Estimating the technical shallow geothermal potential for heating: A case study of Lörrach, Germany

Master's thesis in Sustainable Energy Systems

SIDDHANT GUPTA

DEPARTMENT OF SPACE, EARTH AND ENVIRONMENT

CHALMERS UNIVERSITY OF TECHNOLOGY
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Fraunhofer ISE

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Abstract

The production of heat accounts close to 50% of global final energy consumption today and was responsible for nearly one-third of global energy related CO2 emissions. Despite this, the heating sector is often left in the backdrop. But as governments pledge to keep the warming to 1.5°C and pass ambitious climate laws, there has been a surging interest to decarbonize the heating sector. Heat pumps are touted as an important element in the fight against climate change and towards decarbonizing the heating sector. The extraction of shallow geothermal energy using borehole heat exchangers (BHEs) is a promising approach for decarbonisation of the heating sector. However, high installation costs and strict regulations often act as barriers. The optimal site-specific system depends on the existing regulations and the local hydeogeological conditions.

In this study, a method to estimate the technical potential of shallow geothermal energy for heating BHEs is presented, and the reduction in CO2 emissions that can be achieved by completely tapping this resource is calculated. The method combines the ground thermal properties, estimation of suitable areas for BHE installation and an analytical equation for determining the theoretical geothermal potential in order to estimate the technically available potential. Two scenarios are formulated and compared in order to evaluate the achievable reduction in CO2 emissions.

The method is used to provide a first estimate of the technical potential of geothermal energy for heating for a district in south-western Germany. The technical potential of the district of Lörrach is estimated to be 1.29 TWh, which can cover 40.6% of the total heat demand. The findings further show that geothermal energy has a high decarbonizing potential in the studied region, and switching to geothermal energy for heating can save up 245.22 kton CO2/ year,which is equivalent to more than 50% reduction in CO2 emissions. The work conducted in this thesis can contribute towards the advancement of decarbonisation strategies for the heating sector by providing an estimate on the potential for renewable heat generation from shallow geothermal energy.

Keywords: heating, geothermal, heat pumps, borehole heat exchangers.

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Siddhant Gupta, Gothenburg, 09 2021

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1
Introduction

The production of heat accounts close to 50% of global final energy consumption today, and more than three-quarters of this heat is currently produced with fossil fuels. The production of heat was responsible for nearly one-third of global energy related CO_2 emissions [1]. Despite this, the heating sector is often left in the backdrop. It has been shown that heating and electricity systems can benefit significantly from mutual synergies on their path towards decarbonisation, by unlocking opportunities to support integration of low-carbon generation technologies and to reduce the cost of decarbonisation [2]. Following COP21, the Lima-Paris Action Agenda and LPAA, more and more countries are taking action to mitigate climate change.

The German energy sector is currently undergoing radical structural changes due to ambitious national climate targets and supportive energy policy. This change is dominated by the expansion of renewable energy generation technologies, which are mainly decentrally exploited due to their characteristics [3]. This has led to the generation of 33% of the electricity in Germany by renewable energies, while the proportion of renewable heat supply is around 13% [4]. The Climate Protection Act, established on July 31st 2013, provides a framework for the state's climate policy with a goal to reduce greenhouse gas emissions by 90% by 2050. Other concrete measures include mandatory municipal heat planning for districts and municipalities [5]. As a result of this, there has been a surging interest to focus on decarbonizing heat.

Germany's heating sector is highly dependent on fossil fuels (25% oil heating in the residential sector, in part due to low taxation on heating oil), and a large share of co-generated district heating is produced from fossil energy sources. Roughly half of the country's houses are heated with gas, a quarter with oil and 15% with district heating (DH) [6]. Given Germany's rapid growth in renewable electricity, there is an attractive opportunity to both increase the direct role of renewables in heat generation and pursue sector coupling, to use more renewables-based electricity for heating. Apart from reducing greenhouse gas emissions, energy security is another motivator. Currently, Germany imports 93% of its natural gas demand with Russia, Norway and the Netherlands being the biggest exporters [7]. Although the German government is focused on a massive expansion of renewables, the phasing out of both nuclear and coal generation will increase Germany's demand for natural gas in power generation, including as a backup fuel source for renewables. The uptick in demand will increase Germany's already-high call on natural gas imports. The increased use of natural gas in electricity generation, especially to meet peak elec-

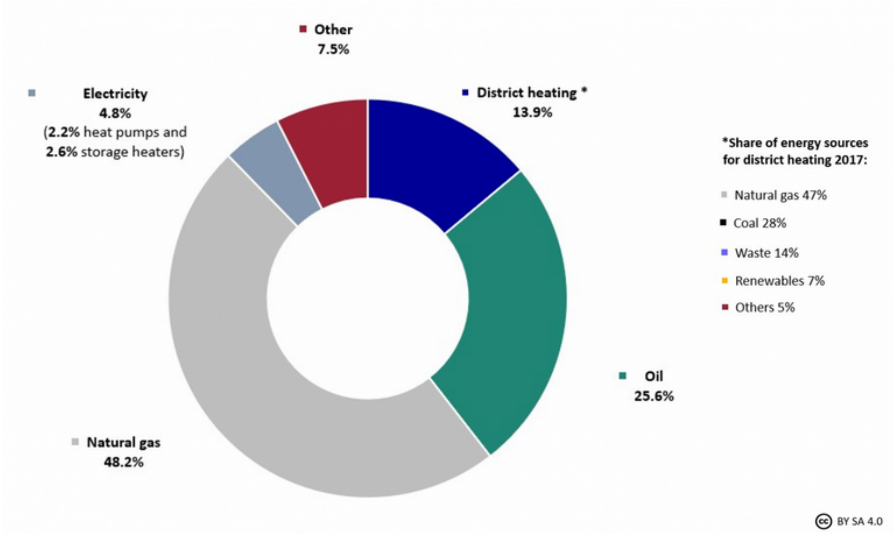


Figure 1.1: Share of different energy sources in the German heating sector [3]

tricity demand, will also increasingly tie electricity security to gas security. Hence, there is imminent need to look for alternative sources.

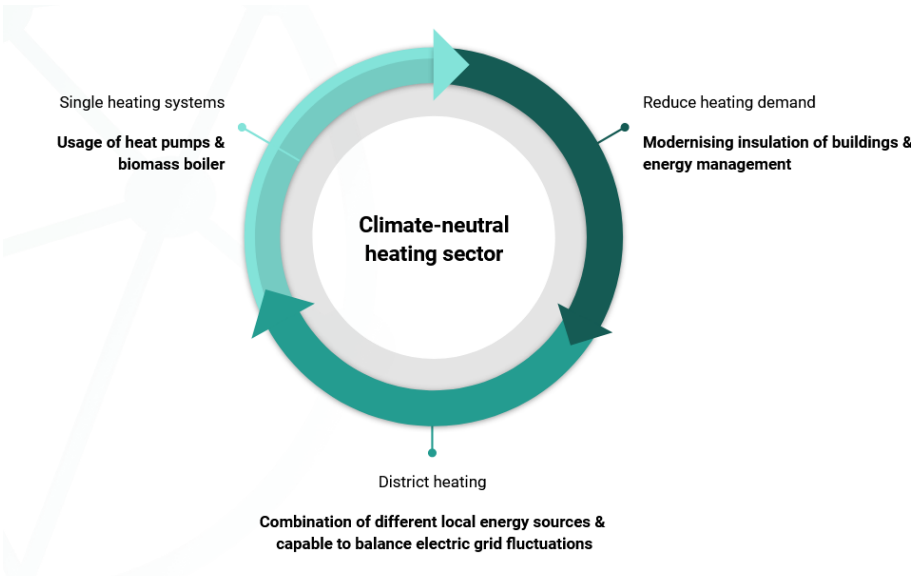


Figure 1.2: Carbon-neutral heating sector

To achieve a carbon-neutral heating sector, an amalgamation of three different measures are suggested - reduced heating demand through improved insulation and energy policy, increased uptake of less carbon intensive heating systems like heat pumps (HP) and biomass boilers, and expansion of district heating networks.
Heat pumps are touted as an important element in the fight against climate change and towards decarbonizing the heating sector. But they share the same paradox like

electric vehicles, which is they tend to be as clean as the electricity used to power them. An increasing deployment of variable renewable energy opens up greater opportunities for HPs to exhibit their potential as an asset to the heating and electricity sector (by replacing carbon-intensive heating systems like oil/gas boilers, and helping in managing variations in the electricity system). Heat pumps can be powered by different sources - air, water and ground. In Germany, the most popular HP systems are air (ASHP) and ground source (GSHP). Figure 1.3 shows the growth of heat pump sales in Germany from 1978-2011 in relation to the oil price. As can be seen from the graph, the growth is highly correlated to the oil price (with increase in oil prices resulting in increase of HP sales and vice-versa). With the oil and gas prices expected to increase in the future due to external factors like carbon taxes, depleting reserves, demand/supply mismatch etc. the future of heat pumps looks promising. But the high installation costs for HPs and strict regulations makes it ever so important to assess the potential of different types of heat pumps, in order to help municipalities, energy planners and users to make better and informed decisions.

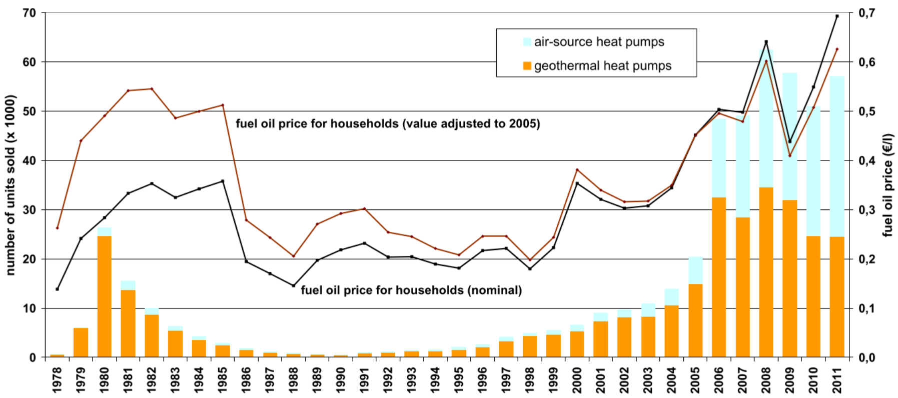


Figure 1.3: Development of heat pump sales in Germany 1978-2011 in comparison to the oil price [8]

1.1 Background

The case study area for the thesis is the district of Lörrach, located in the south-west part of the state of Baden-Württemberg in Germany. The district covers a total area of 806.81 km^2, consisting of 8 towns and 27 municipalities. The total population of the district is 228,842 with a population density of 280/km^2 [9]. Since the district is a part of the state of Baden-Württemberg, it is obligated to follow the Baden-Württemberg Climate Protection Act. One key element of this act is mandatory heat-planning for all municipalities. Municipal heat-planning requires estimates on the current heat demand and the heat supply options. According to the estimates of the Landesanstalt fur Baden-Württemberg (LUBW),the total heat demand of the district is estimated to be 3.16 TWh/a [10]. The share of buildings connected to the district heating network is just 1.89%. Majority of the houses use single heating systems powered by fossil fuels to heat their homes. This gives an

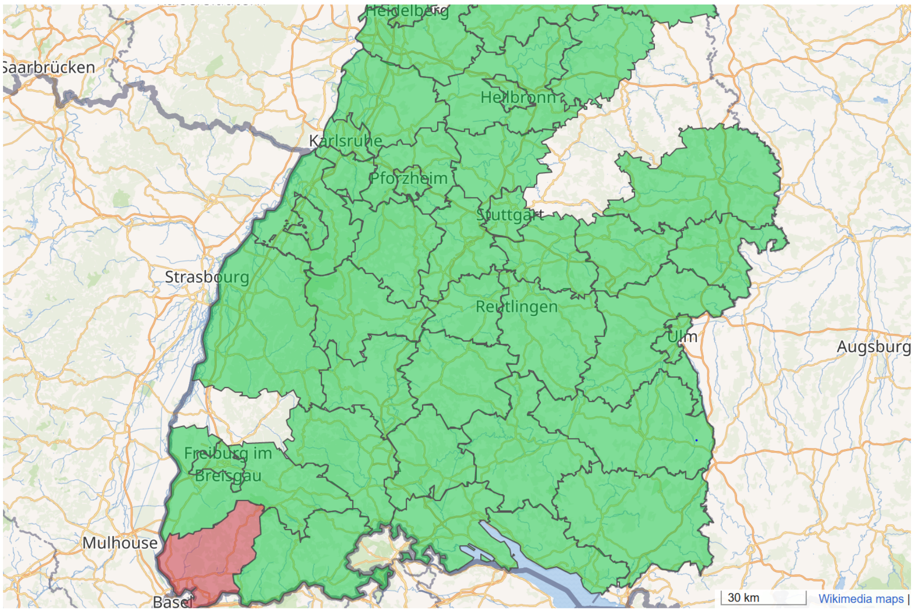


Figure 1.4: The district of Lörrach (marked in red) along with neighbouring districts

immense potential for switching to greener alternatives like heat pumps and biomass boilers.

