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Evaluation of Geothermal Heat Pumps System for Energy-Efficient Heating in Norway

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Summary:

The utilization of geothermal heat pump systems has emerged as a promising solution for sustainable and energy-efficient heating/ cooling in Norway. Norway, as the third-largest exporter of energy in the world and with an electricity supply dominated by hydropower, has benefitted from heat pumps to reduce electricity consumption peak loads and dependency on fossil fuels for energy production. This thesis aims to model a geothermal heat pump system, considering a single borehole within the Norwegian context. A comprehensive literature review is conducted, encompassing shallow and deep geothermal energy sources alongside various geothermal heat pump systems. The mathematical framework for heat transfer modeling in the wellbore is applied based on the infinite line source solution (ILS). To implement the mathematical model, phyton programming is applied. The effect of various factors governing heat transfer to the fluid, such as time, heat load, distance, soil thermal conductivity, geothermal gradient, inlet temperature, flow rate, and heat conductivity of wellbore/ grout material, is investigated. A sensitivity analysis is performed to investigate the impact of variations in key parameters on system performance. The technical and economic results indicate the vertical geothermal heat pump system, due to the higher temperature gradient and heat transfer area, can be an effective way to provide energy-efficient heating since power is produced from free and zero-emission source.

Preface

This work was done at Faculty of Technology, Natural Science and Maritime Sciences, Department of Process, Energy and Environmental Technology at the University of South-Eastern Norway in spring 2024. The project represents the deep research and thoughtful analysis undertaken with the kind guidance and support of my supervisor, Professor Carlos F. Pfeiffer, and my external co-supervisor, Professor Mohsen Assadi.

As I share this thesis, I hope it inspires further exploration and inquiry within the academic community. May it contribute to the advancement of knowledge and serve as a foundation for future research endeavors.

Porsgrunn, 15.05.2024

Afsaneh Sadat Boloorchi

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Nomenclature

AAHP	Air-to-air heat pump
ASHP	Air source heat pump
AWHP	Air-to-water heat pump
BHE	Borehole heat exchanger
CLGS	Closed loop geothermal system
COP	Coefficient of performance
DOE	Department of Energy
EGS	Enhance geothermal system
FLS	Finite line source
GCHP	Ground coupled heat pump
GHP	Geothermal heat pump
GSHP	Ground source heat pump
GWHP	Ground water heat pump
HDR	Hot dry rock
HVAC	Heating, ventilation, and air conditioning
ILS	Infinite line source
IRENA	International renewable energy agency
NOVAP	Norwegian heat pump association
NVE	Norwegian water resources and energy directorate
SSB	Norwegian Statistics bureau
SWHP	Surface water heat pump
TR	Thermal resistance

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1 Introduction

Global warming poses a significant challenge to society as it arises from greenhouse gas emissions. To mitigate global warming and its dramatic effects on our nature, solutions are proposed to reduce CO_2 concentration in the atmosphere by either reducing the emission of CO_2 or capturing CO_2 and underground storage. According to the Paris Agreement (2015), to keep the average global temperature increase below 2 ^oC, the CO_2 concentration in the atmosphere should be kept below 450 ppm [1]. In addition, the Intergovernmental Panel on Climate Change (IPCC) scientific consortium has urged the reduction of fossil fuel combustion in power generation by 20% by 2050 and to completely stop using it by the end of the century [1]. To achieve this goal, many countries seek new energy forms and focus on developing renewable energies [2], [3].

A substantial portion of the world's fossil fuel-based energy supply is used for heating, almost 50%, while only 20% and 30% go to electricity production and transportation (IRENA [4]). As a result, energy supply for heating and cooling accounts for over 40% of global CO_2 emissions, which has a huge negative impact on the environment [5]. According to IRENA, almost 62% of energy for heating purposes is derived from fossil fuels, and the rest is obtained through biomass (26%) and renewable energies (12%). These values highlight the importance of developing renewable energies to reduce CO_2 emissions. On the other hand, according to IEA (2018), the demand for cooling energy will increase up to 45% by 2050. Higher standard levels of living and global warming are the main reason for increasing cooling energy demand. To satisfy energy demands for cooling/heating purposes, geothermal energy has attracted outstanding focus [6].

Geothermal energy is considered a crucial solution for providing secure and sustainable energy and concurrently reducing the need to burn fossil fuel for energy production purposes, mitigating the emission of greenhouse gases, and avoiding the problem of acid rain precipitation [6], [7], [8]. Geothermal energy can be utilized for three purposes: electricity generation, direct heating, and indirect heating/cooling through heat pump systems [9], [10]. According to IEA, one-sixth of natural gas globally and one-third in Europe is currently used for heating purposes. However, heat pumps are currently four to five times more efficient than natural gas boilers [11]. Heat pumps make householders less vulnerable to fossil fuels' prices and play a significant role in achieving a net-zero emission target by 2050 [12].

Geothermal heat pumps, called ground source heat pumps (GSHP), transfer heat between buildings and ground through wellbores [13]. The main idea of using heat pumps is to mobilize heat rather than generate it. Based on this concept, heat is extracted from the heat source and transferred to a needed place. When heating is required, heat will be transferred from the ground (i.e., heat source) to the building, and when cooling is required, heat is taken from the building and transferred to the ground (i.e., heat sink). Ground temperature deeper than 20 m is independent of seasonal fluctuation and is almost constant throughout the year, following the geothermal gradient [14].

Although most of the heat pump installations occur in North America, Europe and China, the number of countries with installations increased from 26 in 2000 to 54 in 2020 [15]. In 2021, heat pumps were only be used for 10% of space heating globally. However, the pace is dramatically increasing; it is expected that heat pump capacities globally increase from 900 GW in 2021 to 2700 GW in 2030. This amount is equivalent to 19% of the required heating demand. In countries such as Norway, Finland, and Sweden, heat pumps have already played a significant role in heating buildings, and according to IEA, 60% of the building in Norway and 40% of buildings in Finland and Sweden are equipped with heat pumps. Interestingly, the cold climate in these countries has not hindered them from using geothermal energy. In addition, Norway, as the third-largest exporter of energy in the world and with an electricity supply totally dominated by hydropower, has benefitted from heat pumps to reduce electricity consumption peak loads and dependency on fossil fuels for energy production [16].

To accelerate using heat pumps, we need to overcome some barriers. Many studies and analyses have focused on addressing some barriers, optimizing the design configuration and developing materials to make GSHP more efficient [17]. Some barriers are global, and some are local and only affect specific countries. Installation of heat pumps is quite expensive in the short-term [12], and attractive financial offers from governments in the form of tax-reduction, CO_2-tax, low-interest loans and green mortgages are required to motivate customers to use them. In a study [6], the cost of geothermal heat pump systems was compared with conventional heating systems in three province of Canada, including Alberta, Ontario, and Nova Scotia. The results showed that GSHP can be economically beneficial if the electricity price is low. On the other hand, from the supply side, a lack of skilled installers and supply-chain vulnerabilities hinder the use of heat pumps.

According to the latest annual report published by the IEA (2022), there are more than 60,000 installations of heat pump systems in Norway, which are primarily air-to-air and air-to-water systems. The total equivalent thermal energy extracted using GSHP in Norway is 3 TWh, and it is expected to be increased to 8 TWh by 2030 [12]. Universities and research centers in Norway are extensively working on improving GSHP systems to accelerate the deployment of geothermal heat [16].

In GSHP, heat from the ground can be extracted through wellbores which can be position in either vertical or horizontal and based on the depths of wellbore, it can be divide into deep (> 400 m) and shallow geothermal energy systems [18]. The deeper the wellbore, the higher amount of heat energy can be extracted. However, in Norway, most of the installed GSHP systems are shallow type. Throughout this master thesis, it is focused on geothermal heat pumps system for energy-efficient heating in Norway, and an energy model for GSHP system is presented.

1.1 Background

Despite being the world's eighth-largest natural gas producer and third-largest exporter of natural gas, Norway has significantly used renewable energies for electricity production. According to Norwegian Statistics bureau-SSB (2023) [19], in December 2023, 14 TWh electricity is produced in which almost 88% is produced by hydropower and around 11% is produced by wind power [20]. Before the recent years, due to the low electricity-price in Norway, electricity has been widely used for direct heating purposes through the use of electric resistances. However, the sharp increase in electricity prices in recent years (especially in 2022) made society, especially researchers and industry, focus on more beneficial substitutions. Among the different options, using GSHP has attracted significant attention.

Despite locating in a cold area, Norway has significantly benefitted from heat pumps over the last decades, and currently, according to NOVAP, more than 60,000 heat pumps have been installed in Norway and produce more than 3 TWh of heat annually. According to the European Heat Pump Association, Norway has the highest number of operating heat pumps per capita in Europe [12]. Furthermore, interest in using heat pumps is increasing, and it is expected to reach 8 TWh by 2050. Developing unique heat pumps that operate perfectly in freezing weather (tested for –30 ^{o}C), longer heating seasons in comparison with other European countries, fluctuations in electricity price, global warming, and possible dry times, which can affect water magazines and consequently reduce hydropower productions, a huge number of skilled installers, proven records and be applicable for remote areas, especially mountain cabins, are among reasons for increasing interests.

Due to the existence of crystalline rocks in the geology of Norway and low heat conductivity (measured in the mainland (heat flow value): 58 mW/m^2 [21]), deep GSHP can be more beneficial, and it has been successfully proven in several pilots. However, most operating heat pumps in Norway are currently considered shallow geothermal heat pump systems [22]. In order to accelerate the deployment of deep geothermal, Norway can benefit from the proven record of industrial and academic expertise in Norway with a focus on drilling deep/horizontal wellbores, well technology, and reservoir management [16].

According to IEA 2022 [16], *"There is no electricity production from geothermal resources, and there are no deep geothermal energy installations in operation in Norway"*. Borehole heat exchangers are used in the majority of vertical closed-loop GHP systems in Norway to extract heat or cold from crystalline rocks [16].

University of Stavanger (UiS) has been working on a project with around 120 wells. Most of them have a 300 meter depth; however, only two well have been planned for a 650-meter depth. Two heat pumps of 1.3 MW will be connected to these wells. The original target of the current Master's project was using the data from the UiS project, but due to the unavailability of information, input data from existing articles have been applied.

1.2 Objectives

The research objectives in this master's thesis can be divided into the following tasks:

- Literature review on geothermal heat pump systems, with a focus on shallow and deep geothermal, both in scientific and available industrial information.
- Advantages and disadvantages of different types of GHPs for specific areas of Norway.
- Develop an energy balance model to determine the main variables of a geothermal heat pump system and estimate the coefficients of performance of the heat pump system under different conditions, using the UiS data if available.
- Analyze the viability of these technologies for different regions of Norway, considering technical and economic factors.
- Optional (depending on time constraints): propose a case scenario (for example, a large public or multi-apartment building) where a GHP system is used for heating/cooling. Indicate how the case scenario can evaluate the system's performance under different demand and seasonal variations.

1.3 Methods

A comprehensive literature review was conducted to investigate different types of geothermal energy and geothermal heat pump systems, considering the advantages and disadvantages of each type and gathering relevant data, theoretical frameworks, and related methodologies. This literature served as the basis for designing the research methodology and guiding the interpretation of results. The literature review was also focused on geothermal energy in Norway and compared it with other Nordic countries.

The mathematical framework for modeling the heat transfer in the wellbore was based on the infinite line source solution (ILS), which provides an analytical expression for the temperature distribution around a vertical borehole heat exchanger. This solution accounts for the heat extraction from the ground by the geothermal heat pump system. It enables the system's performance to be estimated, which means how much heat can be extracted from the surrounding wellbore soil/ rock under varying conditions.

The Python programming language was applied to implement the mathematical models and algorithms necessary for simulating the energy model, which was used to find the heat extraction from the surrounding rock/ soil to the wellbore and the power output from the ground-source heat pump system (GSHP).

Several parameters govern heat transfer to the fluid in the wellbore. The key parameters include the thermal conductivity of soil, geothermal gradient, heat transfer area, inlet temperature and flow rate of the fluid, wellbore diameter and length, thermal properties of the fluid, and thermal conductivity of wellbore/ grout material. Sensitivity analysis was performed to investigate the impact of variations in input key parameters on system performance. This analysis provides insights into the robustness of the system designs and helps identify critical factors that influence the system.

Norway was considered as a case study, and the input data were extracted from scientific articles and academic research documents.

1.4 Report Outlines

The thesis is divided into 5 chapters and 3 appendices.

Chapter 1 covers the introduction and the general information about the project. A literature review on the topic and previous studies are presented in Chapter 2. This includes briefly reviewing of the geothermal heat pump systems, considering shallow and deep geothermal, and evaluating geothermal heat pump systems in Norway. The review in this chapter presents the advantages and disadvantages of different types of geothermal heat pump systems. Chapter 3 is dedicated to the energy balance model, the sensitivity analysis of various parameters of the energy model, heat extraction from geothermal sources, and the determination of the main variables of a geothermal heat pump system.

Results and discussion are reported in Chapter 4. This chapter contains the main findings, and draws conclusions based on the results and analysis. Input data, which was used in this project, extracted from different papers. Chapter 5 explains the conclusion of the project. Some suggestions for future works are presented in conclusion.

2 Literature Review

In this chapter, a literature review on the various types of geothermal heat pump systems (GSHP) focusing on shallow and deep geothermal energy has been done. The advantages and disadvantages of different configurations of geothermal heat pumps, as well as the operation principle of GSHP, have been investigated. In the literature review, Norway is considered as a country to investigate statistics and potential in geothermal energy and geothermal heat pump systems.

2.1 Geothermal energy

Geothermal energy emerges as a promising renewable energy option owing to its inherent characteristics of reliability, safety, and environmental sustainability [7]. It refers to internal heat energy stored within geological materials such as rocks, groundwater, sediments, and magma spanning the Earth’s surface to its core [1].

Geothermal resources are typically categorized into three types based on temperature: low, moderate, and high-temperature resources. The classifications are widely accepted within geothermal communication and are available in geothermal standards [23]. Geothermal energy is a sustainable resource that can be used in electricity generation, as well as applications involving direct heating and indirect heating and cooling heat pump systems. Electricity generation uses high-temperature resources while direct heating and indirect heating and cooling systems use medium, and low-temperature resources, respectively [10].

Since high and medium-temperature thermal energy resources can be reached within the Earth’s depth, it brings with it the high cost of drilling; however, low-temperature resources are easily accessible and can be extracted in most locations [24], [6].

Shallow and deep geothermal energy resources represent the main categories of geothermal energy. Unlike petro-thermal energy, both categories enable heating, cooling, and underground heat storage, employing similar technological concepts for heat recovery from the subsurface. In other words, the terms “shallow” and “deep” pertain to the depth at which the heat absorber is either from an open-loop subsurface water system or solid ground via a closed-loop heat exchanger [25]. Considerable attention has been devoted to shallow and deep geothermal energy resources. Some researchers have advocated for an additional classification termed semi-deep (medium) geothermal sources, supplementing the existing shallow and deep categories. Moreover, experts disagree regarding the depth classification of shallow geothermal sources, with some defining it as extending up to 300 meters. In comparison, others argue for a limit of up to 400 meters. In this project the shallow geothermal considered up to 400 meters.

Figure 2.1 illustrate a schematic of shallow, medium, and deep geothermal energy resources.

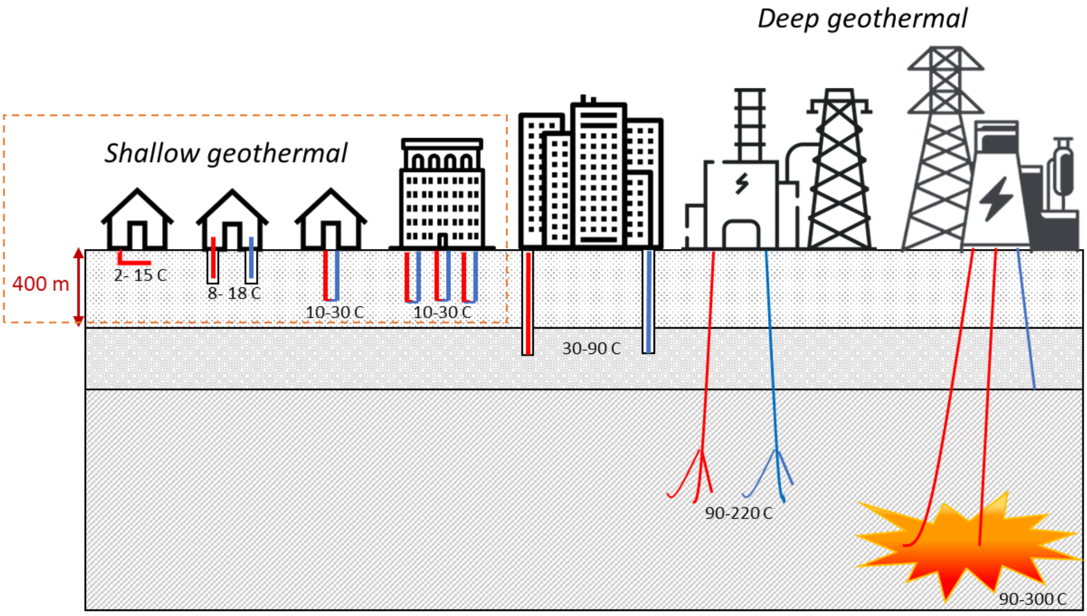

Figure 2.1: Schematic of shallow and deep geothermal energy [1]

2.1.1 Shallow geothermal energy

Shallow geothermal energy refers to low-temperature heat (approximately below 30 ^{o}C) retained in the shallow, typically at depths up to 400 m [26].

The primary purpose of the deep geothermal system is to produce geothermal power. The fundamental idea is to heat groundwater using infinite geothermal energy, convert it to superheated steam, and then use that working fluid to move the turbine and produce electricity. The second law of thermodynamics elucidates the differentiation between shallow and deep geothermal energy [23].

In order to enable the shallow geothermal energy utilization of any terrain, research and development of closed-loop geothermal heat exchanger technology began concurrently in Sweden and the USA in the 1970s [1]. For more than 50 years, shallow geothermal heat pumps have been applied to heating and cooling aims [27].

Heat pumps extract thermal energy at low temperatures and elevate it to levels suitable for practical applications. Geothermal heat pumps offer an environmentally and economically advantageous solution for space heating and can also be effectively employed for space cooling objectives [28]. Although the earth's geothermal energy is freely accessible, the heat pump for improving the lower-grade heat uses comparatively costly electricity [27]. The primary benefit of geothermal heat pumps is their ability to utilize soil and groundwater temperatures ranging from 5 to 30 degrees Celsius, which are typical at suitable depths around the world [6].

There are four varieties of geothermal heat pump loop systems that transfer heat to or from buildings and the earth. Horizontal, vertical, and pond are closed-loop systems. The open-loop option is the fourth category of them [28].

