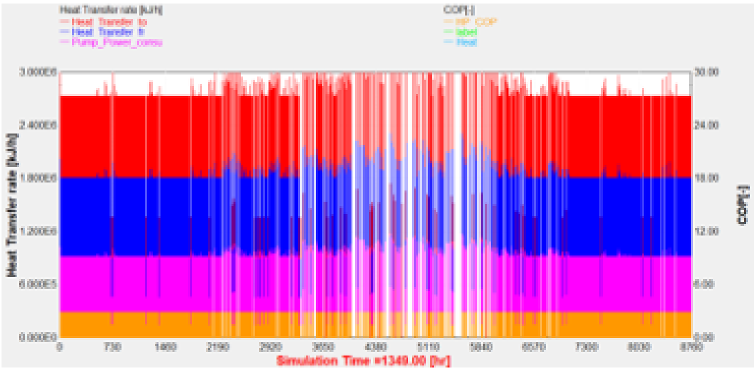

Figure 18: Heat transfer from the heat pump to the building, heat transfer from the source to the heat pump, COP as a constant and the compressor power (not pump power).

This figure shows the heat transfer from the gas cooler to the building. It also shows the heat transfer from the source and the COP. The source side is in this instance given as constant values for temperature and flow rate. The COP is also a constant because of the fixed ratio between Q_{gc} and power draw for the compressor.

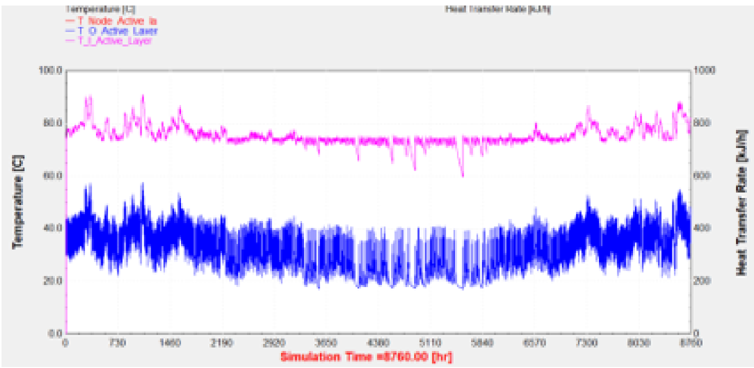

Figure 19: Temperature profile for inlet and outlet of the active layer.

This graph shows some added outlet parameters defined just for the active layer. The pink color represents the temperature at the inlet and the blue color represents the temperature at the outlet.

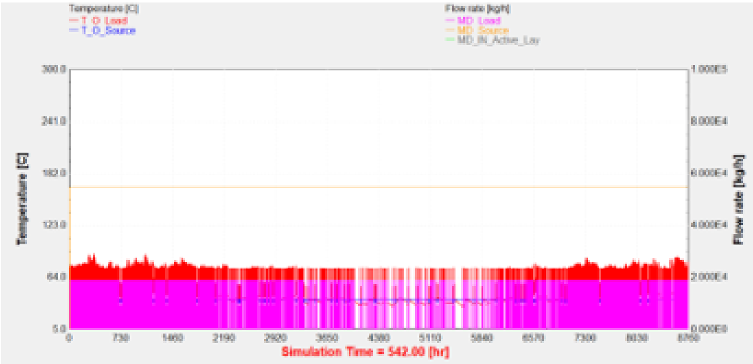

Figure 20: Temperature and flow rate for the outlet on the load side of the heat pump.

This graph shows the temperature for the water at the outlet of the heat pump as well as the mass flow rate.

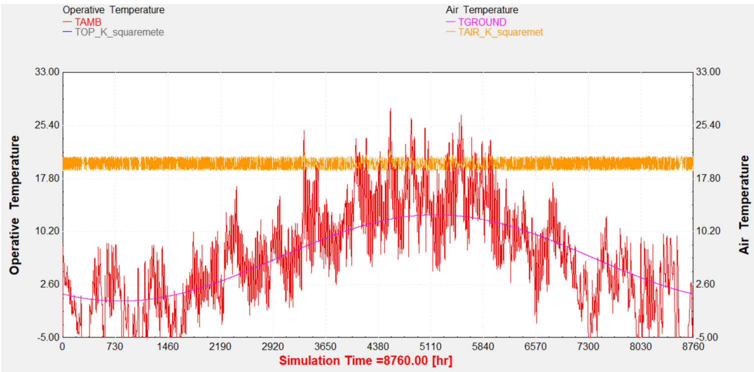

Figure 21: Temperature of the air in the building, ambient air temperature and temperature in the ground.