1.2 Aim

The aim of the thesis is to estimate the technical shallow geothermal potential for heating using BHEs for the district of Lörrach, and identify the share of the total heat demand this potential can cover and the corresponding reduction in CO_2 emissions that can be achieved. As BHEs have to follow strict guidelines and regulations, they are allowed to be installed only at certain locations. This makes it important to filter out the areas where installation is prohibited in order to get an accurate estimate of the geothermal potential. This thesis aims at answering the following questions:

1. Which areas are suitable for installation of BHEs?
2. What is the technical potential of shallow geothermal energy for heating in the district of Lörrach?
3. What share of the total heat demand can be covered by this potential and what are the reductions in CO_2 that can be achieved?

2
Theory

In this chapter, related works to the topic are analysed and discussed in a literature review. An introduction to the heating sector is presented. Then, a detailed explanation about the ground as a heat source is given, concluded by an introduction to different types of heat pumps along with their advantages and disadvantages.

2.1 Related Work

There have been many studies already to analyse the geothermal potential, but most of these studies estimate the theoretical instead of the technical potential. The geothermal potential is an indicator of the economic feasibility for the installation of BHE(s) at a certain site: the higher the potential, the shorter the BHE(s) to be drilled to provide the required thermal load, and hence the shorter the payback time of the geothermal heat pump compared to other technologies [11]. There have been a few methods already developed for the estimation of the shallow geothermal potential for closed loop plants, the most common one is the German VDI 4640 norm which provides the value of the extractable power per unit length (W/m) for different lithologies and considering two different usage profiles (1800 and 2400 h per year) [12]. Gemelli et al. [13] adopted this method for assessing the potential of GSHPs in the Marche region (Central Italy), estimating that a BHE length ranging between 80 and 160 m is necessary to satisfy a standard thermal load of 5 kW. The Department of Energy and Climate Change of the United Kingdom provides reference tables to evaluate the geothermal potential of vertical and horizontal closed loop systems, depending on the length of the heating season, the thermal conductivity and the temperature of the ground [14]. These tables can be used for the dimensioning of small closed-loop geothermal plants. A method was recently developed by Galgaro et al. [15] to evaluate the techno-economic feasibility of GSHPs in 4 regions of Southern Italy (Campania, Apulia, Calabria, Sicily), both in heating and cooling mode. This method is based on heat transfer simulations for the calibration of empirical correlations, which are valid on the mapped territory. Garcìa-Gil et al. [16] studied the potential of BHEs and GWHPs in the metropolitan area of Barcelona (Spain), deriving a method to quantify the maximum thermal power per unit surface that can be exchanged with the ground in a densely populated area. Methods to quantify potential have also included estimation of ground temperature [17], heat capacity [18] and thermal conductivity [19]. These parameters are mapped from the thermal properties of the rock types [20], from 3D models of the subsurface [16], using kriging [21] and/or applying Machine Learning algorithms [22]. Several

regional-scale studies quantify the extractable heat from a single borehole, which is estimated using engineering norms [23], simulation tools [15], or analytical models [24, 25].
Heat pumps have gained popularity in the last two decades and are considered an important element in reaching towards a carbon-neutral heating sector. A quick search on ScienceDirect reveals about 356,000 articles containing the word "heat pump" and a yearly increase in the number of articles published since 1999. Figure 2.1 shows the gradual increase in publications containing the word "heat pump" since 1999. Heat pumps exploit different renewable heat sources, such as the air, surface water, aquifers, and the ground (GSHPs). GSHPs are generally the most efficient and environmentally friendly HPs, since they take advantage of the relatively stable temperature of the subsurface to achieve a higher seasonal performance factor (SPF).

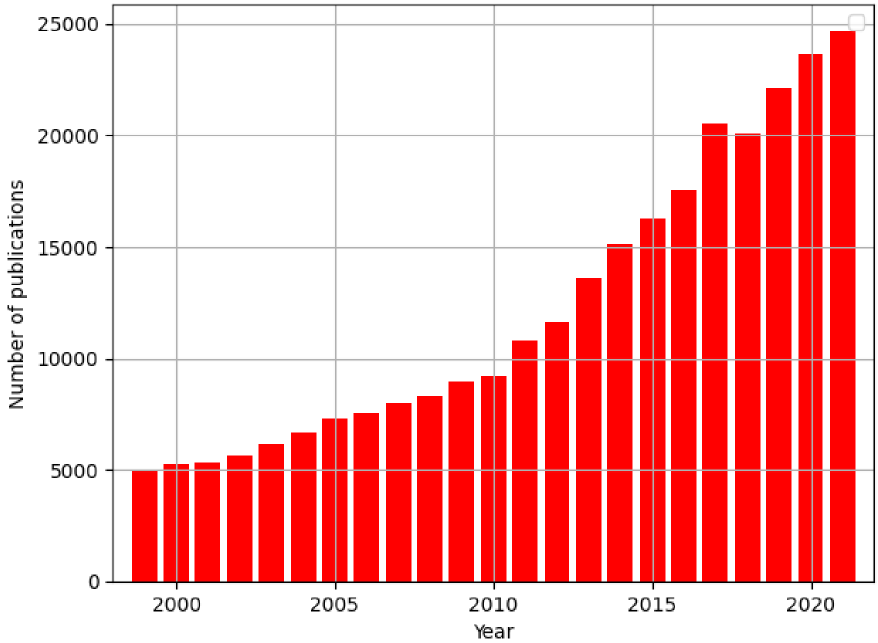


Figure 2.1: Number of published papers yearly from 1999 to 2021 containing the word "heat pump"

2.2 Heating sector

The pressure to achieve reductions in global greenhouse gas emissions have been clearly and comprehensively assessed in the synthesis report of the IPCC Fifth Assessment Report [26] and the need for ambitious action has been increasingly reflected in sequential iterations of European climate policy frameworks and legislation. The heating sector accounts for almost half of the EU energy consumption. The residential sector is the biggest consumer of heat, followed by industrial and tertiary. In general, the heating and cooling sector is characterised by low efficiencies, large amounts of waste heat and it is mostly fossil based. As per figure 2.2, highest share of the heat demand is for space heating, process heating and domestic hot water production.

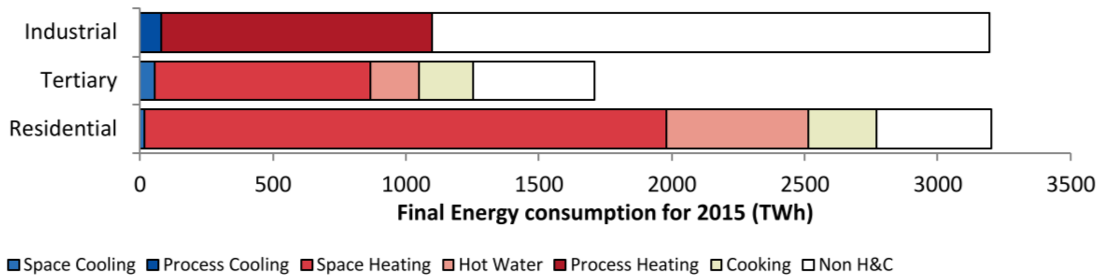


Figure 2.2: Shares of final heat demand per end-uses

The residential sector alone is responsible for 51% of the heating and cooling consumption [27]. Due to the long lifetime of buildings, 80% of today's building stock would still remain in 2050. Improved building insulation, smart appliances or energy management systems will be required to reduce the heat demand of buildings. Still, all these measures alone cannot fulfil the decarbonisation targets and would need additional help. Electrification of home heating for the residential sector has the potential to reduce aggregate emissions of NO_X, CO_2 and particulates, and this can deliver positive environmental outcomes as well as reduced human health impacts. The general concept of residential heating electrification is to displace emissions from local-level fossil-fuel combustion with electrified technologies powered by increasingly clean renewable energy [28]. Electrification of heating and expansion of district heating powered by renewable sources will pave the road towards a carbon-neutral heating sector. But incumbent home heating technologies can be expensive to replace and there can be an understandable inertia from householders with regard to shifting away from well-known technologies for home heating to a comparative newcomer to the mainstream home-heating market. Concerns surrounding installation and operational costs, as well as heating performance, can slow the market uptake to a new technology [28]. This is why it is important to create awareness and incentivize new technologies to make it popular.

2.3 Heat plan

Heat plan is an early stage energy planning tool that maps the existing and future heat demand of buildings in an area, as well as the current and potential heat resources [29]. Heat plan is one of the mandatory requirements of the Baden-Württemberg Climate Act. It serves as the basis for climate–neutral heating sector. The central steps in the formulation of heat plans are – inventory analysis, potential analysis, scenario creation and heat reversal strategy (figure 2.3).
Heat plans are becoming increasingly popular as their role in influencing the heating sector is being recognized. It appears the presence of a stable heat plan helps foster long-term confidence in DH systems by reducing real and perceived risks to consumers, heat suppliers, the municipality and DH system owners [30]. Danish

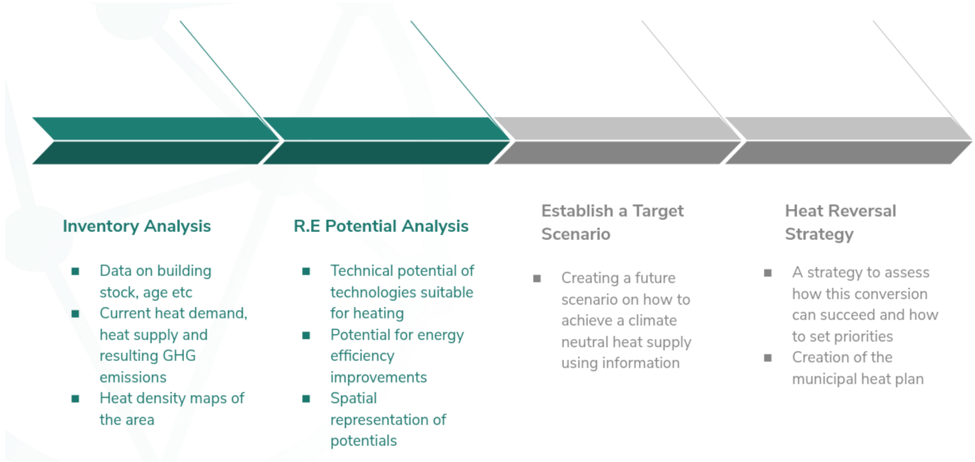


Figure 2.3: Typical steps involved in the formulation of a heat plan

heat planning has played a role in the energy policy and influenced the development of locally appropriate and cost-effective DH networks. The Municipal Energy plan of Zurich was established with the goal of securing an economically viable, ecologically friendly supply of heating and cooling. It plans to achieve this goal by expansion of DH systems, the coordinated use of ground and lake water and the replacement of combustion-based systems with heat pumps [31]. A blueprint of the planning map can be seen in the figure 2.4