2.1.2 Deep geothermal energy

The heat retained at depths over 400 meters is known as deep geothermal energy. Earth's temperature rises with depth by the regional geothermal gradient. For instance, average

subsurface temperatures in the UK are approximately 40, 90, and 140 °C at 1000, 3000, and 5000 meters, respectively. These temperatures are high enough to produce heat directly for space and hot water heating without needing a heat pump [26].
Another possible heat source for heat pumps is deep heat wells found in bedrock. A deep heat well has the capacity to extract a significantly greater amount of heat from a given area, thus facilitating the installation of heat pumps in areas with a high population density [29].
The most promising advancements in future geothermal energy lie in developing deep geothermal heat, which resides in hot, dry rocks at technically feasible depths ranging from 3 to 10 kilometers. Remarkably, K.E. Tsiolkovsky initially proposed the concept of extracting energy from solid hot rocks as early as 1897 [30].
To utilize deep geothermal systems for power production, industrial operations, agriculture, and residential or commercial space heating, deep wells must be drilled to reach temperatures high enough to be used directly (without the need for a heat pump) in district heat networks [26]. Deep geothermal opportunities arise in geological formations, like deep sedimentary basins and radioactive granites. Electricity generation from deep geothermal sources can utilize the heat naturally present in hot water within the ground, known as hydrothermal geothermal energy. These energy resources are classified as conventional [31]. By forcing high-pressure water injections into deep rocks, heat can also be retrieved from such fractures. This is known as a petro-thermal geothermic system, where the geothermal system is referred to as an upgraded system and the energy resources are referred to as unconventional. Figure 2.2 shows various type of deep geothermal reservoirs [31].

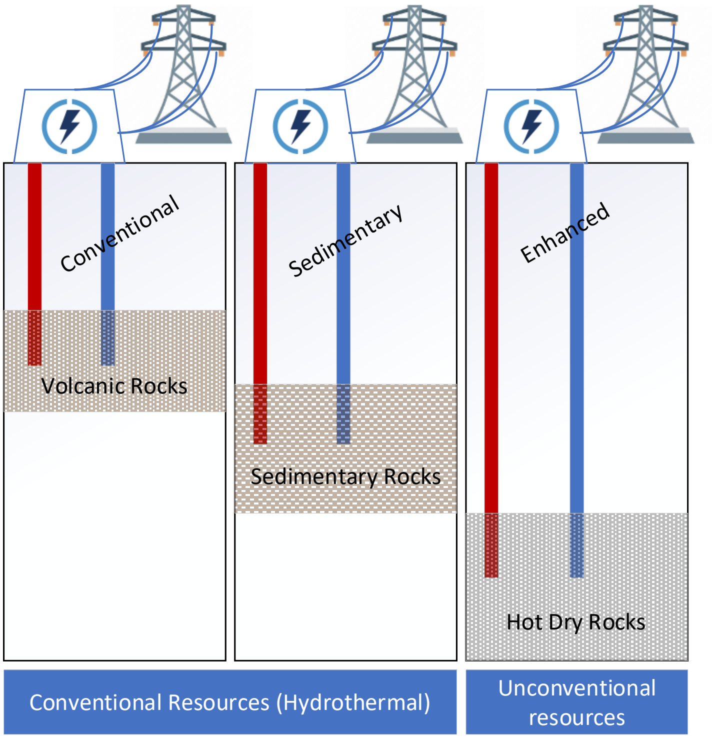

Figure 2.2: Different types of deep geothermal resources

The enhanced geothermal system (EGS) is a novel technology that generates energy from water circulating in hot rocks at vast depths without the need for natural hydrothermal sources. The idea is straightforward. It entails using hydraulic stimulation to create hydrothermal sources in hot dry rocks (HDR) [31]. Enhanced geothermal systems encompass a range of terms, including hot dry rock, hot wet rock, and hot fractured rock [32].

In the deep subsurface, where temperatures reach levels suitable for power generation, typically ranging from 150°C to 200°C, an extensive fracture network is created or expanded. These fractures serve the dual purpose of establishing new pathways for fluid movement while also functioning as heat exchangers within the reservoir. Water from the surface is injected into the deep reservoir through injection wells and subsequently recovered via production wells in the form of hot water. The heat extracted from this process can be utilized for district heating or power generation purposes [32].

The primary benefits of deeper geothermal energy well systems are greater heating capacity per unit length and higher temperatures. This leads to a reduction in the number of wells required to achieve the same heating effect. In Scandinavia, the geothermal gradient is 10-30 C/km [29]. There is a shortage of deep well experience in the Nordic region [29].

2.2 Geothermal heat pump systems

The prevalent form of geothermal energy utilized in residential and commercial buildings is geothermal heat pumps, known also as geo-exchange systems. These systems operate by extracting heat from the ground during winter to heat buildings, and during summer, they return excess heat back to the ground. Typically, the ground serves as the heat source, although water can also be employed. A fluid mixture of water and antifreeze is utilized to transfer heat within the system [33]. The use of geothermal heat pump systems takes advantage of the earth’s constant temperature through the year’s seasons. Temperature varies based on location and height. Taking advantage of the natural heat source is what gives the geothermal heat pump greater efficiency than a standard heat pump. This source of heat is also naturally renewable, making it a great energy source [34]. The geothermal heat pump system comes with various options for tapping into this natural reservoir of heat which will be explained in other parts of the current report.

The geothermal heat pump system (GHP) represents the most rapidly expanding sector within geothermal technology and is among the swiftest-growing applications of renewable energy technologies on a global scale [32]. Heat pumps utilize electricity to extract freely available heat from the environment. This heat is typically sourced from the outside air, energy wells in the ground, or seawater. On average, a heat pump delivers between two to five times more heat than the electricity it consumes over a year [35].

A geothermal heat pump adjusts the temperature by transferring heat from the earth to the houses. This system offers affordable, efficient heating with minimal emissions [36]. Similar to refrigerators, heat pumps transfer thermal energy from a lower temperature medium to a higher one [6]. Heat pumps have been understood since the 1800s and have been used commercially for roughly 60 years [37]. Heat pumps use electricity to power compressors, which carry out the required work for the concentration and movement of thermal energy. Figure 2.3 shows a simple schematic of heat pump. As mentioned before, a heat pump is a thermodynamic system operating in a cycle that absorbs heat from a low-temperature source and delivers it to a high-temperature sink [38].

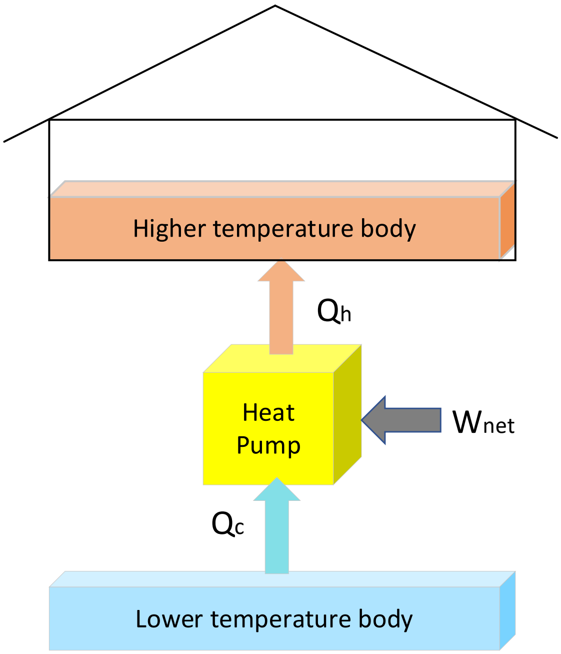

Figure 2.3: A schematic of energy flow diagram for heat pump

In general, the heat pump system consists of 4 elements. Figure 2.4 shows four basic heat pump components, including the evaporator, compressor, condenser, and expansion valve. In the heating mode, heat transfer Q_c occurs to the working fluid in the evaporator from a lower temperature source, turning it into a gas. The electricity-driven compressor increases the pressure, and following that, the temperature increases, then forces it into the condenser. Since the gas temperature is higher than the temperature in the room, heat transfer from the gas to the room causes gas to condense to liquid. Then, the working fluid is cooled as it flows back through an expansion valve to the evaporator [39].

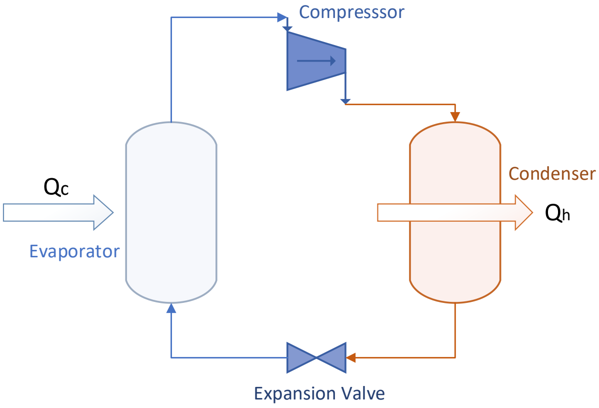

Figure 2.4: The main components of heat pump

The PV (pressure-volume) diagram for heat pump system is similar to reversed Carnot heat engine cycle since heat pump operates in reverse of the Carnot heat engine cycle which shows in Figure 2.5. The PV diagram of heat pump demonstrates the compression and expansion processes involved in transferring heat from low-temperature source to high-temperature sink.

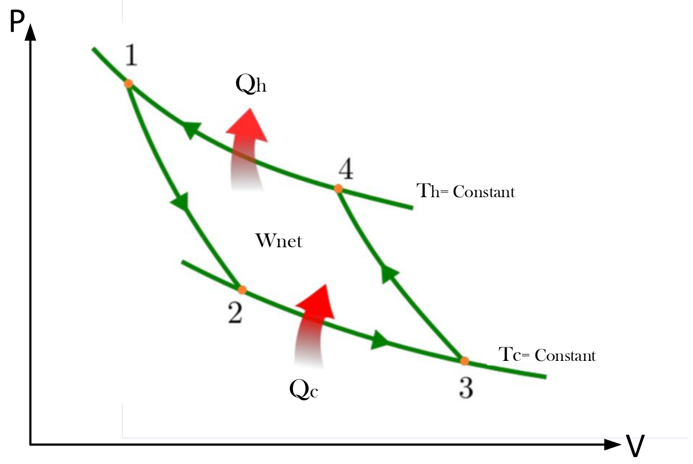

Figure 2.5: Carnot heat pump PV diagram

The Carnot heat pump cycle (reversed Carnot heat engine cycle) contains 4 processes as below:

- Process 1-2: Reversible adiabatic expansion. The temperature of working fluid decreases in this process
- Process 2-3: Reversible isothermal expansion. Heat is transferred from low temperature sink to working fluid at constant T
- Process 3-4: Reversible adiabatic compression. The temperature of working fluid increases in this process
- Process 4-1: Reversible isothermal compression. Heat is transferred from working fluid to high temperature source at constant T

By understanding the above processes, the coefficient of performance of the Carnot heat pump (COP_{HP}) for heating purpose can be defined as equation (2.1).

$$COP_{HP} = \frac{T_h}{T_h - T_c} = \frac{1}{1 - {T_c}/{T_h}} \tag{2.1}$$

Here, T_h and T_c are absolute temperatures in Kelvin.
The efficiency of heat pump system is defined as equation (2.2).

$$\eta = \frac{COP_{actual}}{COP_{Carnot}} \tag{2.2}$$

The above general information explained to better understand the thermodynamic concept of heat pump systems.

Below is a concise overview of the historical development of geothermal heat pump systems. The initial shallow exchangers were placed inside groundwater wells and featured a closed-loop design. This occurred at Klamath Falls, Oregon, USA, in the late 1920s. Low-temperature heat exchangers for heat pumps were first used commercially in Portland, USA, in the 1940s. According to the Department of Energy (DOE), an average geothermal heat pump system costs about 2500 dollars per ton of capacity. For instance, If the home requires a 3-ton unit, it will cost about 7500 dollars plus installation and drilling costs. A comparable air source heat pump system with air conditioning would cost about 4000 dollars, but the energy costs could easily equate to the extra cost of installing a geothermal heat pump. Geothermal heat pump systems have an average 20+ year life expectancy for heat pumps in

life and 25 to 50 years for underground infrastructure. In 2022, tax credits were extended through 2034 for energy-grade geothermal systems [34].
When it is hot outside, an air-source heat pump transfers heat from the building to the outside air. This is how geothermal heating and cooling systems differ from each other. The system finds it more difficult to release heat from the building into the already heated outdoor air as the summertime temperature rises. As a result, when the air-source heat pump is used to cool the building, the system's efficiency decreases just when it is most needed. On the other hand, this issue is not present with a geothermal heat pump system. Furthermore, a geothermal system with an underground loop is installed safely within the building. There is no outdoor equipment exposed to the weather or the possibility of vandalism even with an air-source heat pump [41].

2.2.1 Operating principle of geothermal heat pumps

The primary parts of a basic heat pump are the compressor, evaporator, expansion valve, and condenser. An evaporator converts a chemical liquid into gas. A heat pump uses a heat-absorbing fluid to evaporate heat and release it when it condenses [42].

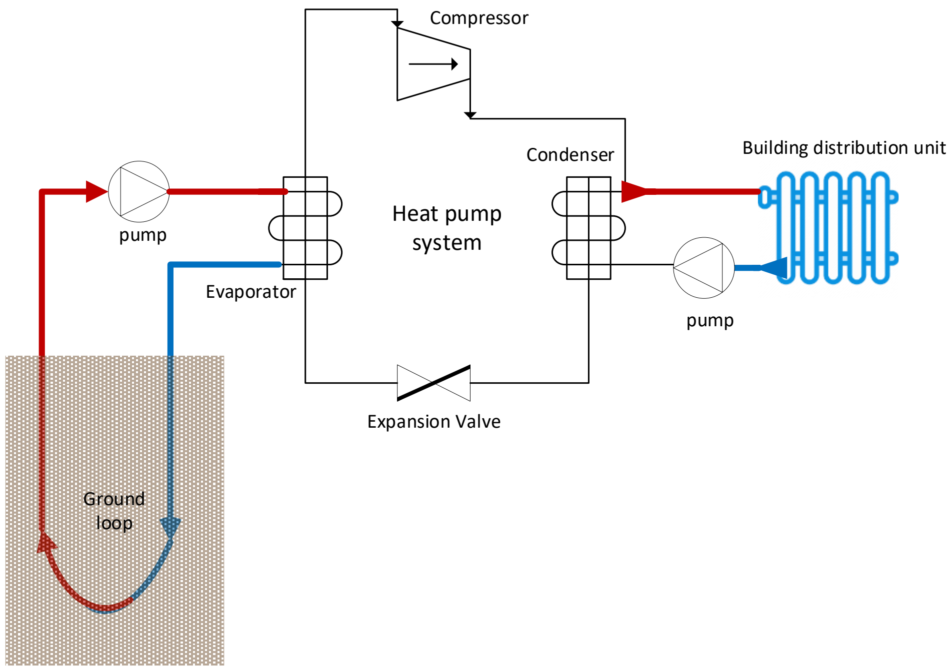

Figure 2.6: General sketch for geothermal heat pump system

In the winter, GHP uses the earth as a heat source, while in the summer, it uses water or antifreeze solution as a heat sink to remove heat. In the winter, the heat pump raises the liquid's temperature. The heat is then transmitted to the inside air and the reversed procedure will happen for the summer [42].
In other words, the ground source heat pump draws warm air from the building when it is in cooling mode. The heat pump indoor coil will absorb warm air from the outside and circulate through a cooled liquid refrigerant. The refrigerant will boil and transform into a gas when it absorbs heat. Cooling water circulating through the system from an underground loop will absorb the refrigerant as it circulates through it. The water then absorbs the heat and circulates underground where it is rejected to the cooler ground. Based on the second law of thermodynamics states that heat moves from warmer to cooler items. The water and refrigerant never meet each other. In heating mode, the opposite occurs. It should be noted

that it will always follow the heat as stated by the second law of thermodynamics. In this situation, the ground provides heat. The cool water is pumped to the ground and absorbs heat from the ground. Following its circulation into the ground source heat pump, the warm water is absorbed by the refrigerant, causing the liquid to boil and evaporate. The hot refrigerant is then circulated to the indoor coil where it meets the cooler return air from space. The cool return air absorbs the heat from the hot refrigerant and heats the leaving supply air [34].
One of the critical parts of GHP is the ground loop, which uses underground tubes filled with antifreeze fluid to absorb heat from the earth. The evaporator in the heat pump unit removes heat from the water in the ground loop. The compressor is responsible for transferring the refrigerant around the heat pump. The environment receives heat from the condenser. The heat distribution system in GSHP is crucial since it includes underfloor heating or radiators [42], [43].

2.2.2 Geothermal heat pump categories

There are various alternative approaches to ground loop design, but all of them fall into two main categories: Closed and open loops [44]. Figure 2.7 shows the different type of geothermal heat pump based on the loop system:

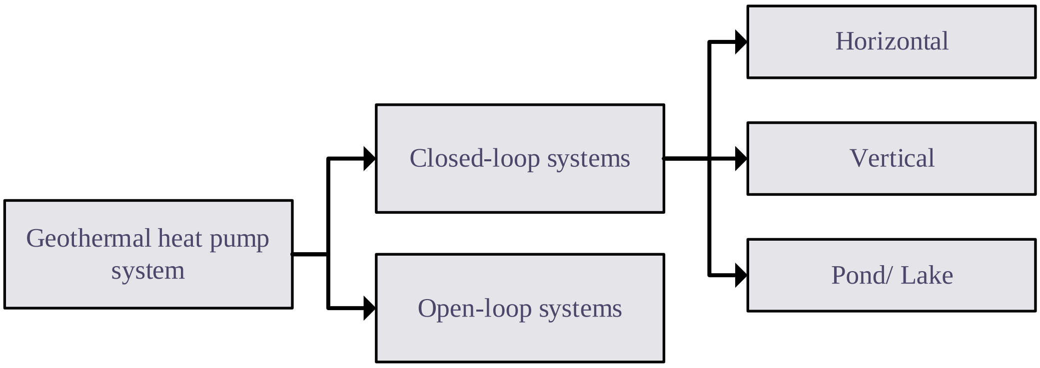

Figure 2.7: Classification of geothermal heat pump system [28]

To tap into the earth's free source of energy, it can be used plastic tubing beneath the surface. The tubing acts as a heat exchanger between the fluid in the tubes and the ground. The tubing is configured in various patterns and depths based on available land area and soil composition below the ground. If there is enough ground area and the soil is suitable for heat transfer, then a horizontal system can be installed. If there is not enough ground area or the soil is not suitable for heat transfer, then vertical tubing is another option. More details are explained below [34].

The thermal conductivity of the ground influences the effectiveness of a geothermal heat pump system. Variability in thermal conductivity among geological formations can impact on the overall system performance. Conducting detailed site inspections is critical for understanding subsurface conditions. The land's geological, hydrological, and geographical aspects will be beneficial in deciding the appropriate ground loop for the location. Below is a brief summary of each factor [45]:
The first factor is geology. When creating a ground loop, the composition and qualities of soil and rock must be examined, which might affect heat transfer rates. Compared to soil with weak heat transfer capabilities, soil with good heat transfer qualities needs less pipe to gather a given amount of heat. The second factor is hydrology. The availability of ground or surface water influences the sort of ground loop that is used. Surface water bodies can be utilized as a

supply of water for an open-loop system or as a storage area for piping coils in a closed-loop system, depending on variables including depth, volume, and water quality.

Additionally, groundwater can be utilized as a source for open-loop systems if the water quality is acceptable and all groundwater discharge rules are followed. The last main factor is land availability. The size and shape of the property, its landscaping, and the location of utilities or sprinkler systems all influence the system design. Horizontal ground loops, which are usually the most cost-effective, are widely employed for newly built houses with appropriate land. Vertical or compact horizontal installations are commonly used for existing buildings to minimize landscape disruption.

2.2.2.1 Closed-loop geothermal heat pump system

The Technical University of Berlin introduced the idea of a closed-loop geothermal system (CLGS) to extract geothermal energy from deep reservoirs [46]. A closed-loop geothermal system circulates the heating solution over buried or submerged plastic pipes. The subsurface pipes link to an indoor heat pump, which provides both heating and cooling [44]. Closed loop systems can be divided into three groups: vertical, horizontal, and pond/ lake type [44]. All of these systems are self-contained, and the liquid heat transfer fluid never touches the ground or pond/lake. The piping arrangement that is utilized to gather and distribute the heat from the substrate is the source that closed-loop systems give their name to.