Figure 21 shows what the temperature profile for the building, ambient temperature and ground temperature looks like over a year.

The data file for the heat pump was modified by basing it on the mass flow rate of CO_2 rather than the nominal case where the COP was constant. It then became a much more realistic simulation where the mass flow rate varied with time, the COP became a bit worse and dropped to approximately 1.9, but at least now it followed the varying temperatures and mass flow rates of the system.

5.3 Borehole heat exchanger development

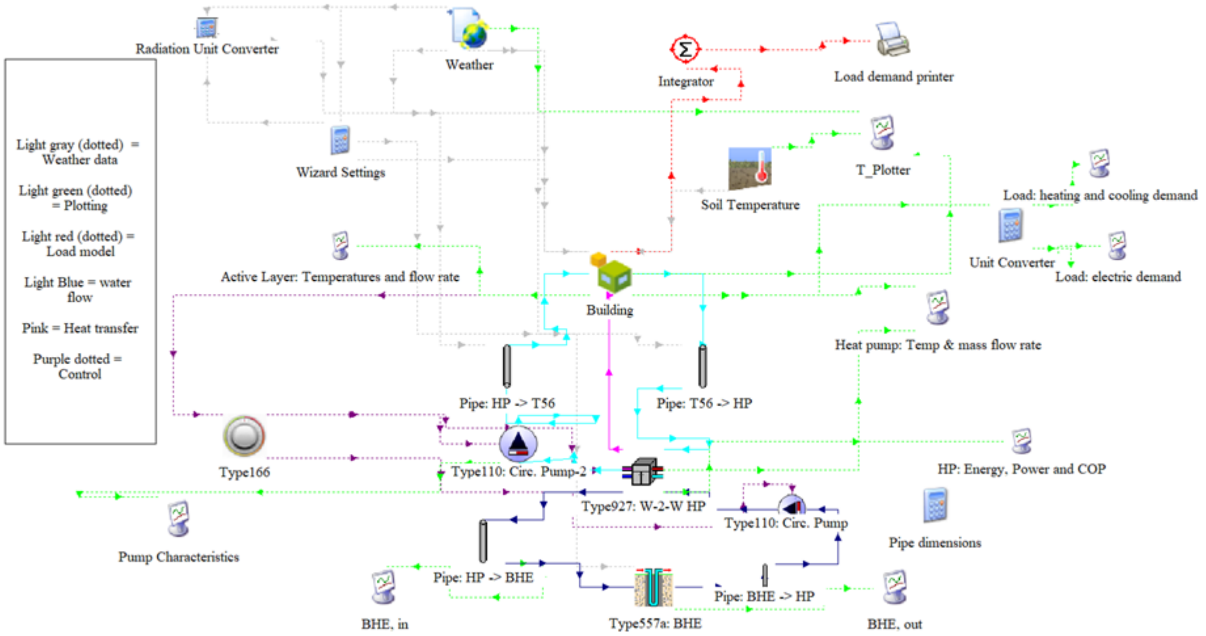

Figure 22: The complete district heating system with heat pump in combination with a borehole heat exchanger supplying heat to a building.

The initial implementation of the BHE component was successful. The constant values used as the source side for the heat pump became replaced with a water flow that went through the BHE and absorbed heat which it delivered to the evaporator in the heat pump. Figure 22 shows how the complete simulation model looked like with everything in place. The default values for the BHE component worked together with the other two subsystems, but of course some modifications had to be done before the BHE was a proper model. Step-by-step modifications to the parameters with implementation of geological conditions for Lanzhou and Trondheim went to plan until something unexpected happened. The depth would not go beyond approximately 1850 meters. All versions of the Type557, a, b, c and d were tested to find out whether it was a limitation in only some of them. But whichever was used, it would stop at this depth. The temperature gradient was also a troublesome parameter. The program would accept only minor adjustments to this variable, but only if the depth had a low value. Throughout the work with TRNSYS, errors had become a common thing whenever a new component was introduced, or parameters were changed. But this issue was a new one. The simulation did not run at all and some specific error messages popped up each time. The error messages are shown in figures 23 and 24.