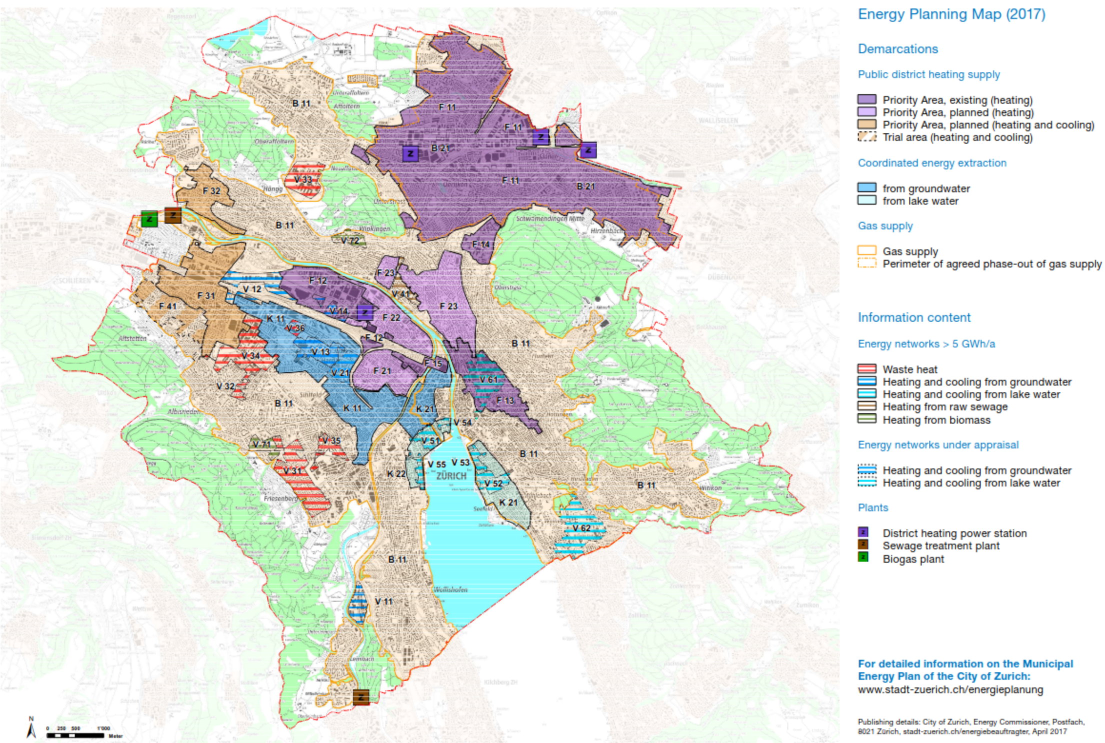


Figure 2.4: Energy Planning Map for the city of Zurich [31]

2.4 Ground as a heat source

The underground can be utilised as a heat source, a heat sink and a thermal energy reservoir. It is highly suitable for many applications in the low-temperature range, due to the large volumes available and the uniform temperature [12]. The ground temperature is determined by an equilibrium between the incident solar energy, infrared emission into space, geothermal heat flow and fluctuations in these factors (Figure 2.5). The heat flows from the earth are 10000 times smaller in magnitude to the solar radiation. Whenever the natural state is disturbed by heat extraction or heat injection, the thermal deficit or thermal surplus must be rebalanced by heat transport [12].

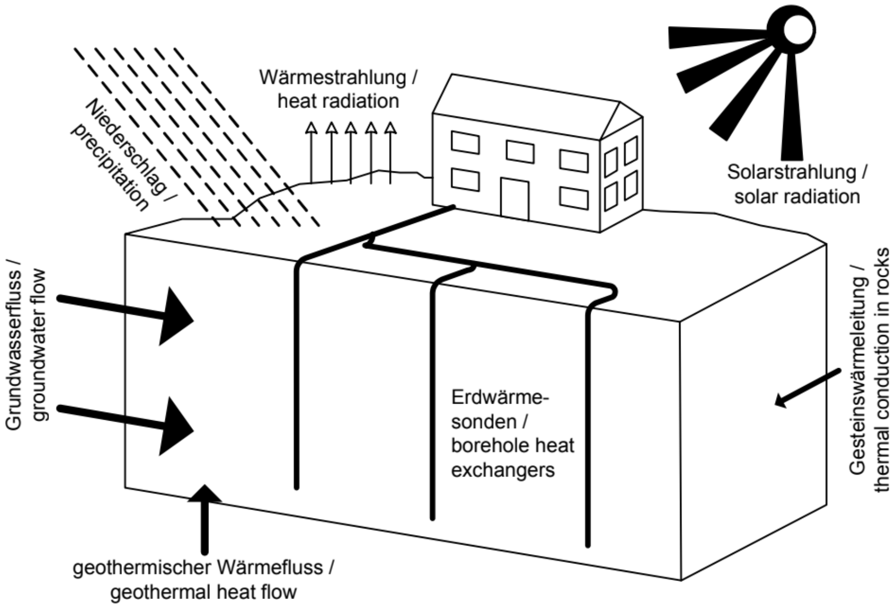


Figure 2.5: Heat regime of the underground [12]

The most important thermal characteristics of the underground which affect the ground thermal potential are:

1. **Thermal conductivity :** defined as the ability of a material to transfer heat, usually expressed in W/m K.
2. **Heat capacity :** defined as the ability of a material to store heat. It is the ratio between the amount of heat to be transferred to a certain mass or volume in order to achieve a defined change in temperature, thus it is expressed in J/K.
3. **Thermal diffusivity :** defined as the physical property governing the heat diffusion in transient conditions measuring the penetration of temperature changes into a material.
4. **Ground temperature :** varies in the shallower layers as a function of the air temperature whilst, from about 10m, is stable throughout the year and increases with depth based on the local geothermal heat flux.

Geothermal energy is the heat contained in the solid earth and its internal fluids. Geothermal energy is stored as sensible or latent heat. The term covers a wide field of applications at different depth and temperature levels or based on different technologies to extract geothermal heat. Although all kind of geothermal energy originates in the Earth's interior, the technologies clearly differ in their range of application and concepts.

Geothermal energy can be classified as "shallow" or "deep" depending on the depth level at which the heat is extracted. Generally, depth levels till 400m are classified as shallow systems and depths below are referred to as deep systems Additionally, temperature and capacity ranges separate "shallow" and "deep" systems. Shallow geothermal systems operate at temperature levels between 0°C and up to 30°C, which is considered as atmospheric ambient temperature. In contrast to the direct use of deep geothermal, shallow geothermal energy requires a heat pump to process the heat for space heating. However, it also has the possibility to offer direct (free) cooling, which makes it very attractive in urban areas. Shallow geothermal energy provides capacities up to 5 MW_{th} for individual buildings or de-centralized 5G low temperature heating and cooling grids. Due to much higher temperature levels (between 30°C and up to 200°C), deep geothermal is predominately used in industrial processes and conventional, centralized 2G to 4G heating networks. Moreover, deep geothermal energy allows for producing electricity at temperature levels above 90°C, which makes it attractive for combined heat and power applications [32].

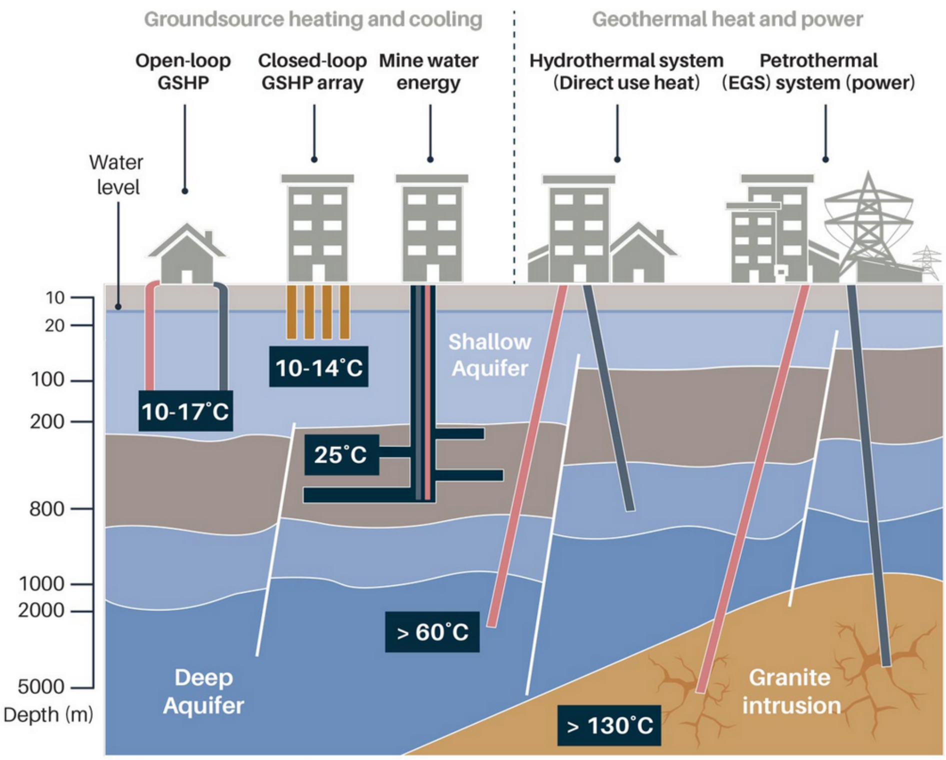


Figure 2.6: Different types of geothermal systems [32]

2.5 Heat pumps

A heat pump is a device that heats or cools an indoor space by transferring thermal energy from a cooler region to a warmer region using a refrigeration cycle. The efficiency of a heat pump is expressed as its coefficient of performance (COP), or seasonal coefficient of performance (SCOP). The higher the number, the more efficient a heat pump is and the less energy it consumes [33]. HPs can be used to cover the space heating and domestic hot water demand. They typically are much more energy efficient than electrical resistance heaters.

2.5.1 Heat pump principle

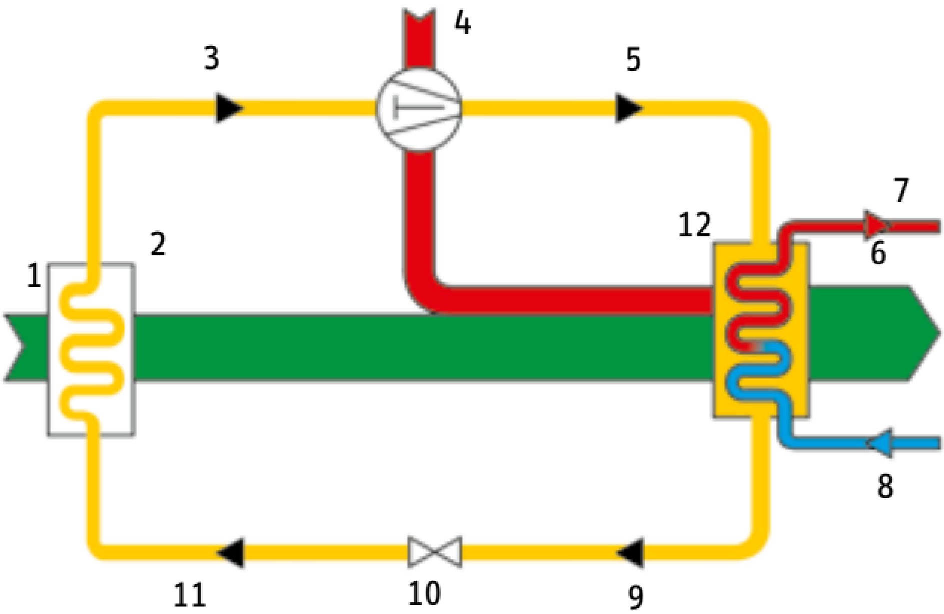


Figure 2.7: Heat pump refrigerant circuit [33]

The heat transfer medium (refrigerant) makes the most important contribution towards the function of a heat pump. The refrigerant can evaporate at the low temperatures. If outdoor air or water is routed via a heat exchanger through which the refrigerant is circulating, the latter extracts heat from the heat source. In this process, the refrigerant changes from its liquid to its gaseous state and also cools down the heat source by a few degrees. In the next step, the refrigerant is passed through a compressor which results in an increase in pressure. The increase in pressure also raises the temperature of the refrigerant; in other words, the medium is "pumped" to a higher temperature level. This requires electrical energy. Next,the refrigerant transfers its absorbed energy to the circulating system of the hot water heating system and is thus converted back into a liquid state again. The prevalent pressure of the refrigerant is reduced in an expansion valve and the cycle starts again

[33]. Figure 2.7 shows a schematic diagram of a heat pump refrigerant circuit.

2.5.2 Air-source heat pumps

Air source heat pumps (ASHPs) absorb heat from the ambient air as their primary energy source. They are able to remain operational in temperatures as low as -20°C, although the coefficient of performance (COP) falls as heat source temperature decreases. Air as a heat source is typically at its coldest when the most heating energy is needed. Benefits include the ease of installation of ASHPs, as no extensive ground work or well drilling is required, and low upfront costs.