- Horizontal type

The most appropriate type of GSHP system for residential applications is a horizontal closed-loop system. In this arrangement, pipes are laid horizontally in trenches dug approximately 4 to 6 feet below the surface ground. This type of system can access the steady temperature of Earth at this depth, which is primarily unaffected by seasonal changes. The trenches' length and spacing are determined by soil qualities, available space, and the building's heating or cooling load requirements, in which the efficiency of heat exchanger will increase by longer trenches and closer spacing. It is ideal for installations that have plenty of horizontal area. Horizontal installations frequently have lower initial costs than vertical drilling systems [47].

Using a horizontal loop is more feasible than drilling vertically. Horizontal loops are economically viable if excavation can be done without difficulty due to soil composition. The required heat transfer or the heat pump's tonnage decides how long the loop should be. A heating and cooling load calculation is performed on the building to determine the length of tubing needed. Tube length can run between 500 to 600 feet per ton of heat pump capacity. For example, a 4-ton system would require 2000 to 2400 feet of tubing. For spacing to achieve efficient heat transfer, an approximate area from ¼ to ¾ acre could be needed for a typical-sized home [34]. Even though horizontal ground loop systems have many benefits, it's crucial to perform a comprehensive site evaluation and speak with a licensed geothermal system installation to guarantee that the size and design are appropriate for the particular geological and site conditions.

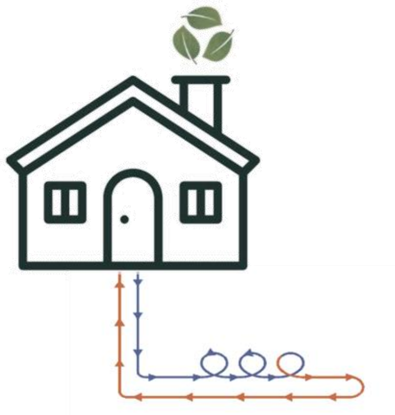

Figure 2.8: Horizontal closed-loop geothermal heat pump system

- Vertical type

The vertical ground loop system is one type of GSHP system that exchanges heat with the Earth through a network of vertical boreholes tubes into the ground. This technology depends on the steady temperature of the Earth at deeper levels and is intended for installations with restricted horizontal space. This system is suitable when greater efficiency may be required. In commercial buildings vertical boreholes are drilled into the ground to depths around 100 to 400 feet, spaced 20 feet apart to allow for proper heat transfer [33], [34]. These holes can be up to 4 to 6 inches in diameter and contain plastic tubing that traverses to the bottom, making a U-turn and coming back out of the hole, which joins to a horizontal manifold. Residential systems require fewer bores and would most likely be 300 feet deep or less [34].

Many items like the site's geology, the rock or soil's thermal conductivity, and the building's particular heating and cooling requirements affect depth determination. Vertical loop geothermal systems are noted for their high energy efficiency.
The temperature of earth is more reliable than the air temperature, resulting in greater efficiency and lower operating costs than typical HVAC systems. Vertical loop geothermal systems have greater initial installation costs but can provide long-term benefits through reduced energy use and running expenses.

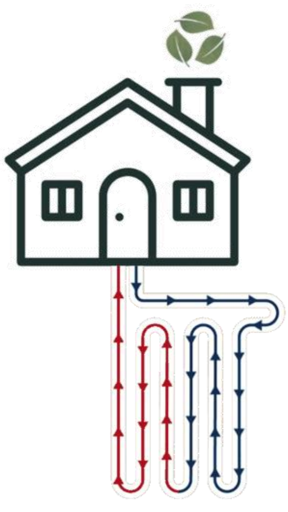

Figure 2.9: Vertical closed-loop geothermal heat pump system

- Pond/ Lake type

Having a body of water near the property allows the use of water as a heat sink where heat is transferred to and from the tubing either in an open or closed loop arrangement. The pond/lake system is similar to the horizontal system, except it needs a pond or lake of specific size. Coils of tubes are put at least 8 feet below the surface to prevent freezing, and the heat transfer fluid is circulated through them. This is the least expensive approach because it does not need drilling [33], but it can only be implemented in the presence of a suitable body of water [47]. In this type, a pump circulates the water and antifreeze solution through tubing within the body of water, where it rejects or absorbs heat from the geothermal heat pump.

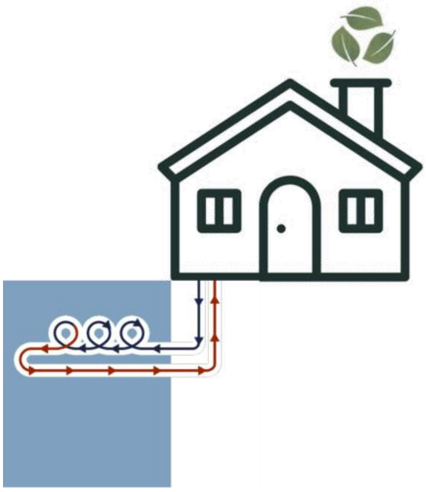

Figure 2.10: Pond/ Lake geothermal heat pump system

2.2.2.2 Open-loop geothermal heat pump systems

Open-loop systems are a less prevalent type of geothermal heat pump system. They use a heat pump to circulate well or surface water rather than a closed ground loop with antifreeze fluid inside. As the water circulates through the heat exchanger and is released back into the environment, open-loop systems must conform to all local requirements for groundwater discharge [44].

The difference between the closed-loop pond/lake systems is that the open system uses the pond well or lake water to circulate through the tubing and up to the heat pump. This raises additional concerns for environmentalists and code authorities about water depletion and groundwater contamination. Open-loop types require more maintenance than a closed loop due to minerals and other impurities that may be in the water [34].

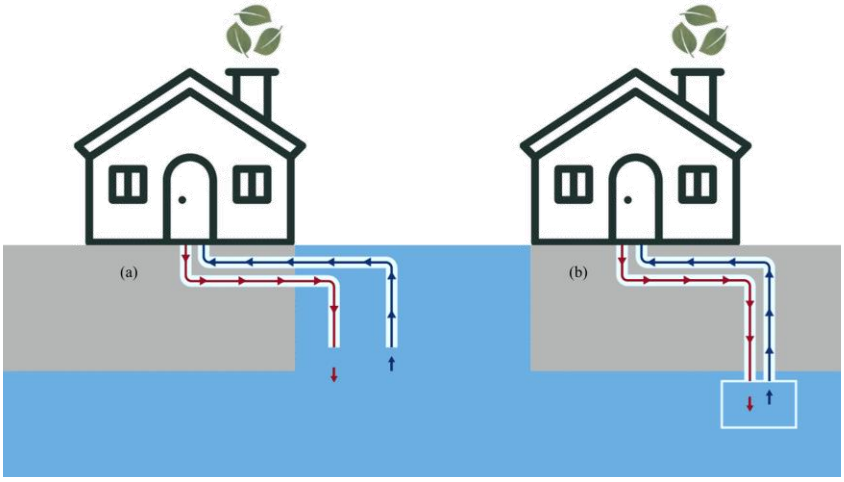

Figure 2.11: Open-loop geothermal heat pump system: (a) Pond/ Lake, (b) Well

2.2.3 Advantages and disadvantages of geothermal heat pump systems

According to U.S. Energy.gov [45], *"The biggest benefit of GHPs is that they use 70% to 80% less electricity than conventional heating or cooling systems"*. Geothermal heat pump systems have various advantages over traditional heating and cooling systems, as shown below [48].

The source of the geothermal heat pump system is clean energy. Since the geothermal system uses the earth loop to provide the building with heat in the winter, burning fossil fuels is unnecessary for heating. No flames, no emission of carbon dioxide, no carbon monoxide, and other greenhouse gases. It is entirely environmentally friendly [41]. Geothermal systems are an intelligent way to heat and cool a building. Using this type of energy causes less operating cost. A geothermal heat pump will quickly save you 30-60% on heating and 20-50% on cooling expenditures compared to traditional heating and cooling systems. GSHP system can also be used in both new construction and retrofit applications. However, it is far more expensive in retrofits that require ducting adjustments. Furthermore, the GSHP system operates significantly more quietly than other types of cooling systems. There is no noise outside compressors or fans. The interior unit is about as noisy as a refrigerator. It means that they are quieter than heating and cooling systems. Considering availability and maintainability, the GSHP system has higher availability and less required for maintenance. Indoor components typically have a life of 25 years, while the ground loop might survive for more than 50 years. The system requires less maintenance because it has fewer moving parts and is kept safe from the outdoor elements.

In addition to the above advantages, this system also has disadvantages. For instance, the cost of a geothermal heat pump system is more than that of a typical heat pump system, but this cost is saved by possible incentives and rebates, in addition to the yearly energy saving which can be covered shortly [34].

Table 2.1: Main advantages and disadvantages of different types of GSHP systems [49]

Type of loop system	Type	Advantages	Disadvantages
Closed-loop system	Horizontal	-Easier to install than vertical -Lower installation cost -High heat transfer area	-Requires a lot of real estate - Lower geothermal gradient
	Vertical	-Requires less real estate to build or less surface area -Consistent performance and less affected by surface temperature fluctuations -Higher geothermal gradient and heat transfer area for deeper wells	-More difficult to install -More expensive
	Pond/ Lake	-Quickest to install -Less digging	-Water temperature is less consistent -Requires a body of water nearby
Open-loop system	Well	-Water temperature is more consistent	-Still requires drilling -More expensive -Prone to fouling and corrosion
	Pond/ Lake	-Easier to install -Less digging -Less expensive	-Prone to fouling and corrosion -Water temperature is less consistent

2.3 A review on Norway geothermal energy and GSHP systems

Geothermal energy consumption in Norway is dominated by the relatively extensive installation of geothermal heat pumps. In Norway, there is no power generation from geothermal energy, and there has not been deep geothermal installation in operation. The Gardermoen airport in Oslo implemented a geothermal de-icing system in 2018. The heat collected directly from two 1500-meter deep BHEs without the use of a heat pump. The BHEs include specifically built coaxial collectors. More initiatives of this kind are being developed.

According to previous studies, heat pump systems are divided into two categories: air source heat pumps (ASHPs) and ground source heat pumps (GSHP). Depending on where thermal energy comes from and goes to, each of these two categories could have three subcategories.
Based on data provided by the Norwegian Heat Pump Association (NOVAP), the residential sector employs four different types of heat pumps: ventilation, liquid-to-water, air-to-air, and air-to-water. Compared to the ASHPs used in Norway, ground source heat is used by just one of the four types of heat pumps that are employed in this country. According to the statistics, air-to-air heat pumps are currently the most often used type of heat pump in operation in Norway. Other cases of extensive GSHP implementations include private businesses and communal housing complexes. In Norway, air-to-air heat pump systems account for more than 90% of installed heat pump systems [12].
NOVAP reported, there are 1.1 million heat pumps in use in Norway, and each year they provide more than 10 TWh of renewable heat from their surroundings. By 2030, there is twice as much potential [35]. Air-to-air heat pumps are the most popular kind for residential areas, but they may be utilized in many kinds of buildings for various commercial and industrial applications. The economic and environmental comparison between GSHP and ASHP is illustrated in Table 2.2. The mentioned data in this table was collected by Singh et al from different resources.

Table 2.2: Comparison between GSHP and ASHP [12]

Parameter	Unit	ASHP	GSHP
Capital cost*	NOK	AWHP:60000-130000 AAHP: 15000-30000	170000-250000
Maintenance cost	NOK	>2500	>2500
COP	-	AWHP: 2-2.5 AAHP: 2-3	3.5-5
Power Factor	-	AWHP: 2.4 AAHP: 2	2.9
Payback time	Year	6-10	8-10
Energy consumption during heating **	$kgCE/m^2$	13.15	10.96
Noise pollution	-	Yes	No
Service Life span	Year	12-15	20

** For heat pumps with capacity of 8-9 kW [12]*

***kgCE/m^2: Kilogram of coal equivalent per unit area in meter square [12]*

According to the Norwegian Water Resources and Energy Directorate (NVE), heat pumps in Norway are estimated to net provide 10.6 TWh of renewable heat from the environment every year. Since 1987, the NOVAP has kept track of heat pump sales in Norway, and releases updated data on a quarterly basis [35]. Figure 2.12 shows the statistics of annual sales of heat pumps per quarter in Norway.

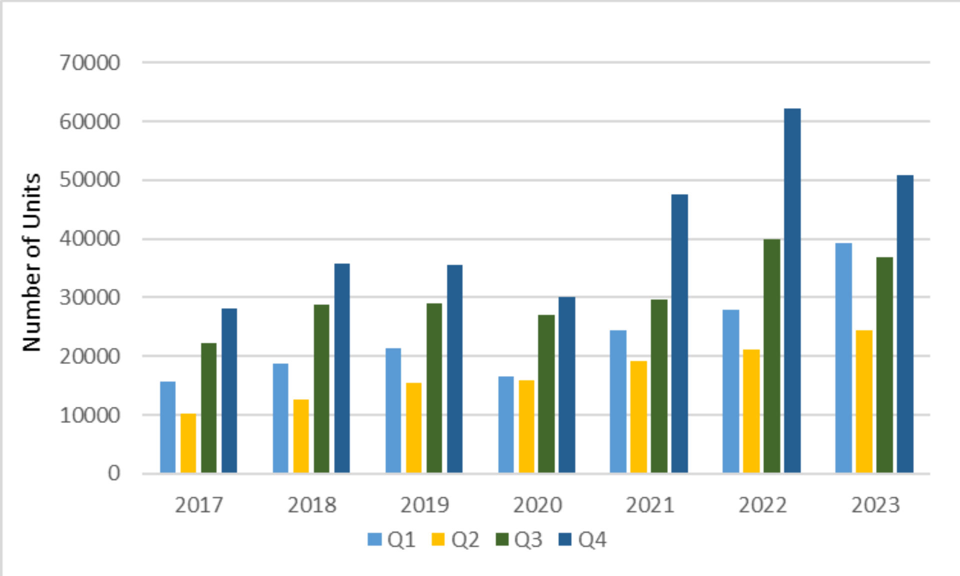

Figure 2.12: Annual sales of heat pump in Norway per quarter (Source: evervis) [50]

According to IEA geothermal [16], in Norway, there are numerous large borehole heat exchanger facilities (>23 BHE) in operation. Heat pump technology is used in all these places. The depth BHEs are under the category of shallow geothermal energy sources because their depth is less than 400 meters. Table 2.3 illustrate facilities for large BHEs in Norway.

Table 2.3: Installed large boreholes heat exchangers in Norway (Source: IEA) [16]

Name	Location	Depth BHE (m)	No. of BHE
Nye Ahus hospital	Lørenskog	200	228
Office/flats Nydalen	Oslo	200	180
Sartor	Bergen	200	162
Norway School of Sport Sciences	Oslo	300	97
Ulven housing housing cooperative	Oslo	316	88
Arcus	Gjelleråsen	300	91
Hospital	Ostfold	246	99
COOP Åsane	Bergen	212	112
Manglerudjordet housing cooperative	Oslo	299	67
Vulkan urban development (Bellona)	Oslo	300	68
Haukland Hospital	Bergen	250	75
Ørlandet airport	Trondheim	250	72
Maridalsveien housing cooperative	Oslo	360	50
University College Bergen	Bergen	220	80
Vestfold University	Horten	244	70

IKEA Billingstad	Oslo	200	82
Ericsson	Asker	247	56
Mandal community	Mandal	164	83
buildings Johan Castbergs Vei	Oslo	300	45
Helsfyr housing cooperative	Oslo	328	40
Offices Alnafossen	Oslo	200	64
Ramstad school	Baerum	281	45
New Hammerfest hospital	Hammerfest	250	50
Finnmark hospital	Hammerfest	250	50
Buildings Westye Egebergs Gate 1-4	Oslo	280	44
Royken Community	Royken	300	41
National Police operations center	Oppegård	300	40
Oslo, Engelsborg housing cooperative	Oslo	340	34
Kulturpark	Kongsberg	299	38
Smedvig Property	Stavanger	299	54
Lørenveien Parallell offices	Oslo	258	41
Modumheimen (care home)	Vikersund	300	35
Bjerkedalen housing cooperative	Oslo	320	32
Høgskolen i Molde	Molde	240	42
BTV	Narvik	201	50
Scandic Hotel Flesland	Bergen	200	50
Workplace Oo, Vitaminveien 4	Oslo	250	40
Workplace Oo offices	Oslo	250	39

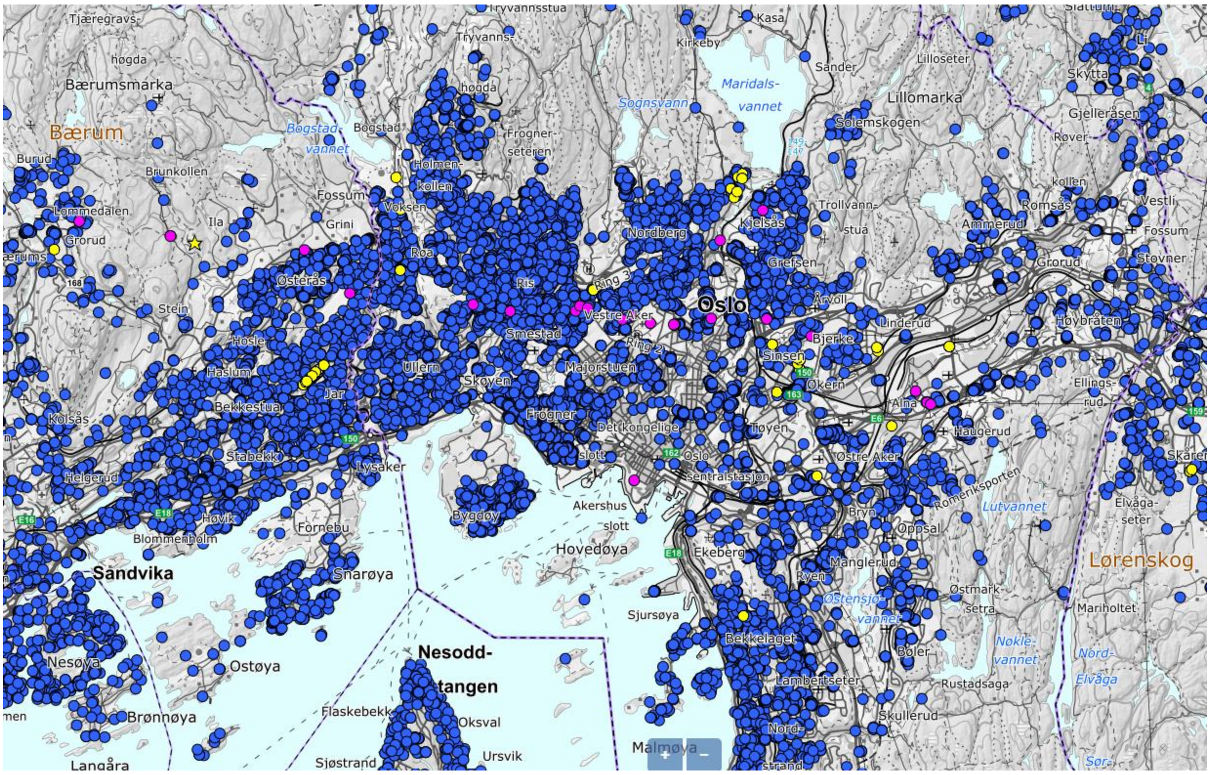

Figure 2.13: Borehole heat exchangers (BHEs) in the Oslo region (Source: GRANADA)

Norway is located on the continental crust of the Baltic Shield, and more than 90% of BHEs are installed vertically into crystalline bedrock. The U-shaped tubes in boreholes are directly in contact with aquifers and filled with water instead of grout [12].