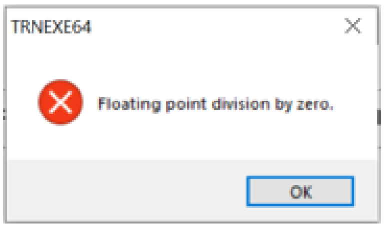

Figure 23: One of the two error messages that popped up whenever the depth of the borehole heat exchanger went beyond 1850 meters.

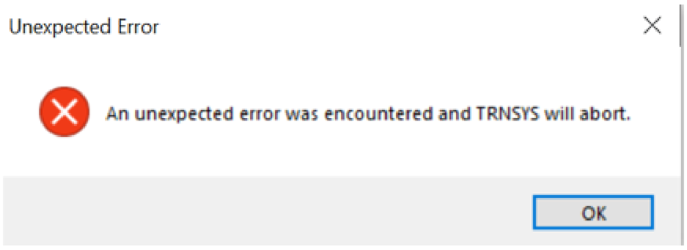

Figure 24: The other of the two error messages that popped up whenever the depth of the borehole heat exchanger went beyond 1850 meters.

Usually the debugging procedure would start by checking the simulation log and look at errors, warnings and notices, which would inform whether there was anything wrong or unclear about any of the components or connections throughout the simulation period. But this new issue did not show any errors, and the warnings and notices did not mention the BHE component.

5.4 Verification

Due to the issues that arose with the BHE implementation, the simulation results never came to a stage where the simulation model could be verified.

5.5 Optimisation

The process of optimising the simulation model was done throughout, at least for the load model and the heat pump model. The optimisation consisted of practical changes to make the model function as a system, rather than to increase the COP, the operation and the performance in general.

5.6 Scientific paper draft proposal

Due to time limitations, this section of the thesis was not prioritised.

6 Discussion

6.1 load model development

The main challenge while setting up the building load model was the scaling of the model. Every possible way of getting the first functioning building model to become a bigger functioning load model had flaws. The ideal way would have been to just create several buildings to match the typical size of a neighbourhood. But the lack of experience with the software, especially with waterborne systems, made that option less desirable since the already challenging part of connecting the heat pump to one zone and make the system work was hard enough. If even more buildings needed to be connected to a heat pump, then it would make the system even more complicated than it already was. During the work with the load model, minor adjustments were necessary throughout the process just to make things work. And the initial desire to understand each component, connection and process was constantly being tested by being provided with an option of simplifying different phases to make things work. The volume test made the building incredibly big, with a ground floor of 104 000 m^2, which does not fit the Norwegian building standards at all. The use of NS - Norwegian standards was mainly chosen to create a more realistic load model. There are however, a lot of specifications and details that are neglected, since the building analysis is restricted to the thermal and the energy aspect, which might make this a less than optimal way of treating the load model.

6.2 Heat pump model development

The heat pump component was a challenging aspect of the simulation model. The reason why it was challenging, was mostly due to the nature of the component itself. It is not made like a real heat pump cycle with several internal components, where the working fluid flows from the evaporator to the compressor and then to an expansion valve via the gas cooler and back to the evaporator again. One of the prerequisites for achieving a good performance for systems with CO_2 heat pumps is that the DHW is a decent portion of the heating demand, as Stene (2005) concluded with. Since all of the heating demands was mixed into a single value, the splitting of the demand into space heating and DHW was not possible. This lead to a low temperature lift of the water on the load side, and therefore a low avg. COP value. Type927 only relies on a data file with given boundary values for temperature and mass flow rate, which then are used to calculate the heating performance and power draw for the entire heat pump. With a given data catalog this would have been pretty straight forward, but since the thesis was based on a promising, yet somewhat limited working fluid, this task was a lot harder than initially thought. An alternative to trying to make the CO_2 fit into TRNSYS, it could have been concluded in an early stage that TRNSYS is not suitable for it. It is very difficult to properly facilitate the system for CO_2, at least for the type927, since several gas coolers, internal heat exchangers or several compressors as a way to improve its performance needs to be reflected in the data file that the component is based around.