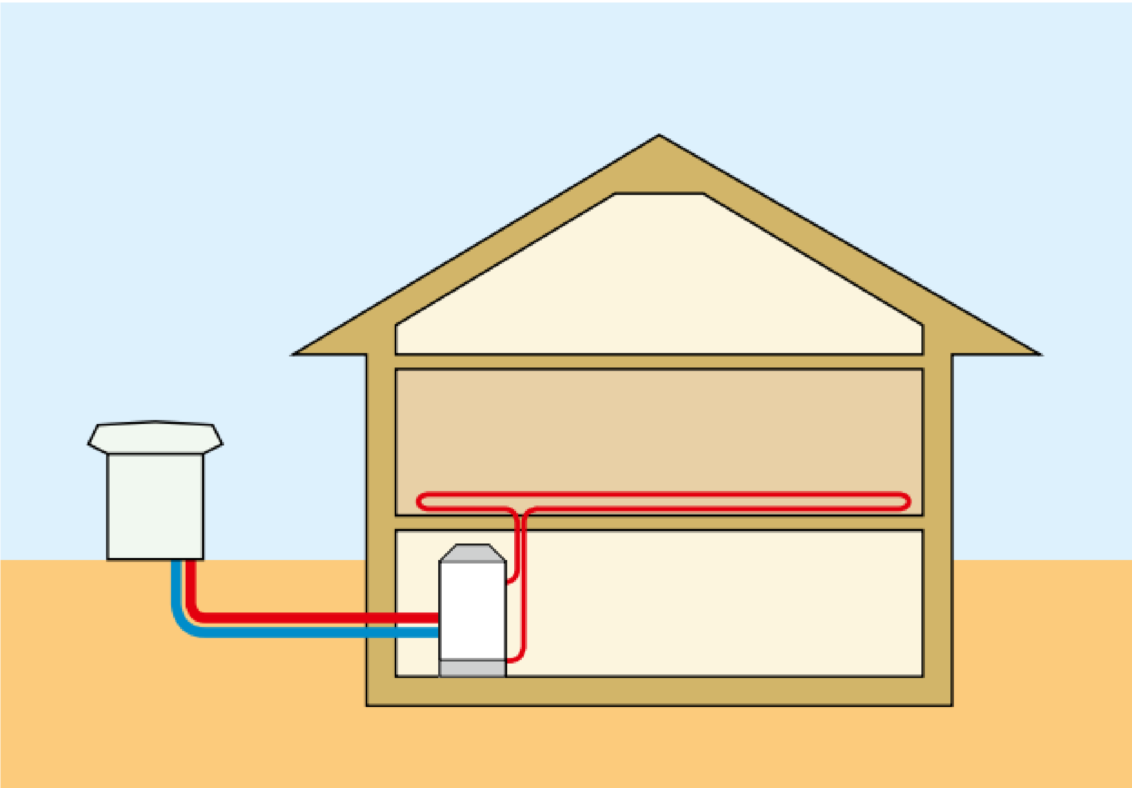


Figure 2.8: A schematic diagram of an ASHP [33]

2.5.3 Ground-source heat pumps

The temperature below the ground is more stable compared to the air. GSHPs use this phenomena to their advantage and extract heat from the ground. As a result of this, GSHPs have better performance and achieve higher COP than ASHPS. The utilization of the near-surface geothermal potential is subject to different technical systems. Basically, the systems are divided into open and closed systems. While in the open systems only groundwater water fountains are used, in the closed systems different variants are available. They are geothermal probes (BHEs), geothermal baskets, geothermal collectors (GHC) and concrete components in contact with the ground (e.g. energy piles, activated diaphragm walls) 2.9, with the most popular being ground GHCs and BHEs [12]. Due to the relatively stable ground temperature, GSHP systems can also provide direct cooling in the summer.

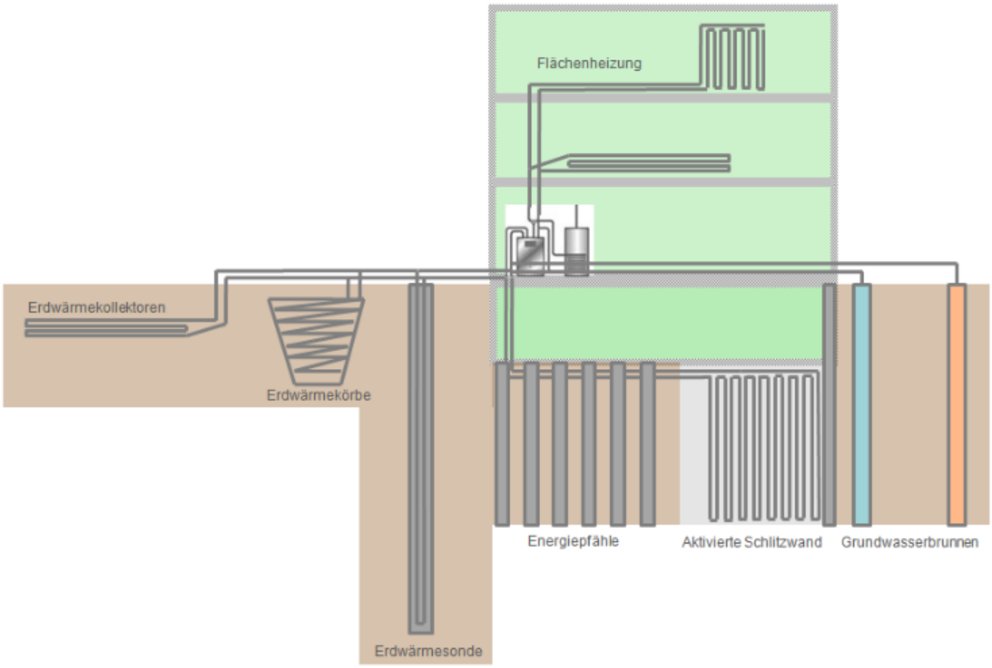


Figure 2.9: Various configurations to extract geothermal energy from the ground [33]

Ground heat collectors extract seasonally stored energy from the underground. In particular, the liquid/solid phase change of the water in the ground is used as a latent heat reservoir in winter. The maximum heat extraction and the annual extraction energy are limited by the storage capacity, the heat transport properties, and the thermal regeneration of the underground, as well as by the collector geometry and the operating mode of the system. The performance of ground heat collectors is determined by their coupling to the earth's surface, as ground heat collectors are regenerated in the spring and summer by heat input from outside air, solar radiation, and precipitation [12]. GHCs installations require large surface areas and therefore, may not be suitable in densely populated urban areas.

Borehole heat exchangers are closed heat exchangers which are installed vertically or inclined in the under-ground and serve to extract and/or inject heat from/into the underground. Depending on application, various types of borehole heat exchanger types can be used for heat transfer. The overall borehole heat exchanger system consists of the heat exchanger pipes with borehole, including all fittings, and the subsequent grouting. Heat transfer in a borehole heat exchanger depends on the effective borehole thermal resistance Rb. BHEs are the most popular technology choice as the area footprint is the lowest amongst all other options, they require very low maintenance, can be used in areas with and without groundwater at high efficiencies and can deliver large amounts of energy.

3
Methods

In this section, the methodology used for estimating the geothermal potential and calculation of the CO_2 emissions is briefly explained. First, the suitable areas are identified, followed by the estimation of the theoretical potential, which was done using the G.POT methodology. The reason for choosing the G.POT method is that it is a simple and flexible tool that can be implemented in a wide range of different scenarios for large-scale mapping of geothermal potentials. Next, the technical potential is computed by combining the results from the theoretical potential with the suitable areas identified in step 1. For the last step, the achievable savings in CO_2 emissions are calculated. Two scenarios are defined - one with the current heating mix, and the other where the current heating mix is replaced by geothermal energy. The CO_2 emissions for both scenarios are calculated and compared. All mathematical relations and assumptions used for modelling are stated.
Geothermal energy can be utilized in several ways. The two most common approaches are shallow geothermal energy with the support of a heat pump system, deep geothermal energy for direct heat use or electricity generation. In this work, only the shallow geothermal potential (upto 100m) is identified using BHEs as the extraction technology.

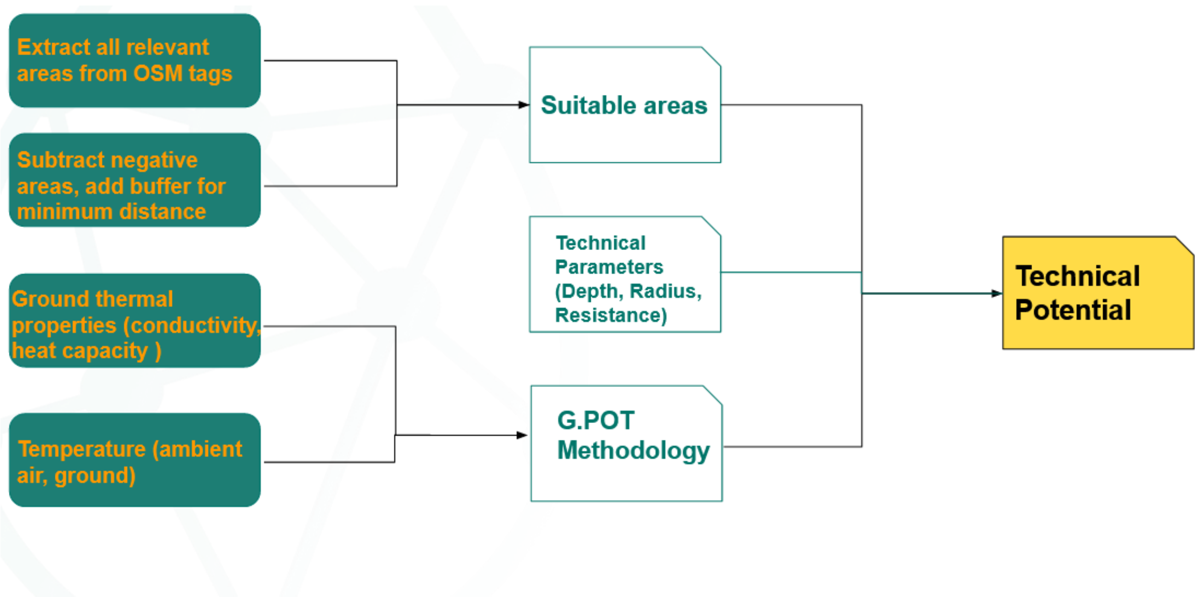


Figure 3.1: General workflow for estimating the technical geothermal potential

3.1 Determination of suitable areas

In order to determine the areas that are suitable for geothermal energy extraction using BHEs, all areas near to a potential supply object (buildings) are considered. All residential and commercial areas are identified using OpenStreetMap (OSM) [34] and considered as positive areas. Meanwhile, the remaining areas are neglected as there is no heat sink near them to utilise the geothermal output. Figure **??** shows the extracted usable landuse areas from OSM.

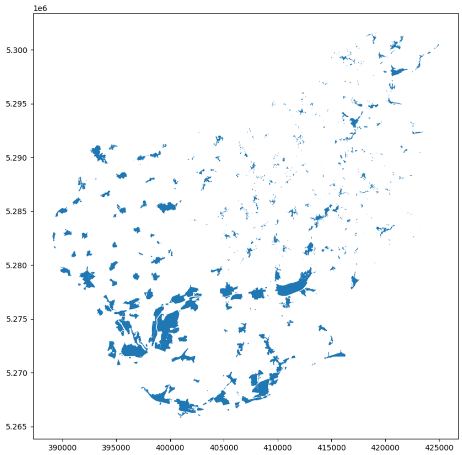


Figure 3.2: Positive land-use areas

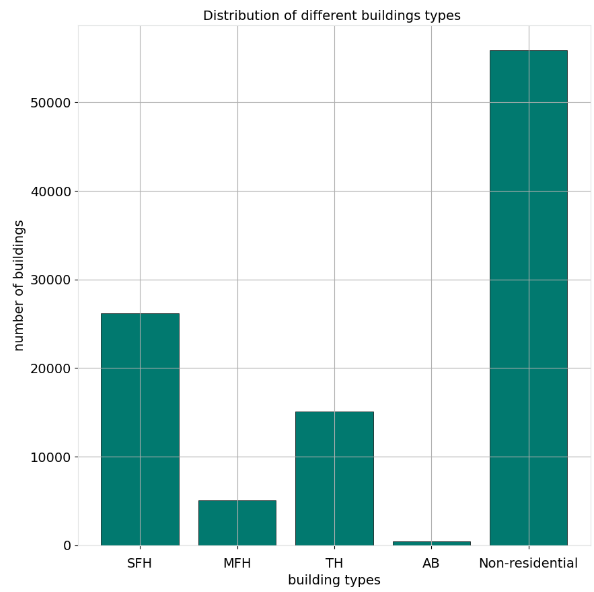
Figure 3.3: Zoomed in view of a positive land-use area

To get an accurate estimation on the total number of heat sinks in the region, the number of buildings were identified using ALKIS data of Baden-Württemberg. The real estate cadastre system (ALKIS) is a comprehensive directory of all parcels in Baden-Württemberg [35]. The parcels are described with their shape, size, location and use. It serves as evidence of the actual condition and location of all the properties booked in the land register and was therefore, was considered a reliable source to get building data. A total of 102,610 buildings were identified in the region of

Lörrach. Each building was then divided into a building type based on the tabula building typologies - single family house (SFH), multi family house (MFH), terraced house (TH), apartment block (AB) and non-residential [36] . The distribution of the buildings as per building types are given below:

Building type	No. of buildings	% share of total buildings
Single family house	26151	25.48%
Multi family house	5068	4.93%
Terraced house	15080	14.69%
Apartment block	435	0.4%
Non-residential	55876	54.4%

Table 3.1: Distribution of buildings in Lörrach (source: [35])



The ALKIS data suggests that the majority of the buildings in the region are non-residential. This holds true as the region is an industrial hub with a low population density.