In Norway, onshore drilling has produced over thirty relatively deep boreholes in the last few decades. Thermal logging indicates that the Svalbard boreholes had the highest temperatures, reaching up to 28,2 °C at 800 m depth. In comparison, the lowest recorded temperatures in Northernmost Norway are found at a depth of 650 meters, at just over 9 °C. At an estimated 800 meters below the surface, the highest temperature in Central Norway was recorded on a small island near the deep sedimentary basins of the Norwegian Sea, with a temperature of 22.2 °C. However, the southwestern part of Norway has a lower temperature. For example, near Stavanger, at a depth of 800 meters, it is measured at 17.6 °C.

The most potential areas of mainland Norway for extracting deep geothermal energy are Western Norway and the Nordland region. The Oslo zone is partially located inside areas with high levels of radioactive materials. Middle Norway's geothermal potential is highest near the shoreline. In conclusion, the results of a geothermal survey in Norway reveal that Svalbard is the finest location for a geothermal site in Norway.

According to the geological survey of Norway, the deep geothermal potential of Norway based on borehole data listed in Table 2.4:

Table 2.4: Deep geothermal potential of Norway based on borehole data [51]

Region	Place	Depth (m)	Measured Temperature ^{o}C
Oslo Region	Gardermoen N	1450	26
	Gardermoen S	450	10,5
	Hamar	820	24
	Arnestad	640	20,8
	Fen LHKB1	1000	23,8
	Fen LHKB2	690	18,2
	Fredrikstad	730	19,5
	Årvollskogen	800	21,2
	Breger	700	14,9
	Hurdal-01	730	21,5
	Hurdal-03	900	23,3
Western Norway	Fyllingsdalen	510	15,8
	Ullrigg	1560	26,8
	Bjerkreim	1050	18,1
Middle Norway	Hjerkinn	670	13,8
	Raudsand 5	350	11
	Veiholmen	800	22,2
	Løkken	970	19,5
	Aure	370	14,8
	Fosdalan G535	1160	23,1
	Fosdalan G588	1180	24,6
Nordland Area	Bleikvassli	600	13,2
	Sulitjelma	960	21,2
	Drag	780	16,6
	Leknes	800	19,5
	Ramså	230	8,2
Northernmost Norway	Vuottasjavri	650	9
	Bjørnevatn	380	6,5
	Båtsfjord	600	4,1

Focusing on Nordic countries, while the climate is rather consistent, there are significant differences in how geothermal energy is used. Deep geothermal energy is widely available and used in Iceland. However, shallow geothermal energy is commonly used in Sweden, Norway, and Finland. The causes for this are not simply geological but also influenced by variances in accessible alternative energy. Table 2.5 illustrates geothermal factors in Nordic countries [52].

The geology of Nordic countries ae different. For example, in Norway has crystalline rock, sparsely covered with marine clay and quarternary deposits. Most of the geology of Sweden and Finland are also crystalline rock. However, Iceland has volcanic rock and the geology of

Denmark covered with unmetamophosed sediments. Compared to other four Nordic countries, Sweden has the most area and population [52].

Table 2.5: Geothermal in Nordic countries [52]

	Norway	Sweden	Finland	Denmark	Iceland
Geothermal gradient (^{o}C/100 m)	1.4-2.7	1.5-2.7	0.8-1.5	2.5-3	5-15
Number of GHSP (2018)	55000	580000	140000	40000	70 (2014)
Geothermal power	None	None	None	None	661 MW
Geothermal direct use (2018)	None	None	None	33 MWh	2130 MWh
GSHP heating/cooling (2018)	1023 MWh	6520 MWh	3000 MWh	400 MWh	1 MWh

3 Methodology

3.1 Energy balance model

Numerical modeling of heat transfer in the ground and thermal interaction between borehole heat exchangers is crucial in designing GSHP systems. Proper numerical modeling and a reliable tool are needed to determine the number of required boreholes and depths to meet users' specifications, optimize purposes, and consider economical evaluation to predict the system's performance over a long time. In addition, analysis of the energy balance model within the borehole heat exchangers provides insights into improving different elements, including materials, which are used.

The ground heat exchangers are presented with complex geometry including both convection and conduction phenomena, where, in most numerical studies, the effect of convection is neglected. In addition, heat flow can happen over a wide range of lengths and time, considering heat exchange over the thickness of the wellbore, which is a few millimeters while the depth of the wellbore is a few hundred meters and the field which expands over a few hundred meters, in each direction. Furthermore, a wide range of time scales should be considered, for example, while the heat pump system should respond to temperature changes within the building over a few minutes, thermal changes within the ground may take a significantly longer time due to the large thermal capacity (e.g., decades).

To model such a complex system, generally, two approaches can be used: either numerical or analytical. Each approach has advantages and some disadvantages. Generally, to choose one approach, parameters such as purpose, desired accuracy, time span, and model size should be known. Numerical modeling mainly considers solving heat transfer equations using either finite difference, finite volume, or finite element methods. Even though these approaches are precise and trustful, they are generally very computationally demanding, and solving large models, including several boreholes, is difficult, if not impossible. On the other hand, the analytical approach is more demanding due to its simplicity to apply, flexibility, and significantly lower computational time compared with the numerical approach. However, the analytical approach may suffer from a lack of accuracy.

In cylindrical geometry, there are three directions, as shown in Figure 3.1, that will be considered in different energy balance models. Energy can be negligible in some directions that can be neglected.

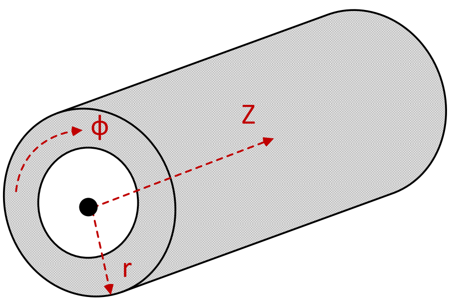

Figure 3.1: Schematic illustration of heat transfer directions in cylindrical geometry

In order to do the thermal modeling of a GSHP system, the medium can be divided into two distinct domains: one is the ground, and the other is the borehole which includes either grout

or water and U-tubes (schematically illustrated in the top-view cross-section in Figure 3.2). The general approach is to find the temperature on the borehole wall by solving the heat transfer equation within the ground located outside the borehole. This temperature at borehole wall is used to model heat transfer along the wellbore. Notable, in heat transfer modeling some simplifications are generally considered: (a) Even though the domain is heterogeneous, constant thermal properties such as thermal conductivity and diffusivity are considered. (b) The axial heat transfer is usually neglected. In short-term simulations, it does not play a significant role. However, for long-term evaluation, it is essential to be considered. (c) The heat transfer through the ground is normally modeled by conduction, and the effect of subsurface water flow, which leads to convection is disregarded.
The main term of energy balance model in a specific geometry can be defined as below:

$$Rate\ of\ accumulated\ thermal\ energy = Rate\ of\ entering\ thermal\ energy + Rate\ of\ thermal\ energy\ leaving + Rate\ of\ thermal\ energy\ generation$$

Based on the above definition, a general heat transfer equation in a cylindrical coordinate is as equation (3.1):

$$\frac{1}{\alpha}\frac{\partial T}{\partial t} = \frac{\partial^2 T}{\partial r^2} + \frac{1}{r}\frac{\partial T}{\partial r} + \frac{1}{r^2}\frac{\partial^2 T}{\partial \varphi} + \frac{\partial^2 T}{\partial z^2} + \frac{\dot{q}_{gen}}{k_g} \qquad (3.1)$$

In the above formulation, T is temperature, r denotes distance along the radial axis, φ and z denotes distance along the circumferential and axial directions, respectively. In this equation, t is time, α is the ground/soil diffusivity, k_g is the ground (soil) thermal conductivity, and $\dot{q_{gen}}$ is heat flux. All the constant parameters can be obtained through a field thermal response test [53].

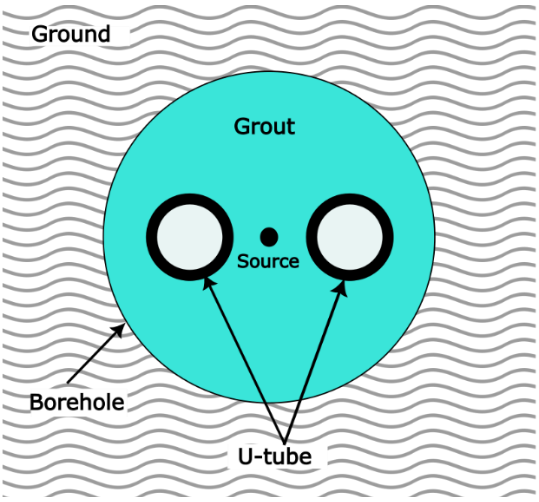

Figure 3.2: Schematic illustration of a top-view cross section of borehole in a GSHP system

3.2 Analytical methods

To solve the heat transfer equation (3.1), wide range of analytical solutions are proposed. In following some of the widely used analytical approaches are summarized:

3.2.1 Infinite line source model

One of the most straightforward approaches is Infinite Line Source (ILS), developed by Ingersoll and Plass (1948). In this model, it is assumed to be an infinite wellbore with a constant heat flow rate surrounded by an infinite homogenous ground. Through this approach, the wellbore geometry is neglected. The axial heat flow in equation (3.1) is also neglected due to a significantly smaller borehole radius in comparison with its length, Consequently, all the heat will accumulate in the center point, known as the source. This model is very easy to use and requires a few calculations which are briefly described below. However, the model notably includes some simplifications which reduce its accuracy. ILS model proposed the following analytical equation [53], which represents the temperature at any radial distance and time:

$$T(r,t) - T_g = \frac{\dot{q}}{4\pi k_g} \int_u^\infty \frac{e^{-u}}{u}\, du = \frac{\dot{q}}{4\pi k_g}\, E_1\left(\frac{r^2}{4\alpha t}\right) \quad (3.2)$$

In the above formulation, $\dot{q}$ is the heat transfer rate per length of line source (W/m), and E_1 is the exponential integral, and the thermal diffusivity was shown by parameter α. A wide range of approximations are proposed for solving the exponential integral, such as Young (2004) which is used in equation (3.3):

$$E\ (x) = -\gamma - \ln(x) - \sum_{n=1}^{m} \frac{(-1)^n x^n}{n.n!} \quad (3.3)$$

In the above formulation, γ is Euler's constant equal to 0.5772156649, and the last term on the right side of the equation is known as m^{th} stage of refinement. One limitation of this approach is that it is only valid for large times approximately larger than 10 hours, while for shorter times, the Gauss-Laguerre quadrature approximation provides a more accurate approximation.

Equation (3.2) calculates the temperature at the wellbore wall. However, to calculate the temperature in the wellbore, the borehole resistance should be added to the equation mentioned above. So, the modification to the above formulation is as equation (3.4):

$$T(t) = \frac{\dot{q}}{4\pi k_g}\, E_1\left(\frac{r_{bh}^2}{4\alpha t}\right) + \dot{q}\, R_{bh} + T_{ff} \quad (3.4)$$

In the above formulation, r_{bh} is the borehole radius (m), T_{ff} is the far field temperature (^{o}C) and R_{bh} is the steady state borehole resistance (mK/W).

3.2.2 Cylindrical source model

Another analytical solution for heat transfer is cylindrical source model. The model considers the domain $r_{bh} < r < \infty$, with heating flux immediately exposed to the cylinder surface or borehole wall. This means that the heat capacity of the "hot rod" is completely neglected [54].

The main equation of this model is mentioned in equation (3.5):

$$\Theta_c(R, F_O) = \frac{1}{\pi}\int_0^\infty (e^{-\beta^2.F_0} - 1)\frac{J_0(\beta R)Y_1(\beta) - Y_0(\beta R)J_1(\beta)}{\beta^2[J_1^2(\beta) + Y_1^2(\beta)]}\, d\beta \quad (3.5)$$

Here, Θ_c is dimensionless temperature excess, R is dimensionless coordinate, F_O is Fourier number, and J_0, J_1, Y_0 and Y_1 are Bessel functions of first and second kind, respectively. The empirical formulation of the temperature increases at the heat source, with R = 1 [54]:

$$\Theta_c(R, F_O) = G(F_O) \tag{3.6}$$

3.2.3 Finite line source model

The finite line source model (FLS) represents the variation of average temperature, which shown by $\Delta T_{ij}(t)$ in equation (3.7) [55]:

$$\Delta T_{ij}(t) = \frac{\dot{Q}_j}{2\pi k_s} h_{ij}(t) \tag{3.7}$$

in which $h_{ij}(t)$ is the finite line source solution which explain in equation (3.8), $\dot{Q}_j$ is uniform heat extraction rate, and k_s is thermal conductivity.

$$h_{ij}(t) = \frac{1}{2H_i} \int_{1/\sqrt{4\alpha_s t}}^{\infty} \frac{1}{s^2} \exp\left(-r_{ij}^2\, s^2\right) F_{ij}(s) ds \tag{3.8}$$

Here, H represents length, α_s is thermal diffusivity, and r_{ij} is distance.

Among these analytical solutions, the infinite line source model (ILS) simplifies calculations. A disadvantage of the infinite line source solution is that it never reaches a steady-state condition [18]. The cylindrical source model is considered a more realistic geometry, and it has a wide range of applications, but it is more complex than the ILS. It should be considered that both ILS and cylindrical model are not accurate for large time period [54]. The accuracy of the finite line source model [55] is higher than that of the ILS model. Depending on the specific problem and boundary conditions, solving the finite line source model may require numerical techniques or advanced mathematical methods, potentially increasing computational effort and complexity. In this project, the infinite line source solution has been considered to simplify the model.

3.3 Model formulations

To explain the energy model, it starts with thermal resistance (TR). Thermal resistance of boreholes is an essential parameter to determine vertical borehole temperature in inlet and outlet points. As can be seen in Figure 3.3, TR in borehole consists of three part including thermal resistance of fluid and inner tube, between inner and outer tube, and between outer tube and material of inside the borehole which can be for example grout.

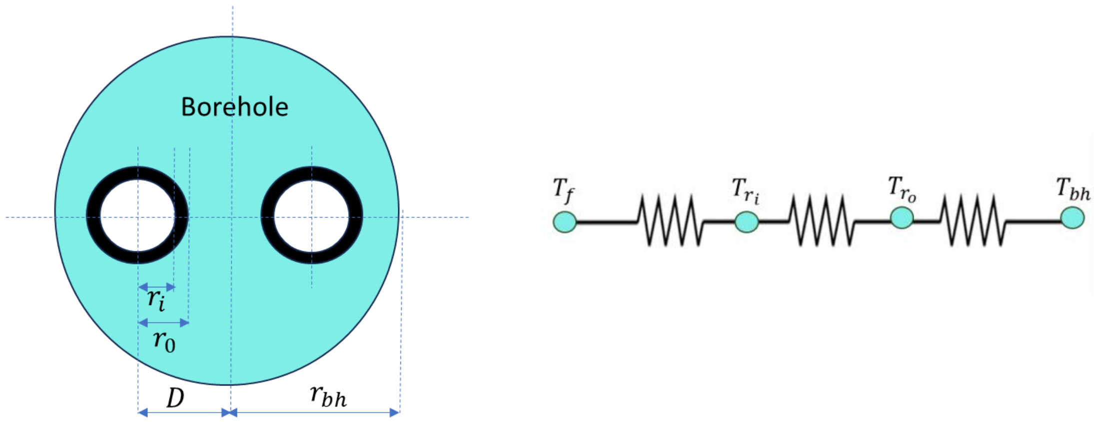

Figure 3.3: Schematic of borehole thermal resistance

The following equations [53] have been used to calculate thermal resistance of borehole and pipe by line source approximation.

$$R_{bh} = \frac{1}{4\pi k_p}\left[ln\frac{r_{bh}}{r_o} + ln\frac{r_{bh}}{2D} + \frac{k_b - k_g}{k_b + k_g}ln\left(\frac{r_b^4}{r_b^4 - D^4}\right)\right] + \frac{R_p}{2} \quad (3.9)$$

$$R_p = \frac{1}{2\pi k_p}ln\frac{r_o}{r_i} + \frac{1}{2\pi r_i h_f} \quad (3.10)$$

The importance of calculating thermal resistance is to calculate the amount of heat transfer. In equation (3.9) and (3.10), R_{bh} is thermal resistance of borehole ($\frac{mK}{W}$), and R_p is thermal resistance of tube or pipe ($\frac{mK}{W}$). The convection heat transfer coefficient of fluid is shown by h_f which can be calculated by Nusselt number from equation (3.15). r_i and r_o are inner and outer radius of tube, respectively. Also, the parameters k_b and k_g represent thermal conductivity ($\frac{W}{mK}$) of borehole and ground/ soil, respectively.

In the next part, to calculate the convection heat transfer coefficient, it requires to calculate Nusselt number. The Nusselt for laminar flow inside the tube is constant, however, for developed turbulent flow is the function of Reynolds and Prandtl number. Equation (3.11) to (3.15) show all the required equations for calculating h_f [56].

$$Re = \frac{2m_f}{\pi\mu r_i} \quad (3.11)$$

$$Pr = \frac{\mu c_p}{k_f} \quad (3.12)$$

$$Nu = 0.023Re^{0.8}Pr^{0.3} \quad \textit{(for developed turbulent flow)} \quad (3.13)$$

$$Nu = 4.36 \quad \textit{(for uniform heat flux)} \quad (3.14)$$

$$h_f = \frac{Nu.k_f}{2r_i} \quad (3.15)$$

The thermal resistance between the soil and borehole (R_s) can be calculated from equation (3.16).

$$R_s = \frac{1}{4\pi k_s} \; E_1 \, (\frac{r_b^2 \rho_s c_s}{4k_s \tau}) \tag{3.16}$$

Then, T_f the average fluid flow temperature is calculated by equation (3.18).

$$T_f(\tau) \cong T_{s,0} + q\{R_s + R_b\} \tag{3.17}$$

As can be seen in the above equation, T_f is a function of borehole and soil thermal resistances.

$$T_f = \frac{T_{f\_in} + T_{f\_out}}{2} \tag{3.18}$$

in which T_{f_in} and T_{f_out} are the fluid temperature in inlet and outlet of tube.

Pressure drop in the tube can be calculated by equation (3.19).

$$\Delta P = f \, \frac{m_f^2 (2L_b)}{\rho_f \pi^2 r_i^5} \tag{3.19}$$

in which mass flow and friction factor have been shown by m_f and f, respectively. Higher velocity causes a higher pressure drop in the fluid, while lower velocity will result in a less pressure drop inside the tube. It is preferable to reduce the pressure drop by increasing velocity, but it should be considered that higher velocity takes more work from the heat pump.

The friction factor in equation (3.19) can be calculated by equation (3.20) and (3.21) for laminar flow and developed turbulent flow inside the tube, respectively [53].

$$f \cong \frac{64}{Re} \tag{3.20}$$

The Reynolds number for the equation (3.21) is in the range of *Re* > 4000.

$$f \cong 0.316 Re^{-0.25} \tag{3.21}$$

All the above equations are for the ground section of GSHP system. To calculate energy input rate from geothermal ($\dot{Q}_{in}$), the outlet fluid temperature needs to be calculated from equation (3.18).