An option that makes sure that the nonlinear relationship between temperature and entropy for CO_2 in the trans-critical area does not affect the heat pump and its impact on the system is to go for an alternative working fluid. Propane is an example of another natural working fluid with many of the same advantages that are related to CO_2 as a working fluid. Another option is to create a new component. This option is an extreme one, that would require a lot of work with coding and development, but it would at least secure the total understanding of the process within the component.

6.3 BHE development

All of the components in TRNSYS have their own mathematical reference. One thing that makes the Type557 stand out is that its mathematical reference is not based on being used for TRNSYS. It is a very old model with detailed thermal processes for the borehole heat exchanger. Since the issues that arose when the depth went beyond 1850 meters were related to a ”Floating point division by zero”, it indicates that there somewhere is an equation with a fraction with a denominator that becomes zero whenever an unknown limit has been reached. After studying the mathematical reference, the origin of this issue did not become any clearer. A theory based on a limited experience with the software is that this component is not meant to serve as a major scale heat source. Other projects within the ChiNoZEN research project focuses on shallow geothermal energy systems, and there are reports on heat storage and for cooling purposes, but not for heat extraction with deep borehole heat exchangers deeper than 2000 meters. As mentioned for the heat pump component, a way forward could be to design a new component for a borehole heat exchange unit where every equation that gets included in its mathematical model is known and perhaps it could be designed to function better as a heat source, than the existing type557.

6.4 TRNSYS

With issues for two out of the three subsystems for this simulation model, it seems only natural to consider if the chosen simulation software, TRNSYS, might not have been the best option available. Or it could be that there is nothing wrong with the components or the software itself, and the errors and issues that were identified throughout the process of developing the simulation model were simply caused by the user. It is safe to say that TRNSYS is a highly complex software that can be used for a lot of different purposes and there are many ways to model real life systems. But perhaps it is not suitable for every system, and there might be a good idea to consider other options for the continuation of the development for the simulation model.

Most of the decisions made while working on the development of the simulation model were made based on a belief that understanding each component, every connection and the system as a whole was necessary in order to analyse, verify and optimise it as soon as it was complete. Looking back, as the model was not completed entirely, some deviations from this initial idea would have made the model development process easier. On the other hand, this would have lead to not understanding completely the process in the subsystems.

7 Conclusion and further work

China and Norway are two countries, both with ambition and the opportunity to focus on geothermal energy as a way to solve their current and future energy problems. Based on price, it seems like Norway might be the better location due to high electricity prices and this could easily make the investment costs of a geothermal system a successful one. On the other side, China has much better geological conditions in terms of temperature gradient and the fact that they already have oil wells that can be modified for geothermal heat extraction. The technology is there, but as of now, the investment costs are the biggest hindrance to really boost the geothermal energy sector. Through projects like ChiNoZEN, technologies that are more cost efficient can be designed and maybe in the future, there will be more geothermal energy systems than today.

The objective with this Master's thesis was to contribute to the development of a district heating system that utilises heat from geothermal borehole heat exchange units in combination with CO_2 heat pumps. The simulation model development did not go as planned, but at least some information on the challenges for this work was identified, and this can be built upon by future project contributors.

7.1 Further Work

Two important components were analysed through simulation model development in addition to a successful load model construction. The two components are type 557 and type 927 which both had their own weaknesses. Type 557 just stopped working due to some unknown mathematical error. For further work, this component can be replaced with a new component made from scratch. This will require a lot of work, but it will have a huge advantage when analysing operation and heat transfer between the fluid and the bedrock because all equations that it consists of have to be put in by the user. For type 927 there were some concerns with the working fluid CO_2, and it might be a good idea to investigate either other components or as for the type 557, create a new one.

In general there might be too many challenges for this type of geothermal system in TRNSYS. Maybe the simplest option is to find a more suitable simulation software in order to develop the simulation model.

Further work for this model development could also include looking at cooling demand in order to use the simulation model for other climates as well. Or to properly design the system for a ZEN, local production of energy has to be completed somehow, and this might also be an interesting study for the future.

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