3.1.1 Existing space restrictions

Installing BHEs for geothermal energy use is not permitted on all of the residential and commercial areas identified in the last section due to certain rules and regulations (e.g. water protection areas, areas with high groundwater level). These restricted areas need to be taken into account and excluded from consideration. Therefore, these designated restriction areas were subtracted from the positive areas identified in the last part . The result are areas on which a geothermal use is possible without any restrictions. The restriction areas were as follows:

1. Negative areas: Buildings, unusable traffic areas (roads, bicycle paths, parks, water bodies,) are considered as negative areas.
2. Buildings that are not eligible for geothermal use based on their designated use. (This includes buildings without need for heating like garages, parking lots)
3. Environmentally relevant and special zones like water protection and medicinal spring zones, areas with high ground-water level, special geological properties etc.

All negative land use areas such as building footprints, roads, railways, traffic-related areas (parking zones, airports), water bodies and leisure zones (eg. sports complex) were extracted and subtracted from the positive areas identified in the previous section. A buffer of 3m was applied to all buildings and streets to ensure that a minimum distance to every BHE is maintained as specified in the VDI [12] guidelines. The figure 3.4 shows the suitable areas with the prohibited zones subtracted and the recommended buffer applied.

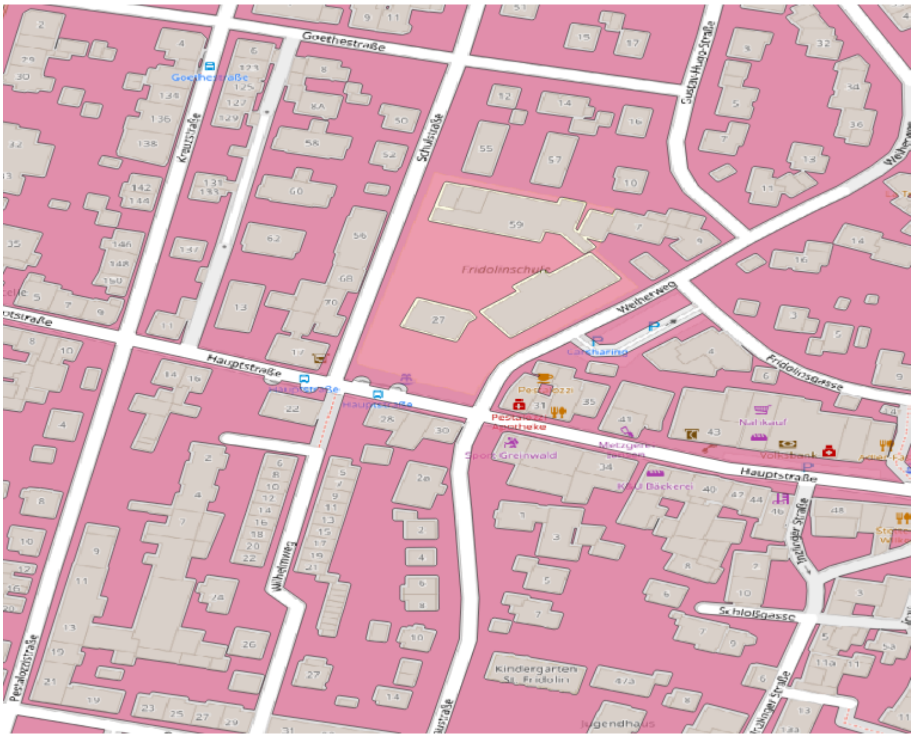


Figure 3.4: Positive land-use areas after subtracting restricted areas

According to the water law, BHEs have to follow the guidelines in accordance with the Water Resources Act (WHG). As a precautionary measure, BHEs are not allowed to be installed in water-protection zones. This is to prevent any damage to water bodies in-case of a malfunction. The water authorities are therefore responsible for the approval of individual BHE systems. A German water protection area consists of three protection zones that differentiate between the water sources, including dams, groundwater/drinking water and lakes. Zone I covers the immediate water catchment area or drainage basin within a radius of at least 10 meters and, under certain conditions, up to 20 meters from the point of withdrawal (POW). Zone II is the next area out from Zone I. The boundary determination is based on the distance it would take a contaminant to reach the POW in 50 days or more. Zone III covers the area from Zone II to the very edge of the catchment area (drainage basin) of the water source. If that edge is more than two kilometers away from the POW, the protection zone can be divided into Zone IIIA and IIIB.

It is expected that in the future, the construction and expansion of geothermal probe systems in the commercial and public sector will be prohibited in protection zones I -II and III/IIIA if substances hazardous to water are used. For this study, protection zones I, II and III are all considered as prohibited areas. Figure 3.5 shows the water protection zones I, II and III in the district of Lörrach [10].

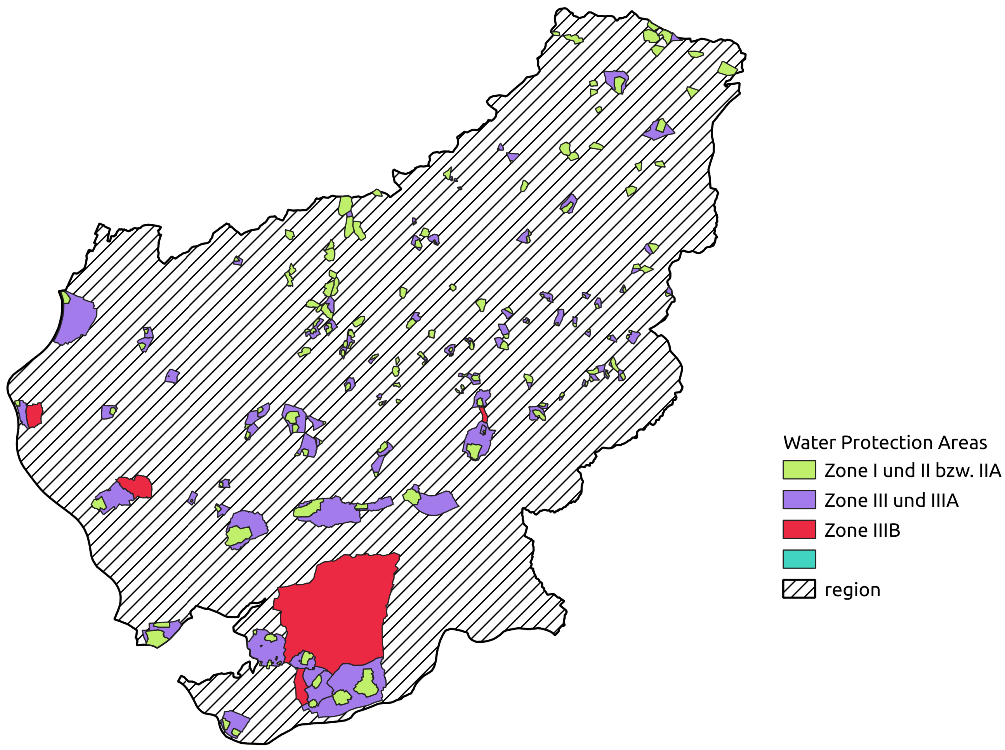


Figure 3.5: Water protection areas in the disrict of Lörrach

Apart from water protection areas, there exists other areas where the use of geothermal energy is restricted. These include :

- Areas with geological faults
- Sensitive groundwater areas
- Old mining areas

The use of geothermal energy in the critical areas is not entirely prohibited but is applicable to a depth limitation. This depth is determined by geological or mining conditions and varies greatly from region to region. In rare cases, the depth can range from 10 m below ground level to the maximum depth of 100 m. Since depth limits are specified differently by the licensing authorities due to the respective local conditions, it is not possible to provide concrete information covering the entire area.

As no information was available for these critical areas, these are excluded from the study. Applying the steps mentioned above, the allowable areas for BHE installations for the entire district of Lörrach were obtained.

Area status	Area [km^2]
Total area	806.58
Positive areas	61.13
Negative areas	38.24
Net available area	22.89

Table 3.2: Suitable areas for BHE installation

3.2 Determination of the technical potential

The technical geothermal potential is primarily dependant on:

- the thermal properties of the ground
- the load profile of geothermal heat extraction.
- the available area for geothermal extraction.

The theoretical geothermal yield was calculated using the G.POT methodology. For dimensioning of BHEs, common values found in literature were used.

3.2.1 Thermal properties of the ground

3.2.1.1 Thermal conductivity

For shallow geothermal energy, the effective thermal conductivity (λ) is one of the most important input variables. λ describes the heat transfer through the ground via conduction (heat flow through temperature difference). The higher the thermal conductivity, higher the geothermal yield. The thermal conductivity depends on the mineral composition, the stratification as well as the size, the geometry and the filling of the rock cavities (pores or fissures). Accordingly, it can vary greatly locally.

For the study, the thermal conductivity data from the Bundesanstalt für Geowissenschaften und Rohstoffe (BGR) was used. For the present dataset, the soil profiles of the BUEK1000N were evaluated according to the soil science method documentation of the Soil Working Group AG Boden. The soil texture, the dry density and the current water content served as input data. These data are incorporated into soil type-specific equations that take into account the respective properties of sand, clay, silt and loam soils as well as those of peat soils. For each legend unit of the BUEK1000N, the dataset gives a minimum and maximum value, the median and a weighted mean value of the thermal conductivity depending on the thickness of the horizons [37]. The distribution of thermal conductivies for the district of Lörrach is shown in the figure 3.6:

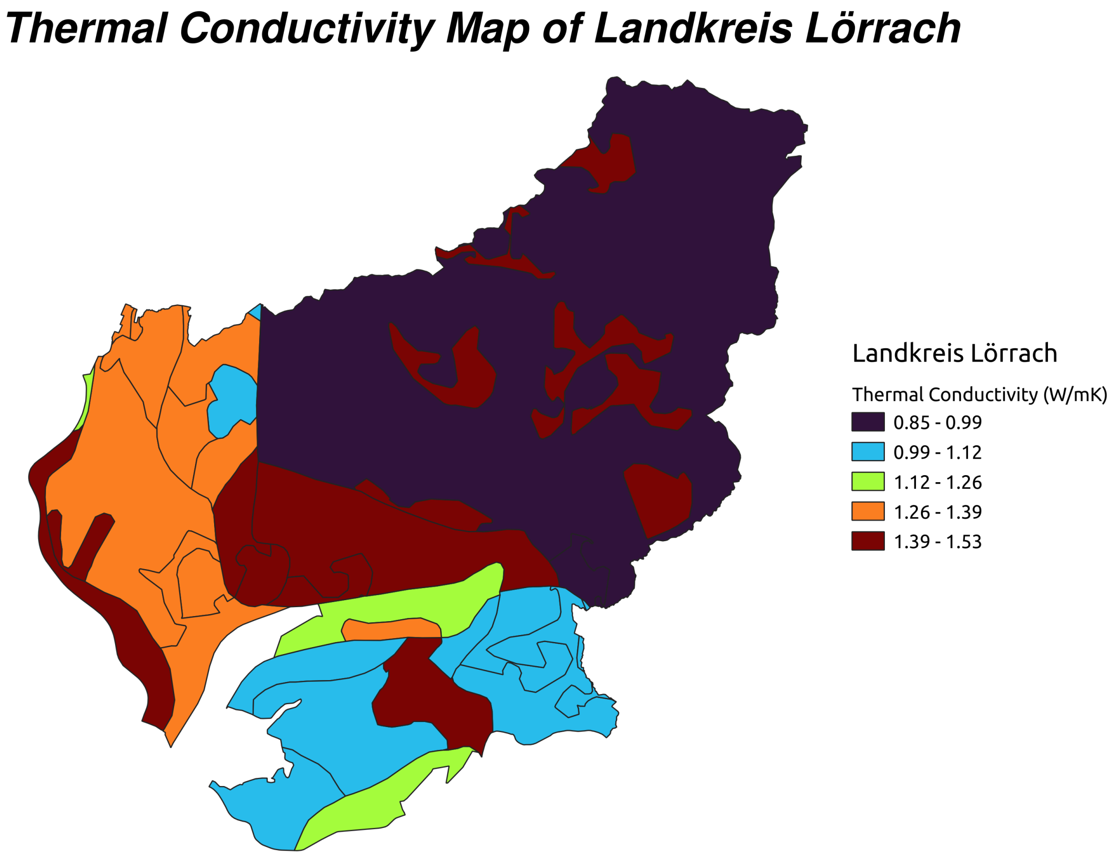


Figure 3.6: Distribution of thermal conductivites for Lörrach

3.2.1.2 Specific heat capacity

The specific heat capacity is a measure for the storage of thermal energy. In shallow geothermal energy, the volume-related specific heat capacity Cs_v with the unit of measurement $MJ/(m^3\ K)$ is generally used. The influence on the geothermal yield due to the heat capacity is generally very small. For this study, a single value for heat capacity was used due to small variation throughout the region.
Based on averaging over the table values of VDI 4640 sheet 1 [12], an average volume-related heat capacity of $Cs_v = 2.3\ MJ/(m^3K)$ was determined for the the type of rocks found in Lörrach.