This part aims to explain the required equations for the heat pump section to reach the GSHP's power output rate ($\dot{Q}_{out}$). First, it is required to calculate the net power input (W_{net}). Equation (3.22) represent the W_{net} for heat pump system [27].

$$W_{net} = W_c + W_p \tag{3.22}$$

in which W_c is compressor power, and W_p is circulating pump power. In the GSHP system, there are usually two pumps, one for pumping the fluid to the heat pump system from the ground, which is named W_{p1}, and the other one is used for circulating fluid to the heat pump from distribution unit as shown in Figure 2.6. W_p can be calculated from Equation (3.23). In this equation η is the pump efficiency [57].

$$W_p = \frac{\Delta P.\dot{m}}{\rho.\eta/100} \quad (3.23)$$

Thus, considering energy conservation for the whole system, which is represented in equation (3.24), $\dot{Q}_{out}$ or power output of heat pump can be calculated.

$$\dot{Q}_{in} + W_{net} = \dot{Q}_{out} \quad (3.24)$$

Here, $\dot{Q}_{in}$ ($or\ \dot{Q}_{BHE)}$ can be calculated by equation (3.25):

$$\dot{Q}_{in} = \dot{m}_f.c.(T_{f,in} - T_{f,out}) \quad (3.25)$$

In this equation, $\dot{m}_f$ is ground source mass flow or mass flow of fluid inside the tube (kg/s).

Finally, the performance coefficient of heat pump represents in equation (3.26) [27].

$$COP = \frac{\dot{Q}_{out}}{W_{net}} = 1 + \frac{\dot{Q}_{in}}{W_{net}} \quad (3.26)$$

Figure 3.4 illustrates a flowchart that is used in this project. All the inputs are mentioned in the figure. Some steps can be changed, ignored or merged with the previous/ next step if more inputs are available.

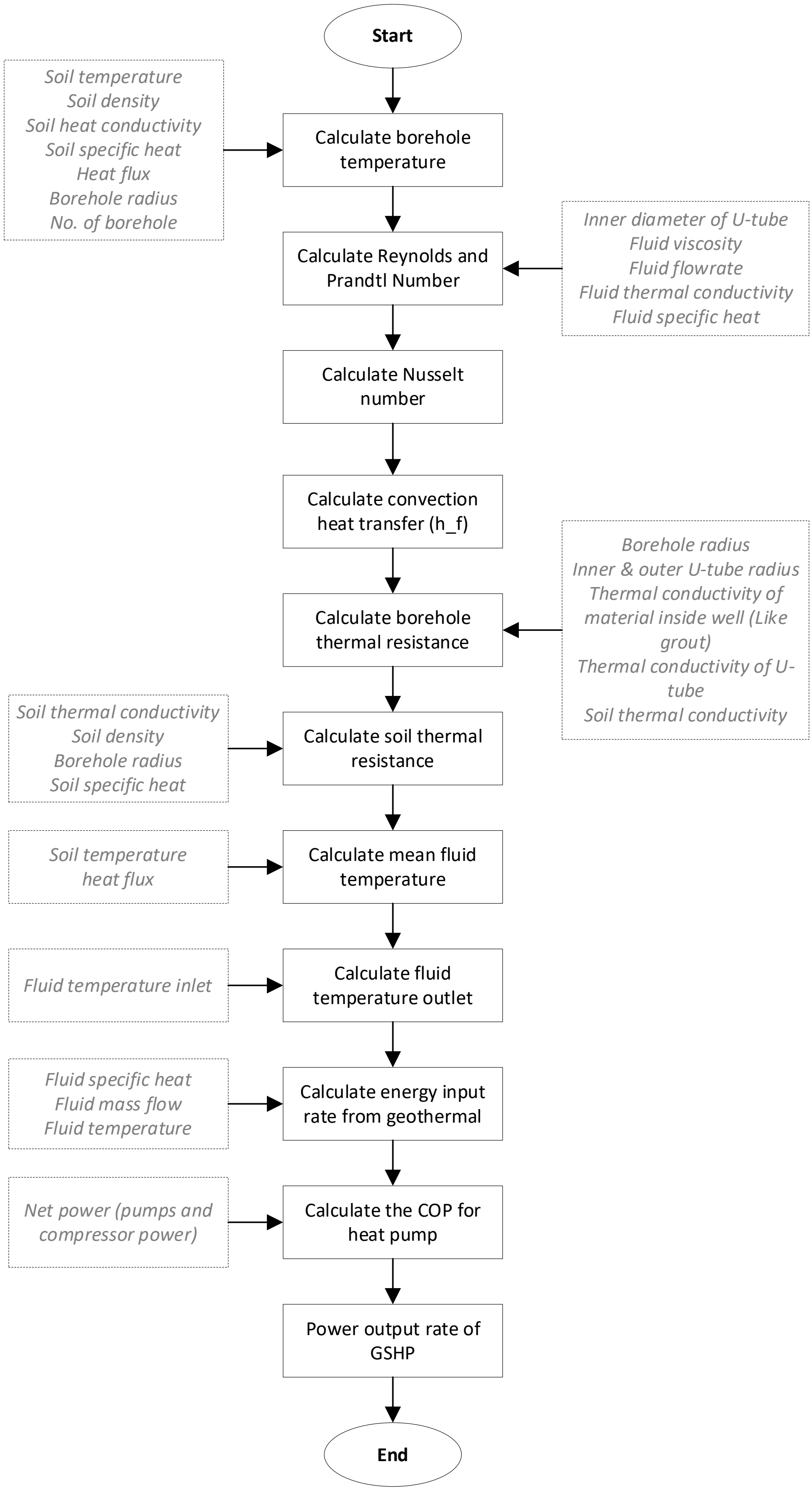

Figure 3.4: Flowchart for Python programming

4 Result and analysis

In this project, the analytical method's infinite line source solution (ILS) was considered, to solve the heat transfer model, which is commonly used for geothermal borehole heat exchangers, especially for simplified analyses. During the heat extraction from the geothermal borehole, calculation of borehole wall temperature is essential since the fluid's temperature will eventually approach that of the borehole wall. Also, the efficiency of the heat transfer process between the fluid and the surrounding ground will be evaluated by measuring the borehole wall temperature. Here, the primary thermal resistance in the system is related to the ground. The heat transfer from soil to borehole wall is based on conduction heat transfer. Equation (3.2) shows the borehole wall temperature as a function of radial distance and time. In this model, the soil properties such as thermal conductivity, density, and heat capacity are assumed to be 3 W/m k, 2600 kg/m^3, and 860 J/kg K, respectively The input data were extracted from scientific literature and academic research [57], [53]. Figure 4.1 shows the radial temperature profile during different years.

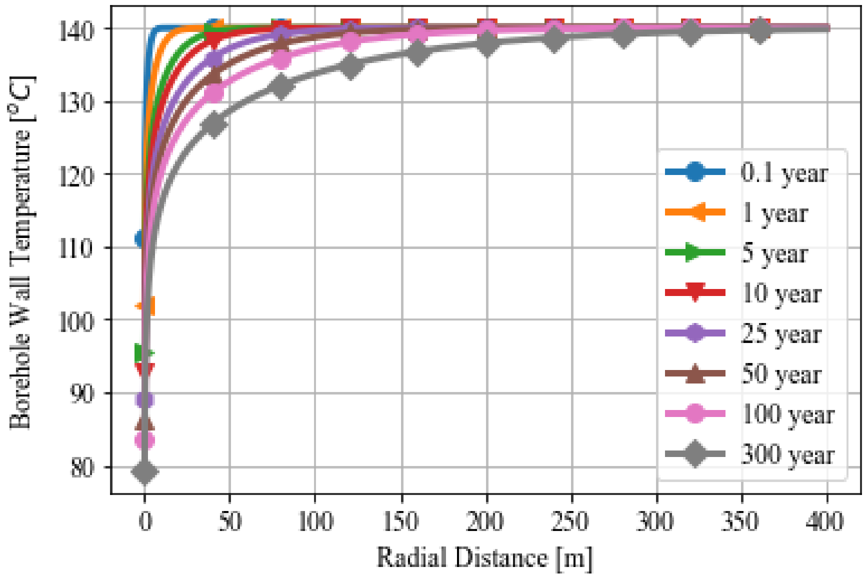

Figure 4.1: Radial temperature profile during 300 years at constant heat load

Here, the radial distance ranges between 0.1 and 400 meters, and the time is between one month and 300 years. The soil/ rock temperature far from the borehole center is assumed to be 140 °C. All the effective parameters on this profile were mentioned in equation (3.2), which is the main equation to find the borehole wall temperature. The graph illustrates that as time progresses, the rate of changing the temperature profile decreases. As time passes, the heat exchange between the borehole wall and the surrounding ground will stabilize. Thus, it causes a reduction in the rate of temperature change over time. Based on this graph, if the soil temperature is assumed to be 140 °C, the wall temperature will rapidly reach the soil temperature after around one month. However, after 300 years, this amount will get around 320 meters in radial distance.

Figure 4.2 and Figure 4.3 show the results on a logarithmic scale to provide a better view of how the temperature profile change is faster in earlier than later years.

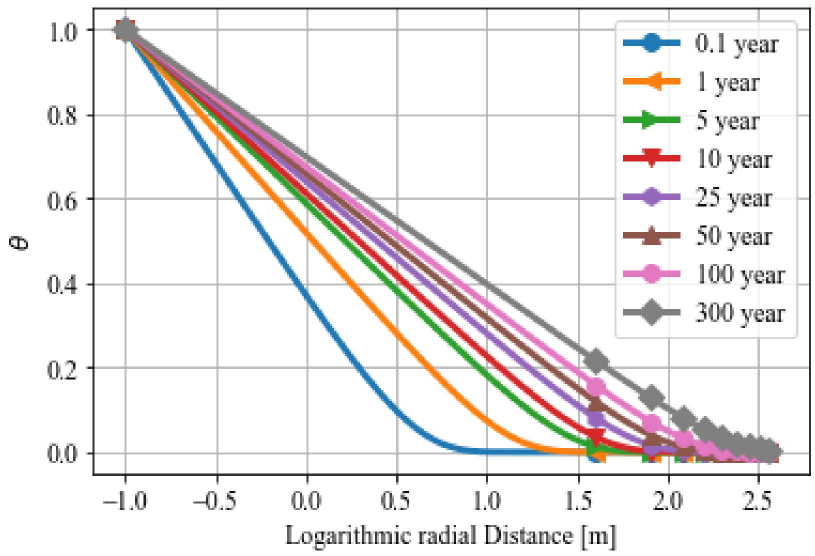

Figure 4.2: Dimensionless radial temperature profile [$\theta = (\frac{T - T_s}{T_0 - T_s})$] at constant heat load during 300 years

Here, the soil temperature is considered constant. The heat extraction load is also assumed to be steady. As shown in Figure 4.2, the temperature change is about 38% after around one month, 50% after one year, 60% after 10 years, and 70% after 300 years at a radial distance of about 1 meter. However, in the distance of 10 meters, the temperature change is zero after around one month, 19%, 25%, and 40% after 1, 10, and 300 years, respectively. This means that the wall temperature decreases as time passes since the surrounding temperature reduces. This happens because the performance of heat conduction will reduce over time, or it can be said that the capacity of heat from well will decrease over time.

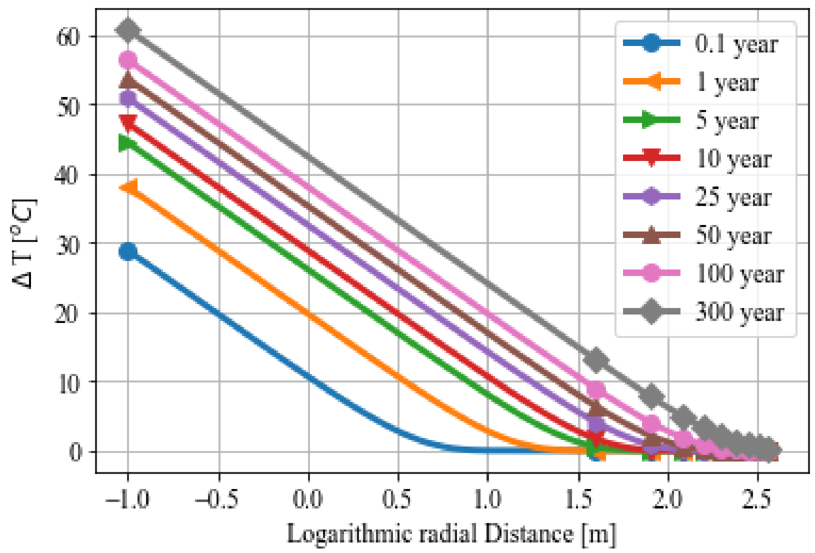

Figure 4.3 Radial borehole wall temperature profile ($\Delta T = T_s - T_b$) at constant heat load during 300 years

Figure 4.3 represents the wall temperature differences with surrounding soil temperature in a logarithmic radial distance. Here, the soil temperature is also assumed to be 140 °C. As seen in this figure, there is a slight change in temperature differences in earlier times compared to later times. This also means that the performance of heat conduction reduces over time, as mentioned above.

To check the effect of heat load on the radial temperature profile, a range of heat load between 25 and 150 is considered. The results show changes over different periods of time as Figure 4.4. For lower heat rate extraction, the temperature change is less than the higher heat load. For instance, after 50 years, the temperature change is around 9, 18, 45, and 54 °C for 25, 50, 125, and 150 W/m, respectively. This means that a higher heat load causes an increase in temperature differences or more reduction in wall temperature. It is due to the principle of heat transfer. When more heat is extracted from the soil through the borehole, it means that more heat is transferred from the surrounding rock or soil to the circulating water within the borehole. This results in a cooling effect on the surrounding soil/ rock and, consequently, on borehole wall temperature.

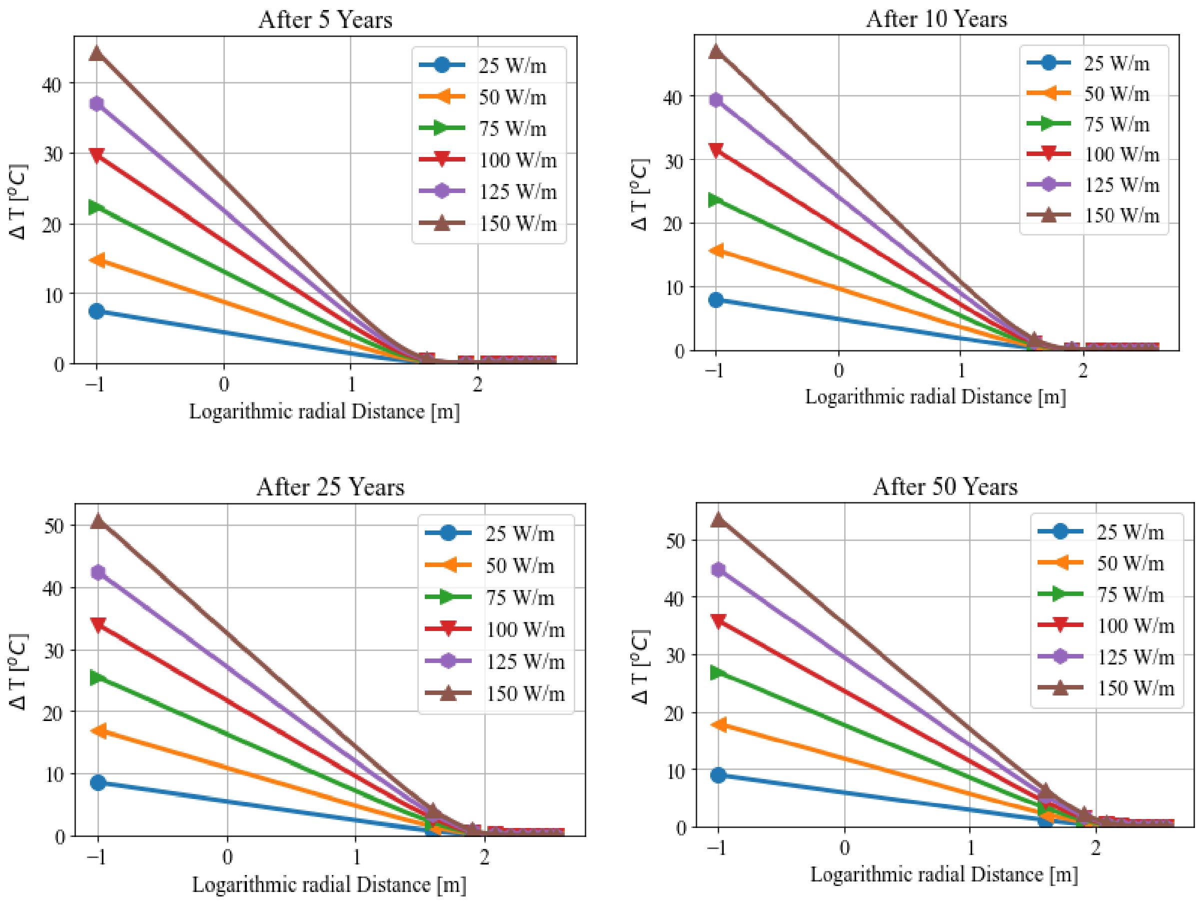

Figure 4.4: Radial borehole wall temperature profile ($\Delta T = T_s - T_b$) in different heat load

As explained in chapter 2, characteristics of soil/ rock surrounding borehole will affect the heat extraction rate. One of these main characteristics is the soil thermal conductivity. Refer to the literatures [53], [58], the range of 0.3 to 4 will consider for different types of rock/ soil. such as sandstone, sand, granite, shale, etc.

Table 4.1: Heat conductivity of different type of rock [58]

Type of rock	Heat Conductivity (W/m K)
Sandstone	2.5-4.2
Shale	1.05-1.45
Granite	1.9-3.35
Gravel	0.3-0.5

Figure 4.5 shows the effect of the thermal conductivity of rock/ soil on borehole wall temperature in different heat loads. For higher thermal conductivity, the temperature change is less than lower thermal conductivity in a constant heat load. For example, temperature change for thermal conductivity in the range of 0.3 to 4.2 W/m K varies between 50 to less than 5 °C for a heat extraction rate 25 W/m after 0.1 year. This means that higher rock/ soil thermal conductivity helps to increase the borehole temperature and consequently increases fluid temperature in U-tube. It should be noted that, according to the heat transfer principle, higher heat conductivity results in lower thermal resistance and, thus, higher heat conduction.

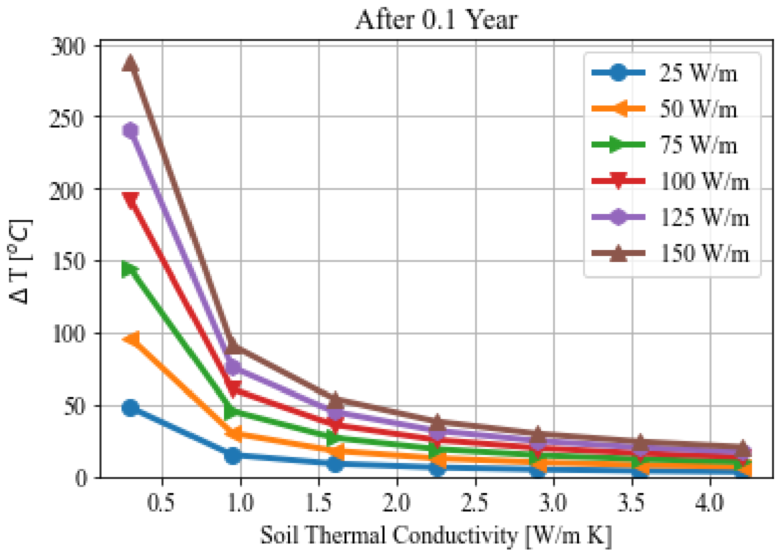

Figure 4.5: The effect of soil thermal conductivity on borehole wall temperature ($\Delta T = T_s - T_b$)

Figure 4.6 illustrate how wall temperature change varies over time in different heat extraction rate.