3.2.1.3 Ground temperature

In addition to the thermal conductivity, the influence of the ground temperature on the geothermal yield is significant.
Higher ground temperatures mean that heat is extracted at a higher temperature which reduces the working temperature range of the heat pump, and thereby increasing its efficiency and the possible heat extraction capacity of the geothermal system. The main factors influencing the ground temperature are:

1. the vertical temperature gradient
2. mean surface temperature

The temperature gradient is in turn dependent on the geothermal heat flow, the thermal conductivity and local influences such as groundwater flow. For lowland and midland areas in Central Europe, a mean temperature gradient 3°C / 100 m is to be taken as a basis [10].

For the mean surface temperature, data from the ERA5 weather API was used. ERA5 provides hourly estimates of a large number of atmospheric, land and oceanic climate variables. The temperature is returned in hourly resolutions for one calender year [38]. From this data, daily mean temperature was extracted and then fed into a ground temperature calculation model. It was observed that the variations in ground temperature are almost negligible below a depth of 10m (can be seen from the figure 3.7). Therefore, a uniform mean ground temperature value was used for the calculations.

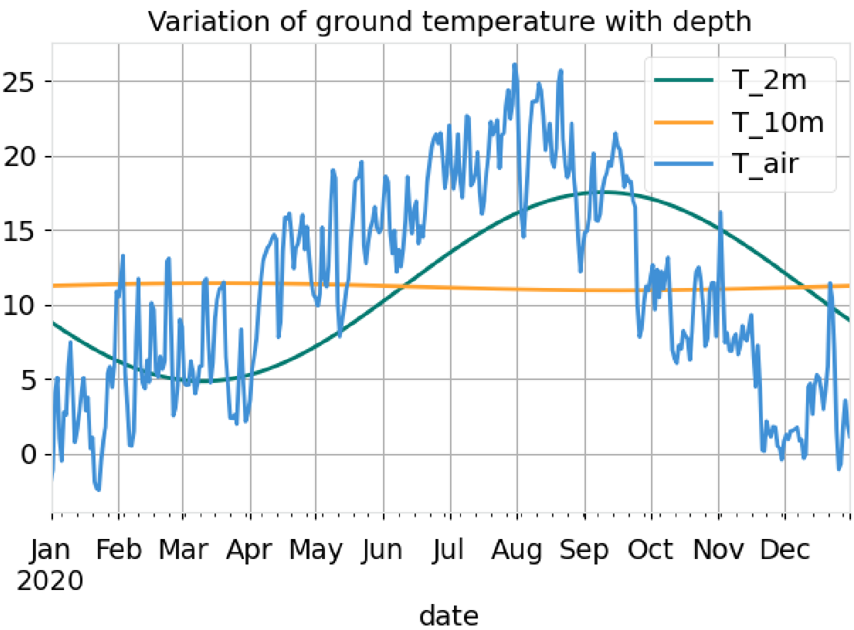


Figure 3.7: Variation of ground temperature with depth

3.2.2 Load profile of geothermal heat extraction

The geothermal potential is not only dependent on the thermal properties of the ground, but also on the amount of heat required and the duration for which it is needed. This trend can be depicted with the help of a heating load profile. The load profile assumed in this study is the same as the one from the G.POT method, having an emi-sinusoidal shape and an annual cycle (Figure 3.8 shows the load extraction profile assumed in this work). In a typical annual cycle, heat is exchanged with the ground during a load cycle with a length tc (i.e., the heating or cooling season), which is followed by a recovery time in which the thermal load is null. The cycle is repeated to reproduce the operation of the BHE over its lifetime. The emi-sinusoidal trend was chosen since it reproduces the thermal heating load of a building, which is mainly influenced by the external air temperature [25]. The benchmark function q(t) is expressed by the following equation 3.1:

$$q(t) = \left\{ \begin{array}{cc} q_{max}.sin(\pi \frac{t}{t_c}) & \text{for } 0 < t < t_c \\ 0 & \text{for } t_c < t < t_y \end{array} \right\} \tag{3.1}$$

where t_y is 1 year, while the average thermal load q is equal to 1 kWh y^{-1} m^{-1} for all the values of tc. During operation, the temperature of the ground surrounding the BHE experiences a drop due to continuous heat exchange. It is assumed that during the period where the thermal load is null, the ground is recharged through incident solar radiation and regains its original temperature. This ensures continuous operation of the BHE across its lifetime.

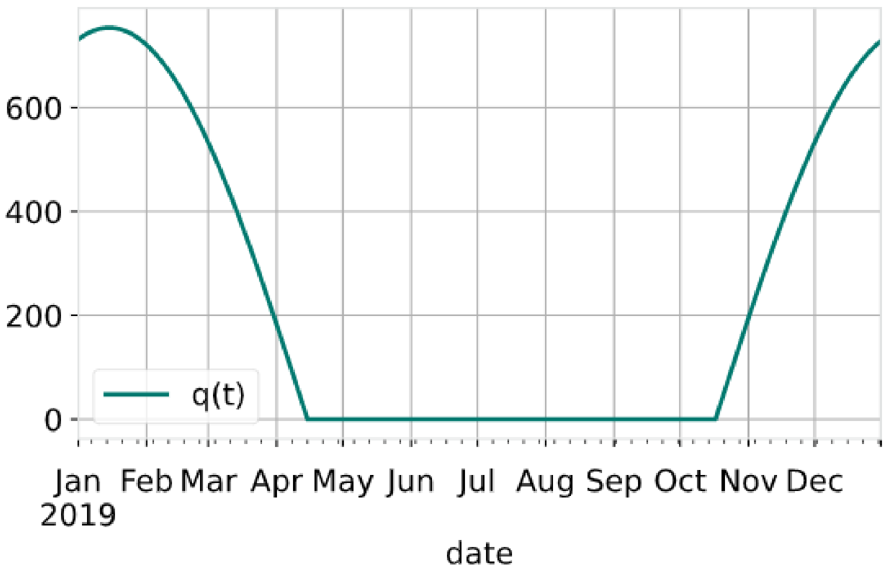


Figure 3.8: Load extraction profile for a year

3.2.3 Geothermal reservoir volume

The geothermal reservoir volume that can be tapped using borehole heat exchangers is determined by the depth of the borehole heat exchanger.

Even though shallow geothermal systems extend upto 400m and yields increase with increasing depths, BHE systems above 100m are rarely observed. This is because the installation costs rise with increasing depth, and a permission from the mining authorities is required for depths greater than 100m. For this study, an average depth of 50m for BHEs is assumed. This is to cancel out the overestimation in the potential arising due to the exclusion of restricted areas with the underestimation due to limiting the borehole depth to 50m throughout.

The geothermal yield also depends on the number of geothermal probes that can be placed on the allocated usable areas. The VDI 4640 assigns minimum distance regulations between geothermal probes which were incorporated while estimating the potential:

1. Distance between two neighbouring geothermal plants is at least 10 m.
2. The distance between probes within a geothermal plant is at least 6 m for 100 m deep geothermal probes.

It is hard to allocate BHEs to the available geometries, due to the increasingly complex shapes arising. In order to maintain a minimum distance of 10m between two geothermal plants, the minimum area required for a single BHE was assumed to be 100 m^2. The total usable area was divided with the area required for a single BHE to get the total number of BHEs possible.

$$\text{Maximum no. of boreholes} = \frac{\text{Total available area}}{\text{Area required by one borehole}} \tag{3.2}$$

3.2.4 Geothermal potential calculation

All the parameters identified in the previous sections served as input to the G.POT method. The G.POT method provides a general empirical relationship for the calculation of the theoretical geothermal potential, Q_{BHE}. The assumptions under which Q_{BHE} calculated here are:

- the ground is homogeneous
- the thermal load of the BHE is annual cyclic with an emi-sinusoidal profile
- the BHE is modelled as a linear heat source with infinite length, i.e. the heat flux is purely radial (Carslaw and Jaeger, [39])
- the heat transfer between the borehole and the fluid is governed by the borehole resistance model of Claesson and Eskilson [40].
- the minimum (or maximum for cooling mode) temperature reached by the carrier fluid is exactly equal to T_{lim}

As per the method, the shallow geothermal potential is defined as the average thermal load that can be exchanged by a BHE with a length L, inducing a maximum fluid thermal alteration equal to the difference between the initial temperature and a threshold value T_{lim} (minimum temperature of the heat carrier fluid) [25]. The equation is given as:

$$Q_{BHE} = \frac{a(T_o - T_{lim})\lambda L t_c}{-0.619 log(u_s) + (0.532 t_c - 0.962) log(u_c) - 0.455 t_c - 1.619 + 4\pi\lambda R_b} \tag{3.3}$$

where a = 8 if Q_{bhe} is expressed in W, λ is thermal conductivity of the ground, R_b is thermal resistance of the borehole, T_o is the undisturbed ground temperature, T_{lim} is the minimum temperature of heat carrier fluid, L is length of the borehole, t_c is length of the heating cycle, u_c and u_s are non-dimensionless parameters.

Table 3.3 shows the different parameters and the values used to compute the geothermal potential.

Parameter	Symbol	Unit	Value(s)
Thermal conductivity	λ	W/mK	0.85-1.53
Thermal capacity	Cp	$Jm^{-3}K^{-1}$	2.3
Length of borehole	L	m	50
Borehole thermal resistance	R_b	mKW^{-1}	0.12
Borehole radius	rb	m	0.065
Heat carrier fluid temperature	T_{lim}	°C	-2
Lifetime	t_s	years	50

Table 3.3: Parameters used for geothermal potential calculation

To calculate the technical geothermal potential, the maximum number of BHEs that can be installed in an available area are calculated (using equation 3.2). In the next step, the number of installable BHEs was multiplied with the theoretical geothermal yield of one BHE (equation 3.3 to give the technical potential. Summing up this potential for all usable areas gives an estimation of the technical shallow geothermal potential for the whole district (equation 3.4).

$$Q_{\text{tech}} = \sum^{\text{total area}} \text{Maximum no. of boreholes} * \mathrm{Q_{bhe}} \tag{3.4}$$

3.3 Reduction in CO_2 emissions

The real benefits of switching to renewable heating can be measured in terms of the reduction in CO_2 emissions it brings. To measure this, the current CO_2 emissions due to the present heating mix and the resulting CO_2 emissions after completely switching to geothermal energy for heating were compared.
For the first scenario, the CO_2 emissions resulting from the present heating mix were calculated. The % share of the different fuels in the heating supply was used for the calculations (figure 3.9). The contribution of each fuel in the heating mix was obtained from the local chimney sweeper's data. The respective shares were multiplied with the total heat demand to get the energy supplied by each fuel (in kWh). The energy supplied by each fuel was then multiplied with the respective CO_2 emission factors (taken from [41]) to get the CO_2 emissions (equation 3.5). The CO_2 emissions resulting from the use of each fuel were summed to get the total emissions.

For the second case, it was assumed that the entire districts heating needs were covered with GSHPs using the available geothermal energy and wood-fired boilers. For calculating the emissions due to GSHP use, the heat supplied using GSHPs was divided with the COP of the GSHPs to get the electricity usage, and this was multiplied with the emission factor of the national electricity mix of Germany to get the resulting CO_2 emissions (equation 3.6).

$$CO_2 = \sum^{\text{fuel}} \frac{\text{Emission factor} * (\text{share} * \text{heat demand})}{\eta} \tag{3.5}$$

$$CO_2 = \frac{\text{Emission factor} * Q_{\text{tech}}}{COP_{\text{gshp}}} \tag{3.6}$$

The difference in CO_2 emissions between the two scenarios gave the savings in CO_2 emissions.

Fuel	Unit	Emission factor
Coal	kg/kWh	0.337
Oil	kg/kWh	0.264
Natural gas	kg/kWh	0.201
Liquified gas	kg/kWh	0.235
Wood	kg/kWh	0.025
Electricity	kg/kWh	0.401

Table 3.4: Emission factors for different fuels (source : [41])

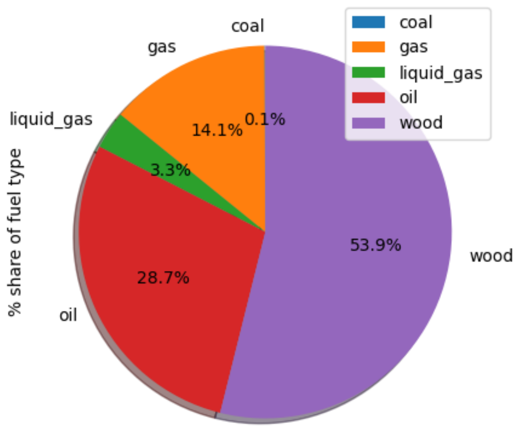


Figure 3.9: Share of different fuel sources in the heating supply

3.4 Validation

This section describes the validation of the model used in the study. To check if the model behaves as expected, the maximum extractable power (kW) was plotted against the borehole depth. The general trend is a linear relationship between the two i.e with increasing depth, the geothermal yield increases. This can be verified from the figure 3.10 as the power output (kW) is higher at greater depths.

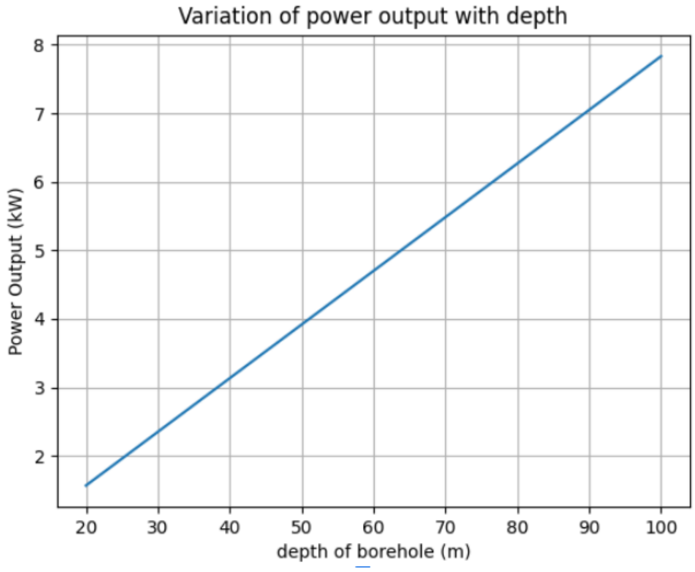


Figure 3.10: Maximum extractable power (kW) vs depth of borehole

The surrounding areas next to a BHE experience a drop in temperature when heat is extracted during the heating season. If the ground isn't given time to replenish and regain its temperature, the lifetime of the BHE is affected. Usually, the borehole is recharged during the cooling season. It is observed that the maximum power that can be extracted decreases with an increase in the heating degree days. This is done to give the ground sufficient time to regain its original temperature. To confirm if the model follows this trend, a graph of the maximum extractable power was plotted against the length of the heating season. From the graph, it can be seen that the maximum extractable power for the blue curve is highest (tc=120 days) and lowest for the green curve (tc=210 days). This verifies that the model follows the general trend.

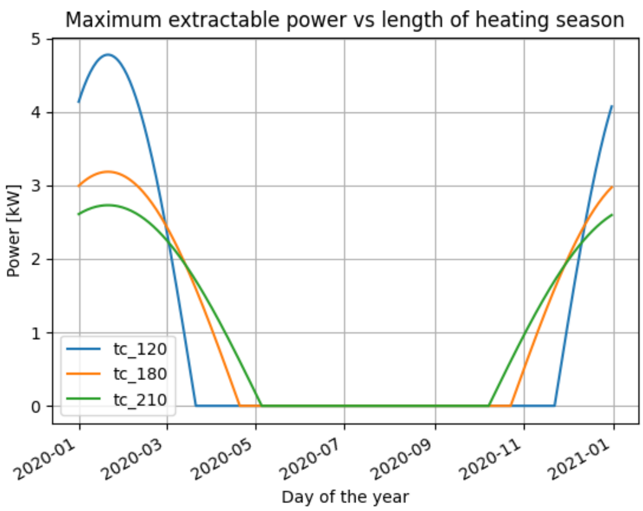


Figure 3.11: Maximum extractable power (kW) vs length of heating season

In-order to analyse the accuracy of the model, the results from the model were compared with ISONG (Information system near-surface geothermal energy for Baden-Württemberg), which provides initial information on the planning of geothermal BHEs and geothermal collectors. It provides detailed information on the maximum extractable power that can be obtained [42].

For the model calculations, two different values for the borehole thermal resistance were used - 0,1 and 0,125 mWK^{-1}. The figures 3.13,3.14,3.12 below show how the model compared with the validation source.

Parameter (R mW/K)	RMSE	Abs. mean error	MAPE	APE	Correlation coefficient
0.1	1.064	0.99	0.166	0.154	0.598
0.125	0.571	0.49	0.079	0.077	0.791

Figure 3.12: Model forecasting results

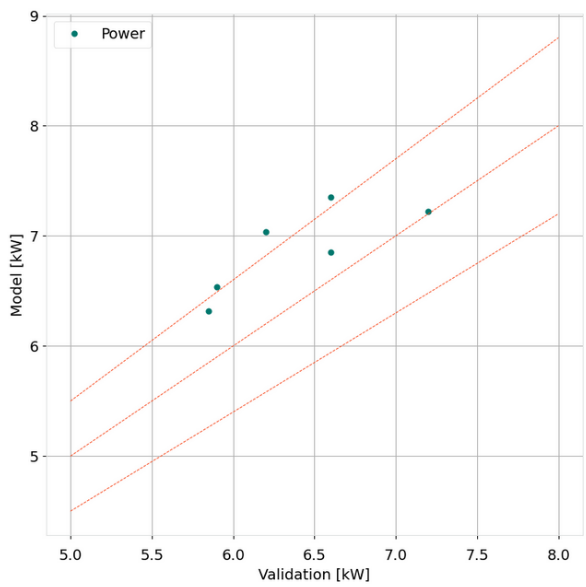


Figure 3.13: Model validation with $R_b = 0.125$

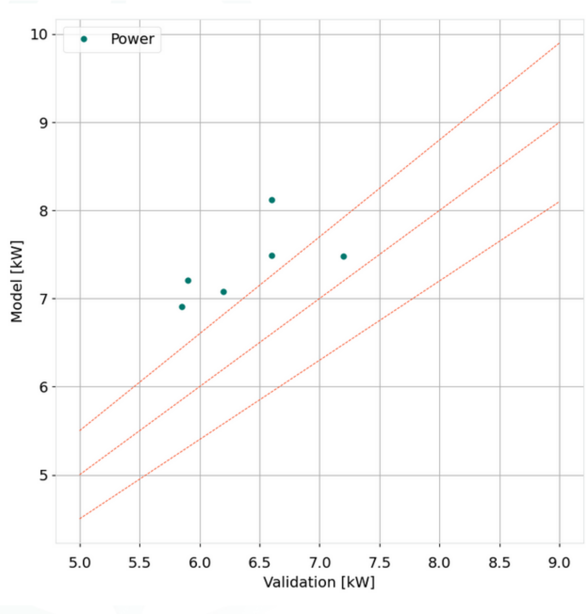


Figure 3.14: Model validation with R_b = 0.1

It was observed that the models forecasting accuracy was better when using R_b 0.125, and therefore, this value was chosen for the calculations in the study. In general, the model has an absolute mean error of 0.49 and a tendency to overestimate the maximum extractable power. The reasons for this has been discussed in the discussion section.

4

Results

In this chapter, the results of the case study are presented. The three questions the thesis set out to answer are all described. The first section presents the suitable areas for BHE installation, the second section gives an estimation on the technical geothermal potential of the case study area, and the final section highlights the reduction in CO_2 emissions that can be achieved.

4.1 Suitable areas

A total area of 22.89 km^2 was deemed suitable for BHEs installation in the district of Lörrach after the exclusion of restricted areas (Figure 4.1). It was assumed that BHEs can be installed in these areas without any restrictions. The available area is small in dense urban areas, particularly in the southern towns of Lörrach and Rheinfelden. In rural areas, the available area is much larger, mostly due to the fact that rural parcels are spaced far apart.

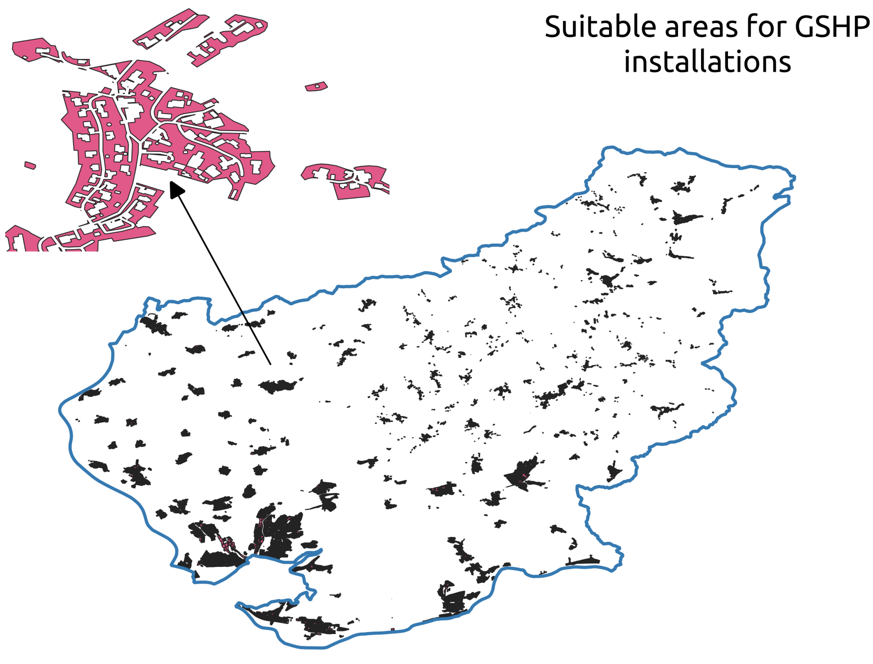


Figure 4.1: Suitable areas for geothermal energy use

4.2 Technical geothermal potential

The highest geothermal potential is observed in the south-west part of the district (figure 4.2). This could be due to the higher thermal conductivity values found there being a part of the Upper Rhine Graben (URG). The Upper Rhine area has unusually good geothermal properties. The temperatures there are by far the highest at a depth comparable to that in other regions in Germany [43]. The geothermal potential shows a high correlation to the ground thermal conductivity. In reality, other factors like ground temperature and the thermal heat capacity also affect the geothermal potential, but for this study both parameters were assumed to be constant as their variation was insignificant throughout the district.

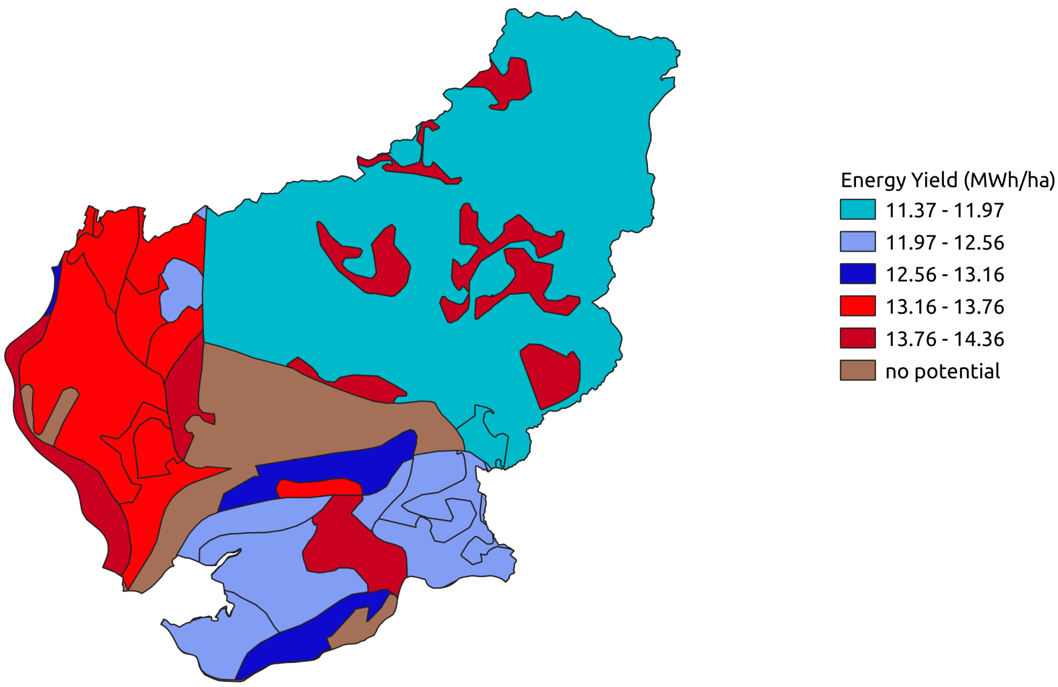


Figure 4.2: Geothermal energy yield using a BHE of 100 m length

Taking the total available area of 22.89 km^2 and dividing it with the area needed to install one borehole, gives a maximum number of installable boreholes equal to 223,315 (equation 3.2) and this yields a technical shallow geothermal potential of 1.29 TWh/a (using equation 3.4) for the district, or 1.59 kWh/m^2 of available area. With the total heat demand of the district close to 3.16 TWh, geothermal energy alone can cover around 40.6% of the total heat demand of Lörrach (figure 4.3). But this potential is unequally divided, with a much higher yield available in most rural areas where it can be used to cover the entire heat demand; in contrast to the urban areas, where the heat demand is much higher and the technical potential much lower due to less availability of space. In these areas, complementary sources of renewable heat would be indispensable.