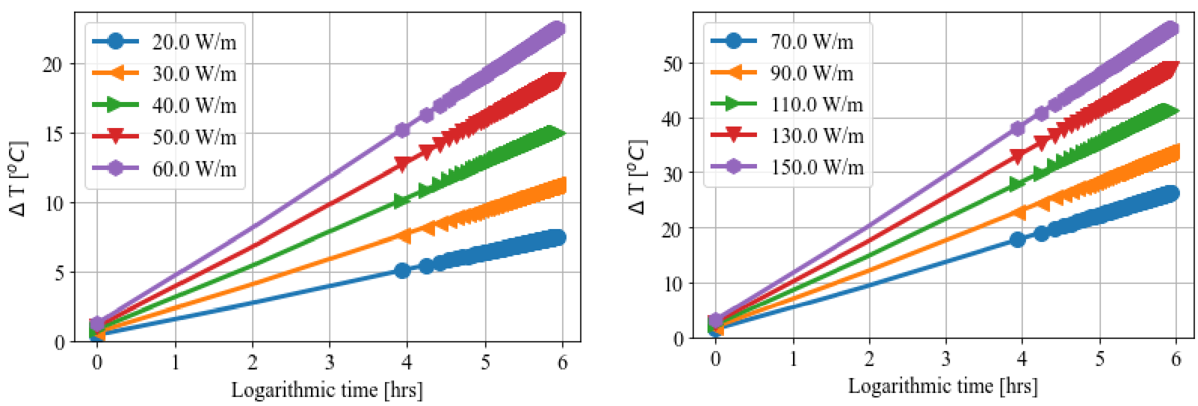

Figure 4.6: The effect of time and heat extraction load on borehole wall temperature ($\Delta T = T_s - T_b$)

When heat is extracted from the soil/ ground surrounding the borehole, the borehole wall temperature typically decreases over time. The reason is that the heat is extracted from surrounding rock/ soil to heat up fluid circulating within the tubes in boreholes. Therefore, soil temperature adjacent to the borehole decreases since heat is transferred to the fluid. As a result, the borehole temperature also decreases. It should be mentioned that the rate of temperature reduction is not constant. Initially, the temperature drop might be more rapid, but as heat is continuously extracted, the temperature gradient between the borehole and the surrounding soil may decrease. This can lead to a slower rate of temperature decrease as the process continues. While, in the injection heating to the soil or surrounding ground of borehole, the borehole wall temperature will increase over time. Heat is introduced into the borehole through a fluid. As the heated fluid is injected into the borehole, it transfers heat to the surrounding soil or rock formations. Heat transfer causes an increase in temperature in the vicinity of the borehole. Over time, the heated zone around the borehole expands as more heat is injected and absorbed by the surrounding soil or rock. It leads to a gradual increase in temperature along the borehole wall.

Figure 4.7 shows the effect of soil thermal conductivity on borehole temperature during injection of heat to the soil for 10 days. The wall temperature will increase more for lower soil thermal conductivity. When the soil has lower thermal conductivity, it means that the thermal resistance of soil is higher, or it means that it is less efficient at conducting heat. Therefore, the heat tends to accumulate near the borehole. This higher temperature gradient results in a higher temperature at the borehole wall.

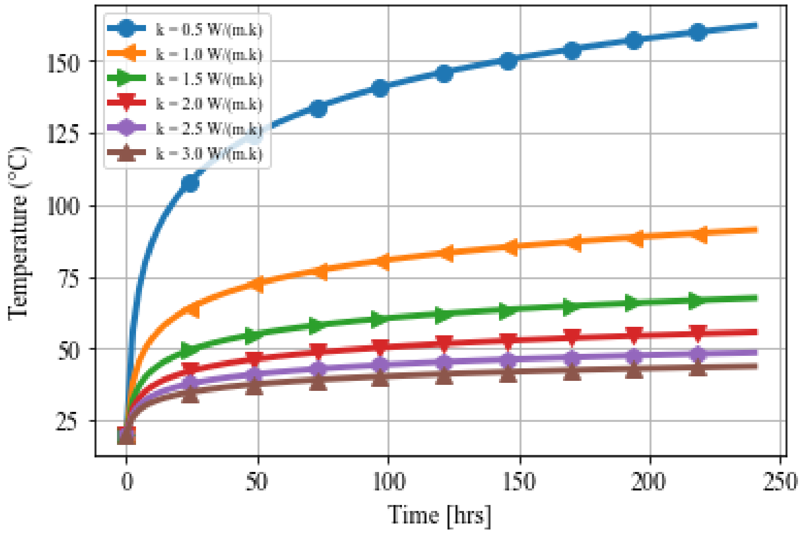

Figure 4.7: The effect of soil thermal conductivity on borehole wall temperature in constant heat injection rate

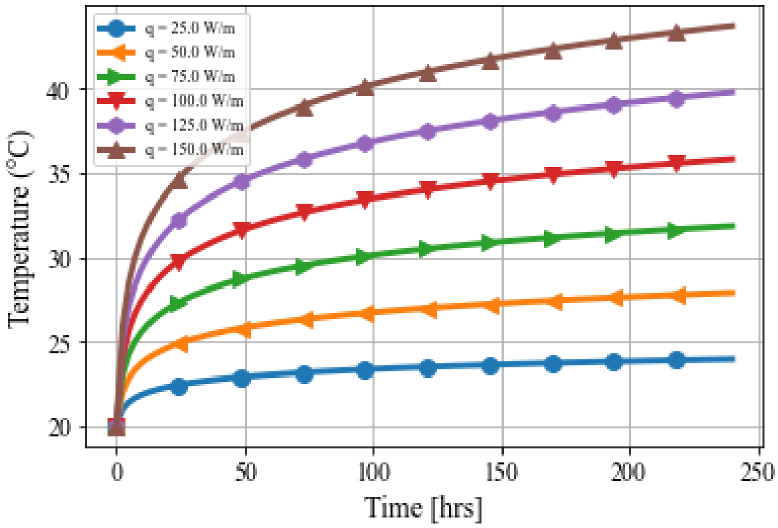

Figure 4.8: The effect of heat injection rate on borehole wall temperature after 10 days

The effect of heat injection on borehole wall temperature in various heat rate is illustrated in Figure 4.8. In constant soil thermal conductivity, during heat injection to the wall, higher heat rate, causes higher in wall borehole temperature as represented in Figure 4.8.

To investigate how the fluid temperature in the borehole will change, the effective parameters are set in the model based on Norway as a case study. All the inputs are extracted from recent years' articles and academic research, which are listed in references. Figure 4.9 shows the measured ground temperature profiles in different locations of Norway with depth [51]. The typical temperature gradient in Norway is between 1.4 and 2.7 °C/m [52].

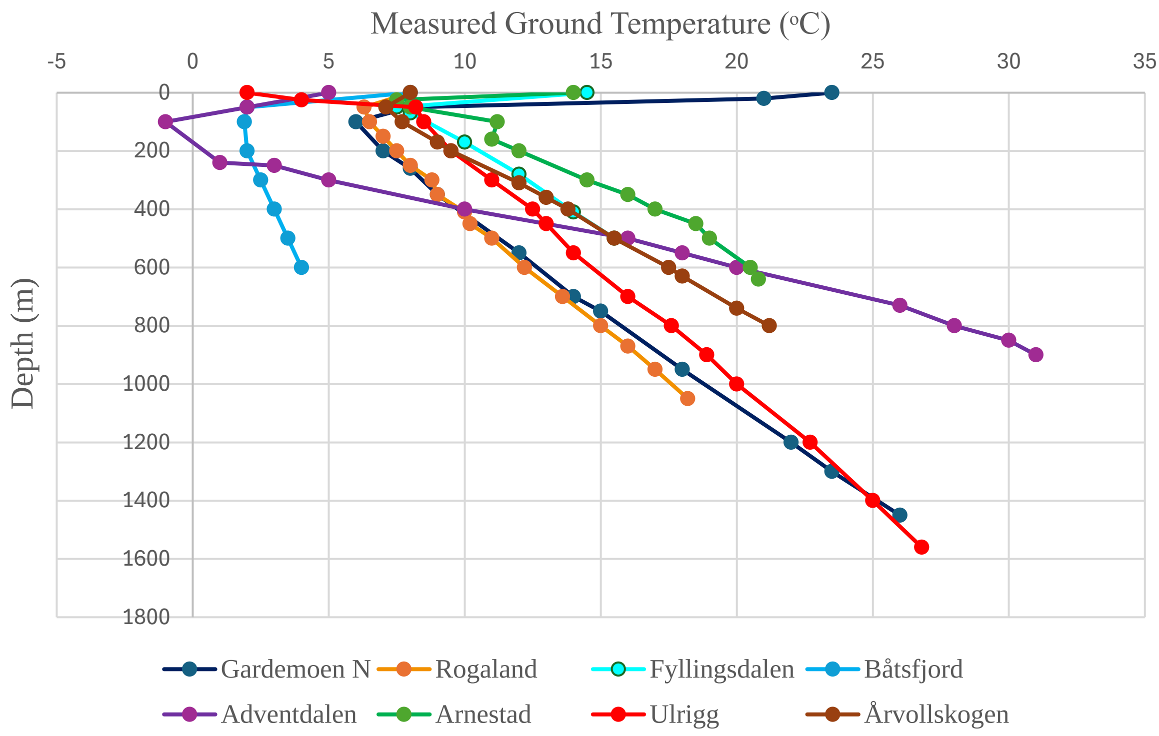

Figure 4.9: Measured ground temperature based on depths in different location of Norway

According to the measured ground temperature in Årvollskogen [51] as a part of the Oslo region, the ground temperature is about 21.2 °C at 800 meters. The specification and geometry of the wellbore considered in this project are as Table 4.2:

Table 4.2: Used borehole and U-shaped tube parameters in the model

Parameter	Unit	Value
Number of boreholes N_b	-	1
Borehole depth L_b	m	800
Borehole radius r_b	m	0.1
Tube outer radius r_o	m	0.02
Tube inside radius r_i	m	0.017
Thermal conductivity of tube k_p	W/m K	0.5
Thermal conductivity of borehole k_b	W/m K	0.6

In this study, the assumed fluid is water with a thermal conductivity of 0.6 W/m K. In reality, pure water cannot be considered in cold conditions since its freezing point is 0 °C. However, it should be considered that water has higher thermal conductivity and lower viscosity. Thus, it can be mixed with antifreeze fluids such as Ethyl alcohol, Propylene glycol, or Ethylene glycol to have a lower freezing point. The freezing point of Ethyl alcohol 30% is -20 °C, Propylene glycol 33% is -17 °C, and Ethylene glycol 33% is -18 °C [58]. Although using the antifreeze fluid prevents water from freezing inside the tube, its toxicity is an important factor to consider. Propylene glycol is less toxic compared to the Ethylene glycol and Ethyl alcohol [58]. So, it is less harmful to the environment. Typically, in Norway, for shallow geothermal boreholes, Propylene glycol is used in as an anti-icing agent. However, for deeper boreholes, it needs to be used an antifreeze with higher density, since in deeper boreholes the water hydrostatic force inside the borehole will increase with depth and can affect the tube/ pipe.

As mentioned in the earlier parts, the borehole wall temperature is an important factor since the fluid's temperature will eventually approach that of the borehole wall. Also, refer to Figure 4.3, the higher heat load causes lower borehole wall temperature. Considering the previous results, Figure 4.10 show how the average fluid temperature will vary over times in different heat load, and Figure 4.11 illustrates how the average fluid temperature will change by increasing heat load in different time. Since more heat is being extracted from the soil/ rock, the fluid circulating within the borehole will experience a cooling effect, leading to a decrease in its temperature. Here, inlet fluid temperature is assumed 1 °C and the soil temperature is 21.2 °C at 800 meters for the case Årvollskogen.

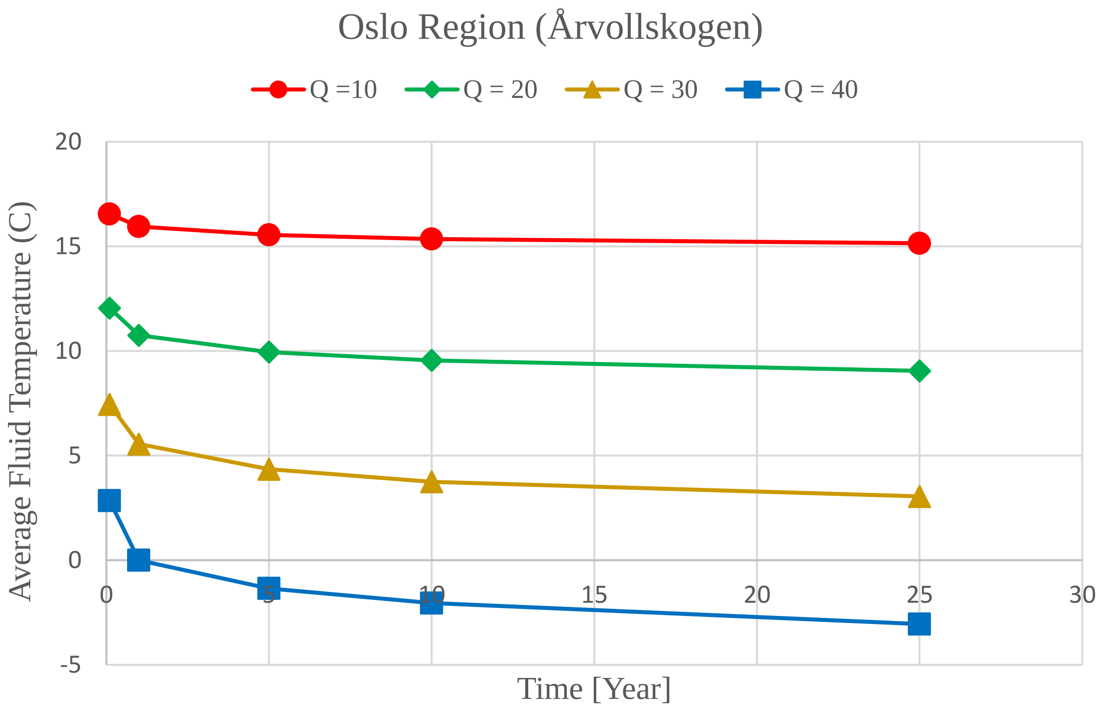

Figure 4.10: The effect of time on borehole average fluid temperature in different heat load

To evaluate the influence of inlet fluid temperature on outlet fluid temperature, the inlet temperature range of 1 to 5 is considered. A higher inlet fluid temperature causes a lower difference with the average fluid temperature at the end of the borehole, thus resulting in a higher outlet fluid temperature. Figure 4.12 represents how increased inlet temperature leads to higher exit fluid temperature in different heat loads after 0.1 year. Lower heat load, with lower incoming fluid temperature, results in greater outlet temperature, given the shorter period.

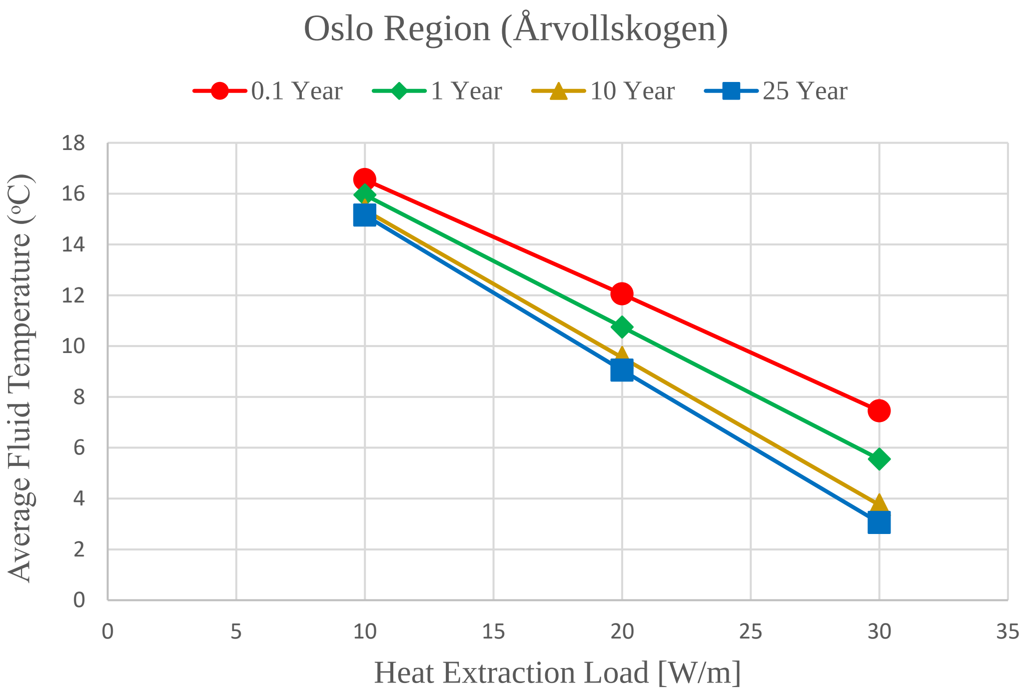

Figure 4.11: The effect heat load on borehole average fluid temperature in different times

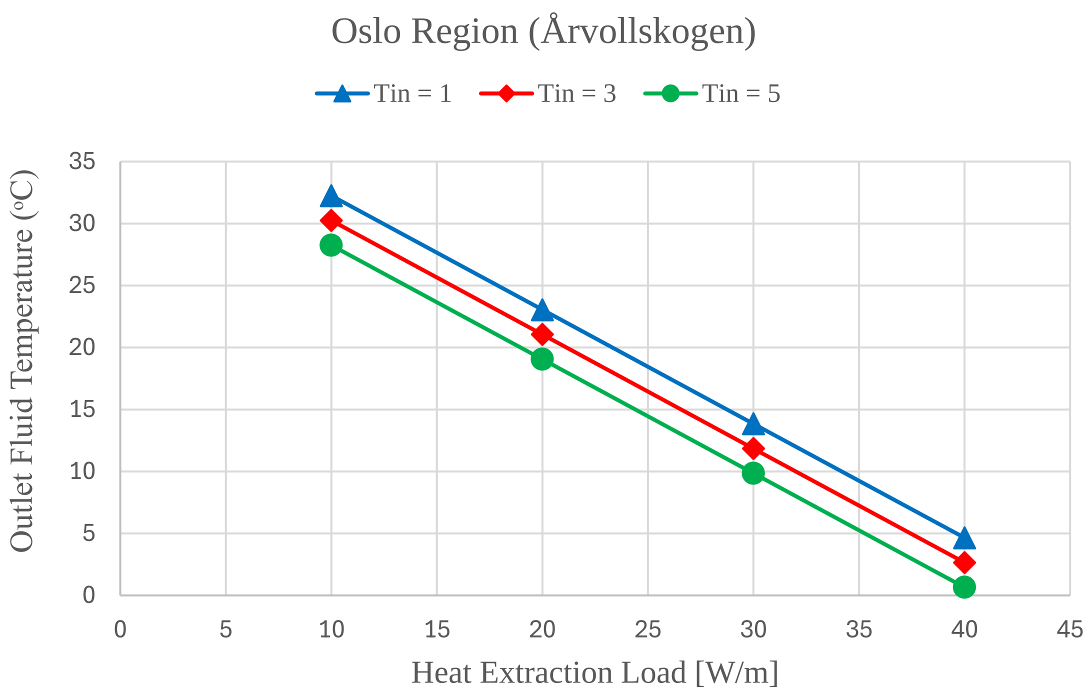

Figure 4.12: The effect of heat extraction load on outlet fluid temperature, considering different inlet fluid temperature

The investigation in this project shows that the soil/ rock temperature is an essential factor that affects the outlet fluid temperature. Table 4.3 shows the soil temperature in different location of Norway and in some other locations of world. Iceland with volcanic rock has higher geothermal gradient in comparison with the other mentioned area [52], [51].