Total area (sq km)	Usable area (sq km)	Area taken by one (sq m)	Total no. of units that can be installed	Total potential	energy / sq m	Heat Demand	% share of heat demand covered
806.58	22.89	100	223315	1.29 TWh	1.59 kWh/sq m	3.16 TWh	40.8 %

Figure 4.3: Results from the estimation of the technical shallow geothermal potential in Lörrach

4.3 Reduction in CO_2 emissions

For scenario 1, the resulting CO_2 emissions were calculated to be 439.70 kton CO_2/year (using equation 3.5). The highest share of emissions came from oil boilers which is not surprising since it had the highest carbon footprint, followed by natural gas and wood. The most popular technology is wood-fired boilers but its contribution to the emissions is significantly less as it has a substantially lower carbon footprint.

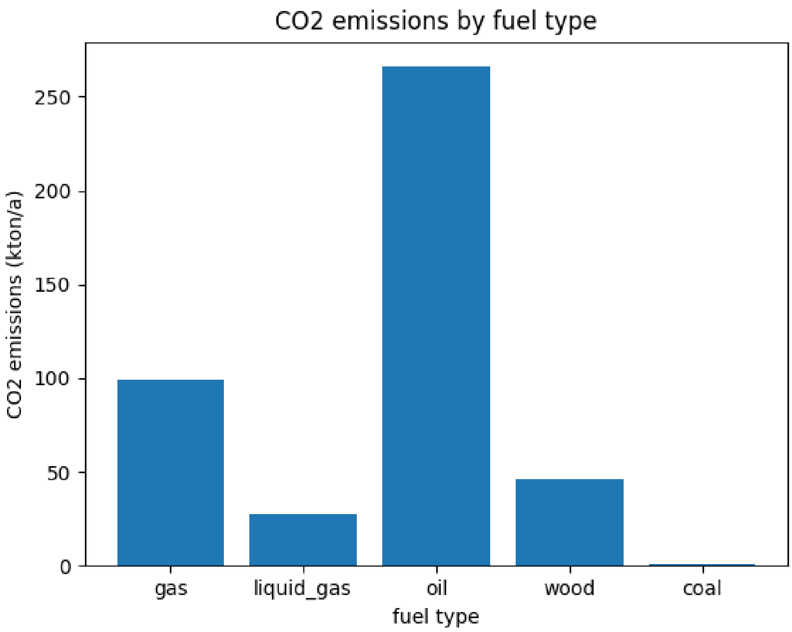


Figure 4.4: CO_2 emissions (kton/year) from different fuel sources

For scenario 2, the emissions were calculated based on the assumption that the heat demand was covered with GSHPs using geothermal energy and wood-fired boilers. 40.6% of the heat demand was covered using geothermal energy (equalling the maximum available geothermal potential) and the remaining 59.4% was met using wood boilers. This resulted in yearly CO_2 emissions of 194.48 kton CO_2/year, which is almost 50% less than in scenario 1. The reduction in CO_2 emissions that can be achieved by switching to geothermal energy use is 245.22 kton CO_2/year. This shows that shallow geothermal energy for heating has a high decarbonizing potential in the district of Lörrach.

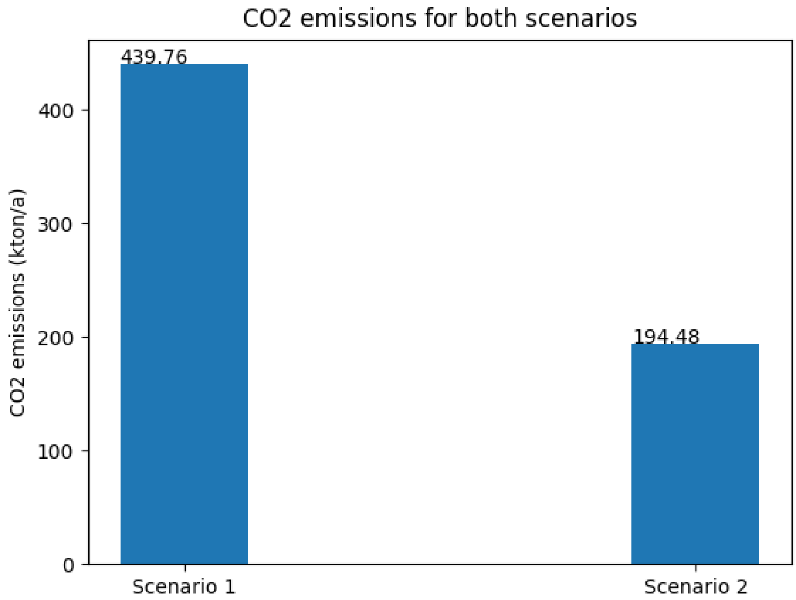


Figure 4.5: CO_2 emissions (kton/year) for scenarios 1 and 2

5

Discussion

5.1 Electrification of the heating sector

Electrification is considered the fastest and most efficient route to decarbonize the heating sector. As a greater share of heating is electrified, it becomes even more important from which source the electricity is supplied. It is true that technologies like heat pumps are highly efficient, consuming only $1/3^{rd}$ of electricity per unit of heat produced. But large scale electrification of the heating sector will result in an increased electricity demand. In order for the transition to be beneficial, this increased demand should be covered with renewable energy or with efficient baseload plants, and not with inefficient and highly polluting peak-load units. This is another motivator to switch to renewable energy.

Coupling with the heating sector can also provide a greater flexibility to the electricity system. With an increasing deployment of variable renewable energy, the electricity system will move from a system where generation adapts to inflexible demand, to a system where flexible demand adapts to variable generation. The heating sector can act as a sink/source and provide the much needed flexibility on the demand side. In times of high variable renewable energy(vRE) output and low electricity demand, electric heating can act as an absorbing technology by consuming excess electricity and reducing curtailment. When the electricity demand is high and the vRE output is low, electric heating can be switched off to reduce the demand and match the supply. This can lead to reduced need for expensive peaker plants. There have been several studies that state higher sector coupling will lead to lower CO_2 emissions and system costs. The current gas prices [44] in Germany are significantly lower than electricity prices [45](6.2 EUR cents/kWh vs 31.3 cents/kWh). This could be one of the reasons for the high share of gas/oil based heating systems. In the future, policies to promote electric heating should be normalized. This can include removal of any subsidies for fossil fuels, an increase in the carbon tax, special electricity prices for HPs and incentives such as rebates/tax cuts for installing HPs. In the end, it will not be one single technology that will dominate and be responsible for meeting all the demand especially since renewable energies tend to vary greatly in space and time, but rather a combination of different technologies all working in synergy towards a climate-neutral heating sector.

5.2 Limitations

The study provides an estimate on the technically exploitable geothermal potential, but the proportion of the potential that is actually feasible cannot be predicted since it depends on various externalities. Factors such as renovation status of the building, heat distribution system within a building, public acceptance and economic viability are obstacles which have been excluded from this study, and will result in the actual potential to be lower than the technical potential. Geothermal energy systems often have a much higher installation cost as compared to their ASHP counterparts. This is why it is recommended to have a well insulated house before installing a HP since a smaller sized unit can lead to lower installation costs. The same argument holds true for heat distribution systems. Traditional distribution systems like radiators distribute heat at a temperature of 60°C. Heat pumps operate at a much lower temperature range (usually around 40-55°C), and operating at a higher temperature results in a drop in performance. To overcome this limitation, either investing in a bigger sized radiator or a compromise on the performance of the heat pump would be needed. Meanwhile, newer technologies like underfloor heating systems distribute heat at a much lower temperature (40-45°C) and therefore, are preferred to be used in conjunction with HPs.

The work is subjected to uncertainties related to the modelling approach and the data. The primary source of uncertainty is the estimation of ground thermal properties as the data is hard to predict accurately. The datasets used in the study are national-scale models and may deviate from measured thermal properties in some locations. Ground thermal conductivity is highly correlated to the geothermal yield, and so incorrect values can lead to grossly overestimating/underestimating the potential. Simplifications made during the determination of specific heat capacity and the ground temperature are also expected to contribute towards uncertainty. In reality, a case-specific assessment of the ground thermal properties is also carried out before installation of GSHPs.

Another uncertainty is the assumption of taking the national average electricity mix for CO_2 calculations. The German electricity mix is undergoing a radical transformation with the expected shutting down of nuclear capacity, increased electricity demand due to electrification of several sectors. Hence, the electricity mix will look very different in the coming years and it is difficult to predict. Therefore, the CO_2 emissions calculated for scenario 2 might yield different results in reality from what is calculated in this study.

Other aspects include that the entire available area is considered suitable for installing BHEs. In reality, this might not always be the case as land is a limited resource having a high opportunity cost, and therefore people might be unwilling to use it for BHEs.

5.3 Applications and future work

The work was carried out to aid in the heat planning for the district of Lörrach. As the focus on decarbonizing the heating sector gains traction, more cities will have the need for a heat plan. Applications for a heat plan include providing support of policy making, urban planning and the development of a framework for the heating sector. Urban planners can use the results to estimate the shallow geothermal potential of a region, compare its feasibility with other sources and devise a carbon neutral heat supply.

Future work will focus on increasing the resolution of borehole deployment. In this study, the available geothermal potential was determined for the entire region. But this is not optimal due to the uneven distribution of the potential. It will be interesting to calculate the potential on a building level. This would require an estimate of the existing heat demand and the parcel boundaries of each property. Using this information, the suitability of BHEs for each property and the share of heat demand that can be covered if installing a BHE can be determined. A further step in this work could be determining the economic potential, which is the portion of the technical potential that can be achieved cost-effectively in the absence of market barriers.

6
Conclusion

This thesis presents a method for the estimation of the technical shallow geothermal potential for heating using BHEs. The method is applied to an area in south-west Germany to estimate the geothermal potential and the reduction in emissions that can be achieved by tapping this resource. The technical shallow geothermal potential is defined as the maximum energy yield that can be achieved by installing BHEs only on permitted areas, taking into account the general recommendations and regulations. The method combines the ground thermal properties, identification of suitable areas for borehole installation and an analytical method for determining the theoretical geothermal potential in order to estimate the technically available potential. The achievable reduction in CO_2 emissions by switching to geothermal energy is evaluated as a further step. Apart from lower climate impact, switching to geothermal energy also reduces reliance on imported fossil fuels and provides increased energy security. The model used in the study was validated using publicly available data, and showed an absolute mean error of 0.49 and RMSE value of 1.064. This proved that the model results show high correlation with real-life instances and can be trusted.

The results indicate the technical geothermal potential in Lörrach to be 1.29 TWh, which is 40.6% of the total heat demand. The results suggests that the geothermal potential can provide sufficient energy to cover a portion of the heat demand, but the proportion of the potential that is actually feasible cannot be predicted since it depends on various externalities. Factors such as renovation status of the building, heat distribution system within a building, public acceptance and economic viability are obstacles which have been excluded from this study, and will result in the actual potential to be lower than the technical potential. The potential is not equally distributed, with the densely populated urban regions having a much lower potential compared to rural areas. This presents a dilemma since the urban regions often have a much higher heat demand compared to rural areas, and therefore, a diverse mix of technologies will be needed to cover the demand in reality. The findings further show that geothermal energy has a high decarbonizing potential in the studied region, and switching to GSHPs using geothermal energy can save up 245.22 kton CO_2/ year, which is equivalent to 50% reduction in CO_2 emissions.

The work conducted in this thesis can contribute towards the advancement of decarbonisation strategies for the heating sector by providing an estimate of the potential for renewable heat generation from shallow geothermal energy.

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