Table 4.3: Soil/ rock temperature at 800-meter depth in different locations

Parameter	Soil/ rock temperature °C
Rogaland	15
Ulrigg	17.6
Oslo Region	21.2
Svalbard	28.2
Germany	40
Middle East	70
Icland	140

As shown in Figure 4.13, the range of ground temperature at 800 meters depth from 15 °C in Rogaland to 140 °C in Iceland get outlet fluid temperatures of 10.65 °C and 260.65 °C in these two locations, respectively. The other parameters, such as time, heat extraction load, borehole geometry, inlet fluid temperature have been considered the same. Here, the heat load extraction is 20 W/m and the considered time is 0.1 year. Thus, higher soil temperature results in greater outlet fluid temperature and consequently, higher power input rate to the heat pump system.

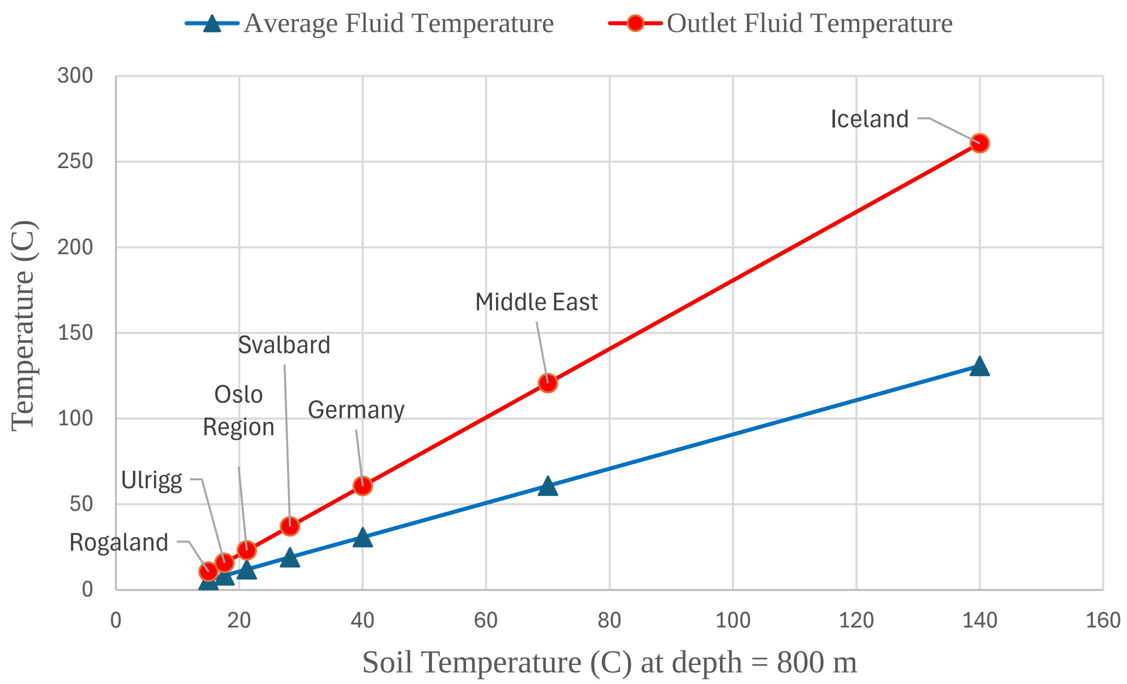

Figure 4.13: The effect of soil temperature at 800-meter depth on outlet fluid and average fluid temperature

Another parameter that may affect the system is borehole heat conductivity. Inside of the borehole can be filled by grout material or water. The thermal conductivity some type of grout material and water are listed in Table 4.4.

Table 4.4: Heat conductivity of water and grout material [59], [60]

Water & Grout Material	Heat Conductivity (W/m K)
Water (@ 20 C)	0.6
Cement	1.9-2
Bentonite based	0.9
Silica Sand Based	2.3

Referring to equation (3.17), the thermal resistance of grout material is directly relation to the average fluid temperature. Lower thermal conductivity results in higher thermal resistance of boreholes, so the fluid, which is heated by the soil, cannot easily lose its temperature. In this project water is used in the borehole instead of grout material. Water can transfer heat through heat conduction and convection transfer phenomena. In this case, it is assumed the heat convection is negligible, so only the heat conductivity is considered in the model.

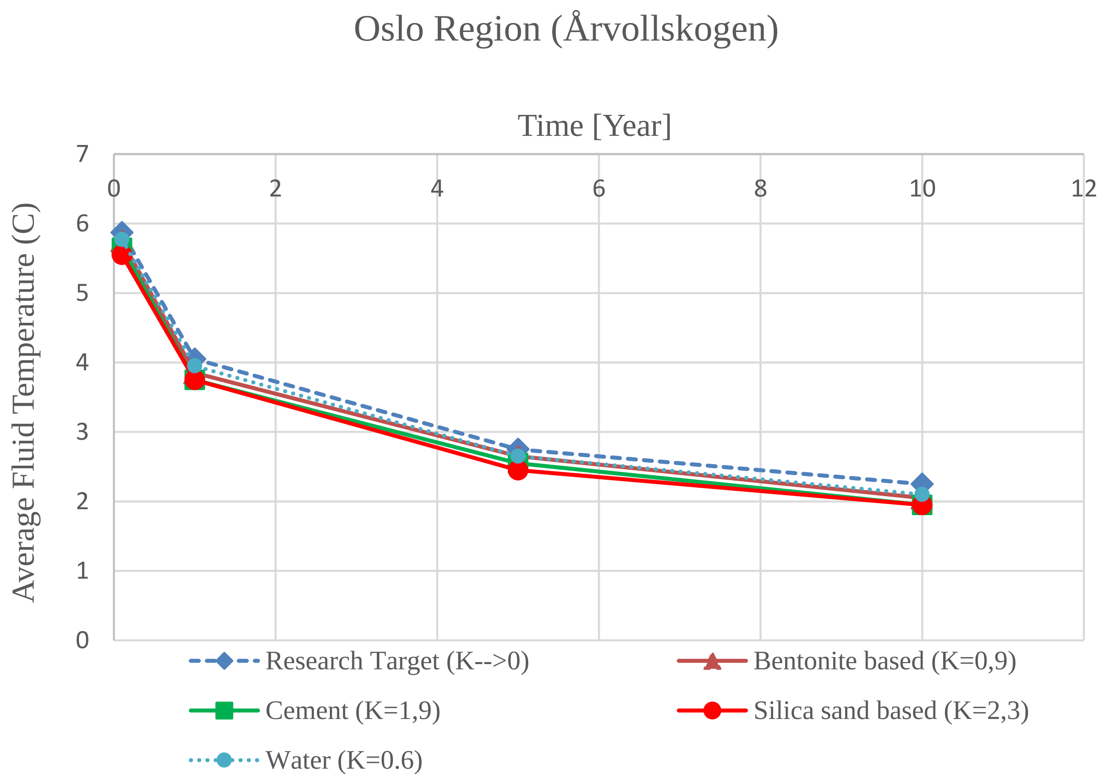

Figure 4.14: The effect of different types of grout material on average fluid temperature

Researchers try to find grout material with lower thermal conductivity close to zero. As shown in Figure 4.14, the results show that different grout materials do not have a significant effect on the average fluid temperature and consequently, on outlet fluid temperature. Here, the considered heat load is 30 W/m.

In all the above results, mass flow is considered constant and equals 0.5 kg/s. Generally, the amount of mass flow will directly affect the Reynolds number, as mentioned in equation (3.11). Figure 4.15 shows the effect of mass flow on pressure drop. The results illustrate that higher mass flow will increase the pressure drop of fluid inside the tube/ pipe. This can also easily be found by equation (3.19).

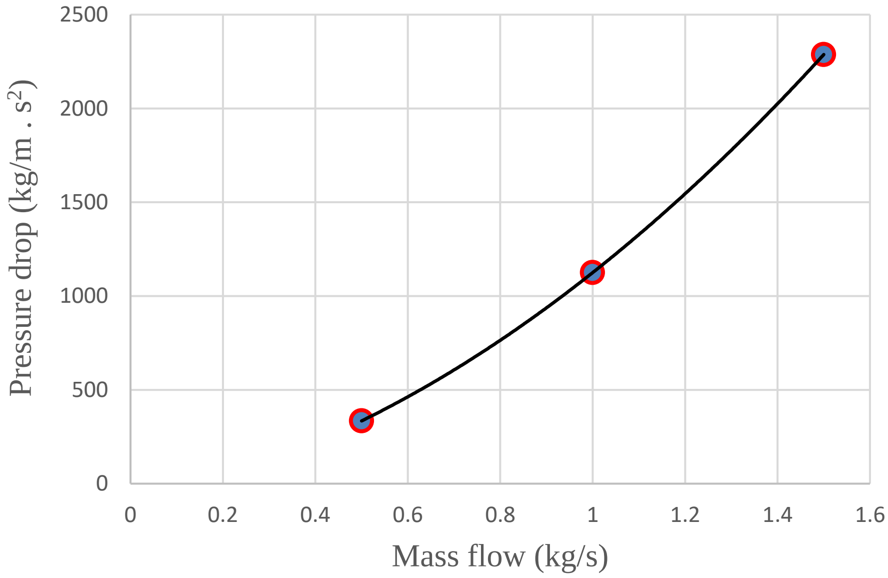

Figure 4.15: The effect of mass flow on pressure drop of circulating fluid inside the borehole

A main disadvantage of higher pressure drop is the effect on the circulating pump, which means that a higher pressure drop requires more effort from the circulating pump. Figure 4.16 shows the effect of pressure drop on circulating pump power. It can also clearly be found in equation (3.23). Here, the efficiency of circulating pump is assumed 75%.

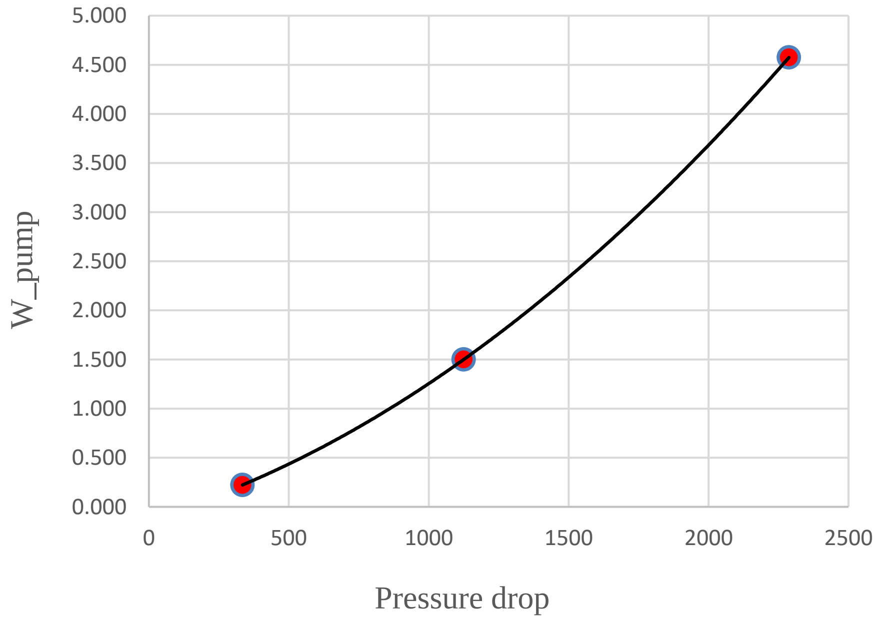

Figure 4.16: The effect of pressure drop on power of circulating pump

Based on the results obtained in Figure 4.13 for outlet fluid temperature in different locations, for constant inlet temperature equals 1°C, the fluid inlet and outlet temperature differences for selected area are shown in Figure 4.17.

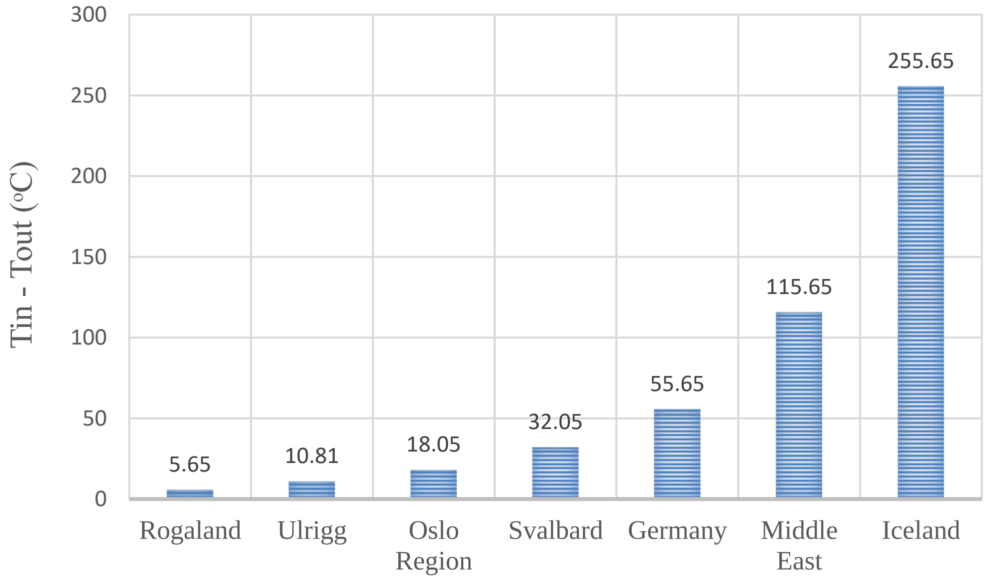

Figure 4.17: The inlet and outlet fluid temperature differences in selected locations with various soil/ rock temperature

Equation (3.25) is used to calculate generated power from ground source (Q_{BHE}) and will use as an inlet power to the heat pump system. For selected cases the results are shown in Table 4.5.

Table 4.5: The result of generated power from geothermal to the heat pump (Q_{BHE})

Parameter	Tin-Tout (°C)	Q_{BHE} (kW)
Rogaland	5.65	11.83
Ulrigg	10.81	22.63
Oslo Region	18.05	37.78
Svalbard	32.05	67.08
Germany	55.65	116.48
Middle East	115.65	242.06
Icland	255.65	535.08

Equations (3.24) and (3.26) are used to calculate outlet power from the GSHP. Generally, the COP of GSHP is around 3 to 5 [57]. In this project it is assumed constant COP is about 4. Thus, the results of net power (W_{net}) and power output from the heat pump are listed in Table 4.6.

Table 4.6: The results of power output from the heat pump

Parameter	W_{net} (kW)	Q_{out} (kW)
Rogaland	3.94	15.77
Ulrigg	7.54	30.17
Oslo Region	12.59	50.37
Svalbard	22.36	89.44
Germany	38.83	155.30
Middle East	80.69	322.74
Icland	178.36	713.43

And finally, Figure 4.18 shows how the geothermal borehole power affect the power output from the heat pump based on the calculated results in Table 4.5 and Table 4.6.

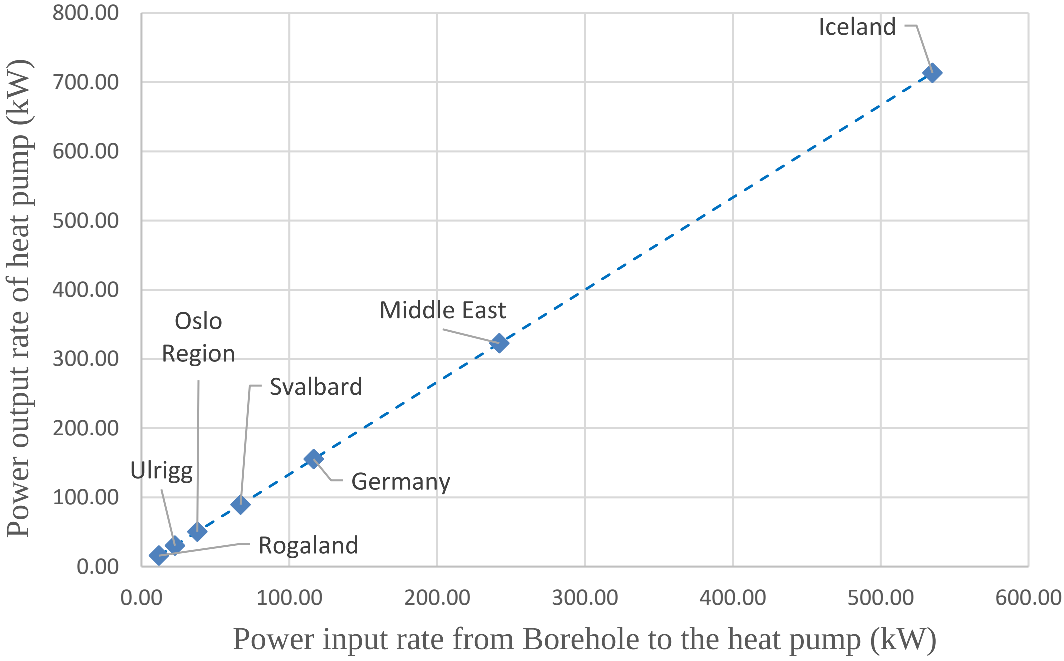

Figure 4.18: Power output rate from GSHP in several locations with different geothermal gradient

In order to calculate a payback period for a geothermal heat pump system in Norway, the following calculations are done, and the results for years 2021-2022 and 2023 based on the price of electricity are presented in Table 4.7. The initial capital cost, COP, and electricity price are used to calculate the payback period. Refer to Table 2.2 [12], the capital cost for the ground source heat pump system is assumed to be 170,000 NOK, and the total energy consumption per household per year in Norway is considered 20,230 kWh. It is also assumed that around 78% of the total energy consumption of houses is related to heating, cooling, and domestic hot water (DHW) [12]. Here, the COP is assumed to be equal to 4.

Thus,

- Annual energy savings:

$$Energy\ consumption\ for\ heating\ \&\ cooling = Total\ energy\ consumption\ \times 78\%$$

$$Energy\ consumption\ with\ GHP = \frac{Energy\ consumption\ of\ heating\ \&\ cooling\ (without\ GHP)}{COP}$$

$$Energy\ saving\ per\ year = Energy\ consumption\ without\ GHP - Energy\ consumption\ with\ GHP$$

- Annual cost savings:

$$Annual\ cost\ saving = Energy\ saving\ per\ year \times Cost\ of\ electricity\ per\ kWh$$

- Payback period:

$$Payback\ period = initial\ capital\ cost / Annual\ cost\ saving$$

Table 4.7: Economic calculation results for GSHP in Norway

Parameter	Unit	Year 2021-2022	Year 2023	Ref.
Capital cost (Uni+ Installation)	NOK	170,000	170,000	[12]
COP	-	4	4	
Electricity price	NOK/kWh	1.81*	1.36**	[12], [61]
Energy consumption without heat pump for heating & cooling	kWh	15779.4	15779.4	
Energy consumption with heat pump	NOK	3944.85	3944.85	
Annual energy saving	kWh	11834.55	11834.55	
Annual cost saving	NOK	21420.5	16095	
Payback period	Years	~8	~10	
*Average electricity price 3rd quarter 2021 till 3rd quarter 2022 [12] **Average electricity price, 4th quarter 2023 [61]				

The results show that the payback period, based on the average of 2021-2022 electricity price, is about 8 years, and considering the 4th quarter of 2023 electricity price, it increases to around 10 years. It means the payback period for higher electricity prices is lower if other effective parameters are considered constant. Thus, it can be concluded that for countries that have high electricity prices, like Norway, geothermal heat pump systems are an energy-efficient solution for heating and cooling applications. It should be noted that to have a more accurate estimation, the capital cost must be calculated in detail, considering all the costs of drilling, installation and equipment. The most part of the capital cost is related to installation costs [12]. These parts of costs can be split between a community of residential or commercial buildings for heating and cooling purposes. So, using geothermal heat pump systems in this situation can be more economical for the end-users.

5 Conclusion

This study evaluated a geothermal heat pump system in Norway. The analytical method's infinite line source solution was applied. The model enables the estimation of heat extraction from the borehole (power input to the heat pump) which is further used for calculating power output from the heat pump. The model can also be used for heat injection to the wellbore during summer. The effect of various key parameters governing heat transfer to the fluid, such as the thermal conductivity of soil, geothermal gradient, inlet temperature and flow rate conductivity of wellbore/ grout material were investigated.

A significant finding of this research shows the importance of wall temperature as a critical parameter of heat extracted from the borehole, since the fluid temperature will eventually approach that of the borehole wall. The results showed a significant decrease in borehole wall temperature over time for a constant heat load. This means the heat conduction performance from soil to the borehole wall reduces over time. Furthermore, the impact of various amounts of heat load on borehole wall temperature illustrated that a lower heat load causes higher borehole wall temperature and, consequently, an increase in fluid temperature.

Soil properties emerged as a crucial determinant of system performance, with thermal conductivity playing a pivotal role. Understanding the thermal behavior of different soil types is essential for optimizing system design and operation in diverse geological environments.

The soil/ rock temperature is another crucial factor that affects the system's performance. The results indicate that in the areas with a higher thermal gradient of the ground, the heat extracted from the borehole is much higher. Based on Norway's geology data, the range of thermal gradient of the ground is approximately between 1.4-2.7 ^{o}C/100 m. For instance, Norway has a lower thermal gradient compared to Iceland and therefore, the results show that the performance of geothermal heat pump systems in Iceland is much better than in Norway. At 800 meters depth, the maximum soil temperature in Norway is around 28 ^{o}C; however, in Iceland, it is around 140 ^{o}C; which cause in around 100 and 700 kW power output from a geothermal heat pump in the same conditions and assumptions, respectively. Although the horizontal geothermal system creates a higher heat transfer area, the cold weather condition in Norway and its effect on the ground temperature in lower depths, makes it an inappropriate choice. Thus, most of the focus in Norway is on vertical systems.

Additionally, the effect of inlet fluid temperature on system performance shows lower inlet temperature in a constant heat load results in higher outlet fluid temperature, leading to higher fluid temperature differences. Pressure drop and mass flow of fluid were also examined, providing insights into hydraulic aspects of the system and their implications for overall efficiency. The results indicate that pressure drop is a crucial factor since a higher pressure drop requires more effort from the circulating pump.

Moreover, the evaluation of different grout materials highlighted that selecting appropriate grout materials is important for maximizing system efficiency and longevity. Higher thermal conductivity of grout material can increase the average fluid temperature. Despite its effect on fluid temperature, the sensitivity analysis shows that the thermal conductivity of selected grout material does not significantly affect the system performance compared to the importance of the thermal gradient of the ground and soil properties. It should be noted that in this study, only the heat conduction phenomenon was considered in the model and heat convention is neglected due to its minor effect.

In conclusion, by comprehensively assessing various factors such as time, heat load, borehole distance, thermal gradient of ground, soil properties, fluid temperature, and grout materials, this study provides a foundation for the design, optimization, and operation of efficient and sustainable geothermal heating/ cooling systems. Furthermore, based on the economic results, using the geothermal heat pump system can be an effective solution for heating and cooling purposes in countries with high electricity prices, such as Norway. Thus, although the temperature gradient of the ground in Norway is not too high, the high electricity price and efficient, reliable, and environmentally friendly heating and cooling solutions by geothermal heat pump systems have caused Norway to pay attention and invest more in this area.

Future research should investigate in more detail the economic aspects, dynamic modeling, considering several boreholes and the effect of each borehole on the adjacent borehole, field validation, and optimization strategies to further advance the understanding and implementation of geothermal technologies in Norway and beyond.

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Appendices

Appendix A: Thesis description

University of South-Eastern Norway

Faculty of Technology, Natural Sciences and Maritime Sciences, Campus Porsgrunn

FMH606 Master's Thesis

Title: Evaluation of Geothermal Heat Pumps systems for Energy Efficient Heating in Norway

USN supervisor: Carlos F. Pfeiffer

External partner: University of Stavanger (UiS), Department of Energy and Petroleum Engineering.
External co-supervisors: Mohsen Assadi and Raoof Gholami (UiS).

Task background:

Geothermal heat pumps (GHPs), or earth-coupled heat pumps, use the relatively constant temperature of the earth as the exchange medium instead of the outside air temperature.

Traditional Geothermal Heat Pumps use shallow heat exchangers just a few feet under earth range from 7°C to 21°C, depending on latitude, but by using deeper wells (over 300 meters deep), higher earth temperatures can be reached, resulting in higher coefficient of performances (COPs).

Since Norway has developed very efficient and cost-effective drilling technologies, it results very attractive to study the use of GHPs to extract heat from wells. Even though the investment price of a geothermal system can be several times that of an air-source system of the same capacity, the higher COPs represent bigger energy savings and can be cost-effective depending on the cost of energy and available government incentives.

Task description:

1. Literature research on available geothermal heat pump systems, with focus on using deep and shallow wells. The review should include both scientific and available industrial information.
2. Discuss the advantages and disadvantages of different kinds of GHPs for specific areas of Norway.
3. Develop an energy balance model to determine the main variables of a GHPS system and estimate the coefficients of performance of the heat pump system during different conditions. Use data from UiS if available.
4. Analize the viability of these technologies for different regions of Norway, considering technical and economic factors.
5. Optional (depending on time constraints): propose a case scenario (for example a large public building or a multi-apartment building) where a GHP system is used for heating/cooling. Indicate how the case scenario can be used to evaluate the performance of the system under different demand and seasonal variations.
6. Write and submit the Master Thesis report.

<u>Is the task suitable for online students (not present at the campus)?</u> Yes

<u>Practical arrangements</u>: The thesis requires some basic programming in Python and/or MATLAB. Real data from existing wells can be shared by the Department of Energy and Petroleum Engineering of the University of Stavanger partner, when available.

<u>Supervision:</u>
As a rule, the student is entitled to 15-20 hours from the main supervision. This includes necessary time for the supervisor to prepare for meetings (reading material to be discussed, etc). The students should agree additional hours with the co-supervisor.

<u>Signatures</u>:

Supervisor (date and signature): 29.01.2024 Carlos A. Pfeffer

Student (write clearly in all capitalized letters): AFSANEH SADAT BOLOORCHI

Student (date and signature): 29.01.2024 Boloorchi

Appendix B: Python Code to calculate borehole wall temperature profile.

```
import numpy as np
import matplotlib.pyplot as plt
from scipy.special import expi, exp1
plt.rcParams['xtick.labelsize'] = 12
plt.rcParams['ytick.labelsize'] = 12
plt.rcParams['font.size'] = 12
plt.rcParams['font.family'] = 'Times New Roman'
#plt.rcParams['fontname'] = 'Times New Roman'

# Function to calculate wellbore temperature using ILSM model
def calculate_temperature(r_b, tau, T_s, Q, k_s, rho_s, c_s, N_b, L_b, alpha):
    # Equation 1 and 2

    q = Q/(N_b*L_b)
    term1 = q / (4 * np.pi * k_s)
    term2 = (r_b ** 2) / (4 * alpha * tau)

    integral_result = -expi(-term2)

    temperature = T_s + term1 * integral_result
    return temperature

year = 365*24*3600
#tau = 0.1*year
T_s = 140
k_s = 3
rho_s = 2600
c_s = 860
Q = -20
N_b = 1
L_b = 800
alpha = 2e-6
```

```
tau = [0.1*year, 1*year, 5*year, 10*year, 25*year, 50*year, 100*year, 300*year]
label = ['0.1 year', '1 year', '5 year', '10 year', '25 year', '50 year', '100 year', '300 year']
mr = ['o', '<', '>', 'v', 'h', '^', 'o', 'D', 'X', '+', 'x']
Radial = np.linspace(0.1,400, 1000)
fig1, ax1 = plt.subplots()
fig2, ax2 = plt.subplots()
fig3, ax3 = plt.subplots()
ii = 0
for tt in tau:
    Temperature = calculate_temperature(Radial, tt, T_s, Q, k_s, rho_s, c_s, N_b, L_b, alpha)
    T_n = (Temperature - T_s) /(Temperature[0] - T_s)
    delta_t = T_s - Temperature
    ax1.plot(Radial, Temperature, linewidth = 3, label = label[ii], marker = mr[ii], ms = 8,
markevery = 100)
    ax2.plot(np.log10(Radial), T_n, linewidth = 3, label = label[ii], marker = mr[ii], ms = 8,
markevery = 100)
    ax3.plot(np.log10(Radial), delta_t , linewidth = 3,label=label[ii], marker=mr[ii], ms=8,
markevery=100)
    ii += 1

#ax1.tick_params(axis = 'both', labelsize = 14)
ax1.set_xlabel('Radial Distance [m]')
ax1.set_ylabel('Borehole Wall Temperature [$^o C$]')

ax2.set_xlabel('Logarithmic radial Distance [m]')
ax2.set_ylabel('$\\theta$')

ax3.set_xlabel('Logarithmic radial Distance [m]')
ax3.set_ylabel('$\Delta$ T [$^o C$]')

#ax6.set_ylim([0, None])

ax1.grid()
ax2.grid()
ax3.grid()
ax1.legend()
```

```
ax2.legend()
ax3.legend()

Q = [25, 50, 75, 100, 125, 150]

fig4, ax4 = plt.subplots()
ii = 0
for qq in Q:
    Temperature = calculate_temperature(Radial, 10*year, T_s, -1*qq, k_s, rho_s, c_s, N_b,
L_b, alpha)
    delta_t = T_s - Temperature
    ax4.plot(np.log10(Radial),delta_t, linewidth = 3, label=f'{qq} W/m', marker=mr[ii],
ms=10, markevery=100)
    ii += 1

ax4.set_xlabel('Logarithmic radial Distance [m]')
ax4.set_ylabel('$\Delta$ T [$^o C$]')
ax4.set_title('After 10 Years')
ax4.set_ylim([0, None])
ax4.grid()
ax4.legend()

fig5, ax5 = plt.subplots()
ii = 0
for qq in Q:
    Temperature = calculate_temperature(Radial, 25*year, T_s, -1*qq, k_s, rho_s, c_s, N_b,
L_b, alpha)
    delta_t = T_s - Temperature
    ax5.plot(np.log10(Radial),delta_t, linewidth = 3, label=f'{qq} W/m', marker=mr[ii],
ms=10, markevery=100)
    ii += 1

ax5.set_xlabel('Logarithmic radial Distance [m]')
ax5.set_ylabel('$\Delta$ T [$^o C$]')
ax5.set_title('After 25 Years')
ax5.set_ylim([0, None])
```

```
ax5.grid()
ax5.legend()

fig6, ax6 = plt.subplots()
ii = 0
for qq in Q:
    Temperature = calculate_temperature(Radial, 50*year, T_s, -1*qq, k_s, rho_s, c_s, N_b, L_b, alpha)
    delta_t = T_s - Temperature
    ax6.plot(np.log10(Radial),delta_t, linewidth = 3, label=f'{qq} W/m', marker=mr[ii], ms=10, markevery=100)
    ii += 1

ax6.set_xlabel('Logarithmic radial Distance [m]')
ax6.set_ylabel('$\Delta$ T [$^o C$]')
ax6.set_title('After 50 Years')
ax6.set_ylim([0, None])
ax6.grid()
ax6.legend()

fig7, ax7 = plt.subplots()
ii = 0
time = np.linspace(3600, 100*year, 10000)
Q1 = np.linspace(20,70,6)
for qq in Q1:
    Temperature = calculate_temperature(0.1, time, T_s, -1 * qq, k_s, rho_s, c_s, N_b, L_b, alpha)
    delta_t = T_s - Temperature
    ax7.plot(np.log10(time/3600),delta_t, linewidth = 3, label=f'{qq} W/m', marker=mr[ii], ms=10, markevery=100)
    ii += 1

ax7.set_xlabel('Logarithmic time [hrs]')
ax7.set_ylabel('$\Delta$ T [$^o C$]')
#ax7.set_title('After 50 Years')
ax7.set_ylim([0, None])
```

```
ax7.grid()
ax7.legend()

fig8, ax8 = plt.subplots()
ii = 0
time = np.linspace(3600, 100*year, 10000)
Q1 = np.linspace(50,300,6)
for qq in Q1:
    Temperature = calculate_temperature(0.1, time, T_s, -1 * qq, k_s, rho_s, c_s, N_b, L_b, alpha)
    delta_t = T_s - Temperature
    ax8.plot(np.log10(time/3600),delta_t, linewidth = 3, label=f'{qq} W/m', marker=mr[ii], ms=10, markevery=100)
    ii += 1

ax8.set_xlabel('Logarithmic time [hrs]')
ax8.set_ylabel('$\Delta$ T [$^o C$]')
#ax7.set_title('After 50 Years')
ax8.set_ylim([0, None])
ax8.grid()
ax8.legend()

fig9, ax9 = plt.subplots()
Q = [25, 50, 75, 100, 125, 150]
k_s = np.linspace(0.3,4.2,7)

ii = 0
for qq in Q:
    Temperature = calculate_temperature(0.1, 0.1*year, T_s, -1*qq, k_s, rho_s, c_s, N_b, L_b, alpha)
    delta_t = T_s - Temperature
    ax9.plot(k_s,delta_t, linewidth = 3, label=f'{qq} W/m', marker=mr[ii], ms=8)
    ii += 1

ax9.set_xlabel('Soil Thermal Conductivity [W/m K]')
ax9.set_ylabel('$\Delta$ T [$^o C$]')
```

```
ax9.set_title('After 0.1 Year')
ax9.set_ylim([0, None])
ax9.grid()
ax9.legend()

plt.show()
```

Appendix C: Python Code to calculate average fluid temperature and outlet fluid temperature.

```
import numpy as np
import matplotlib.pyplot as plt
import math
from scipy.special import expi, exp1
plt.rcParams['xtick.labelsize'] = 14
plt.rcParams['ytick.labelsize'] = 14
plt.rcParams['font.size'] = 14
plt.rcParams['font.family'] = 'Times New Roman'
#plt.rcParams['fontname'] = 'Times New Roman'

# Function to calculate wellbore temperature using ILSM model
def calculate_temperature(r_b, tau, T_s, Q, k_s, rho_s, c_s, N_b, L_b, alpha):
    # Equation 1 and 2

    q = Q/(N_b*L_b)
    term1 = q / (4 * np.pi * k_s)
    term2 = (r_b ** 2) / (4 * alpha * tau)

    integral_result = -expi(-term2)

    temperature = T_s + term1 * integral_result
    return temperature

# Function to calculate Reynolds number
def calculate_reynolds_number(flow_rate, ri, viscosity):
    # equation 7
    Re = 2*flow_rate/(np.pi*viscosity*ri)
    return Re

# Function to calculate Prandtl number
def calculate_prandtl_number(viscosity, specific_heat, thermal_conductivity):
    # Equation 8
```

```
    prandtl_number = (viscosity * specific_heat) / thermal_conductivity
    return prandtl_number

def caluclate_convection_heat_transfer_coef(Re, Prandtl_number, thermal_conductivity, ri):
    # Equation 5 and Equation 6
    if ((Re> 1e4) & ((Prandtl_number > 0.7) & (Prandtl_number<160))):
        Nu = 0.023 * (Re ** 0.8) * (Prandtl_number ** 0.3)
    else:
        Nu = 4.36
    h_f = Nu * thermal_conductivity/(2*ri)
    return h_f
# Function to calculate borehole thermal resistance
def calculate_borehole_thermal_resistance(r_b, r_o, r_i, D, h_f, k_p, k_b, k_s):
    # Equation 4 and 5
    R_p = (1/(2*np.pi*k_p))*math.log((r_o/r_i)) + 1/(2*np.pi*r_i*h_f)
    R_b = (1/(4*np.pi*k_p))*(math.log(r_b/r_o) + math.log(r_b/(2*D)) + ((k_b - k_s)/(k_b + k_s))*math.log((r_b**4)/(r_b**4-D**4))) +R_p/2
    return R_b

# Function to calculate soil thermal resistance
def calculate_soil_thermal_resistance(k_s, r_b, rho_s, c_s, tau):
    term1 = r_b**2*rho_s*c_s/(4*k_s*tau)
    integral_result = exp1(term1)
    R_s = (1/(4*np.pi*k_s))*integral_result
    return R_s

def calculate_mean_fluid_temperature(T_s, q, R_s, R_b):
    T_f = T_s + q*(R_s + R_b)
    return T_f

def calculate_fluid_temperature_outlet(T_f, T_f_1):
    T_f_2 = 2*T_f - T_f_1
    return T_f_2
def calculate_friction_factor(Re):
    # Equation 15 and 16
```

```
    if ((Re > 1e4) & (Re<1e6)):
        f = 0.316*Re**(-0.25)
    else:
        f = 64/Re
    return f

def calculate_pressure_drop(f, m_f,  L_b, rho_f, r_i):
   delta_P = f*((m_f**2) *2*L_b)/(rho_f * (np.pi**2) * (r_i**5))

   return delta_P

def calculate_mean_fluid_temperature_Eq19(T_f1, T_f2):
    T_f_m = (T_f1-T_f2)/(math.log(T_f1/T_f2))
    return T_f_m

year = 365*24*3600
#tau = 0.1*year
T_s = 21.2 + 273.15
k_s = 3
rho_s = 2600
c_s = 860
Q = -20
N_b = 1
L_b = 800
alpha = 2e-6
m_f = 0.5
r_b = 0.1
# mu: fluid viscosity
mu = 0.001
# ri: inner radius [m], range: [0.009, 0.018]
r_i = 0.017
# r_o: outer radius [m], range: [0.012, 0.022]
r_o = 0.02
tau = 0.1*year
c_p = 4186
```

```
k_f = 0.6
D = r_b/2
k_p = 0.5
k_b = 0.6
T_f_1 = 1 + 273.15
#T_b = calculate_temperature(r_b, tau, T_s, Q, k_s, rho_s, c_s, N_b, L_b, alpha)

# calculate Re and Prandtl numbers
Re = calculate_reynolds_number(m_f, r_i, mu)
Pr = calculate_prandtl_number(mu, c_p, k_f)



# Calculate the coefficient of convection heat transfer
h_f = caluclate_convection_heat_transfer_coef(Re, Pr, k_f, r_i)
R_s = calculate_soil_thermal_resistance(k_s, r_b, rho_s, c_s, tau)
R_b = calculate_borehole_thermal_resistance(r_b, r_o, r_i, D, h_f, k_p, k_b, k_s)
T_f = calculate_mean_fluid_temperature(T_s, Q, R_s, R_b)
T_f_2 = calculate_fluid_temperature_outlet(T_f, T_f_1)
T_b = calculate_temperature(r_b, tau, T_s, Q, k_s, rho_s, c_s, N_b, L_b, alpha)

print(Re)
print(T_b)
print(T_f)
print(T_f_2)
```