# GIS-based potential assessment and scenario analysis for integrating geothermal heat pumps technologies in urban energy systems

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Vorgelegt von

**Alejandro Zabala Figueroa**

aus Cali, Kolumbien

Immatrikulationsnummer:19659


Hauptberichter: Prof. Dr.-Ing. Michael Bierhoff

Mitberichter: Dr.-Ing. Alaa Alhamwi

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## Declaration of academic integrity

I hereby declare that the undersigned has written this master thesis without the unauthorized assistance from third parties.

Furthermore, I confirm that no sources have been used in its preparation than those indicated in the thesis itself.

Stralsund, 02/03/2023

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## Dedication

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# Abstract


Urban areas are significant consumers of primary energy. They are responsible for a large proportion of global $CO_2$ emissions, with buildings accounting for most of the worldwide electricity consumption and heating being the immediate energy use in European residential buildings. While efforts are being made to reduce the $CO_2$ footprint of cities, unforeseen events such as the Covid-19 pandemic and international conflicts can pose a challenge. These events have increased energy prices but also created an opportunity to increase renewable energy deployment. The implementation of heat pumps has recently raised to find alternatives to conventional fossil fuel-sourced heating systems and decarbonize city energy matrixes. This study compares ground source heat pumps (GSHP) and aerothermal heat pumps, as the latter is cheaper and easier to install but less efficient and could strain the electricity grid.

By incorporating shallow geothermal energy (SGE), urban energy systems (UES) can reduce their average power and electrical energy requirements from the power grids to supply heat, compared to using aerothermal heat pumps. However, the feasibility of deploying shallow geothermal heat systems depends on the energy potential of the underground rock and the absence of any restrictions related to water stream contamination at the site. Thus, this study aims to utilize Geographic Information System (GIS) and opensource data to develop a heat supply model using SGE. One of the objectives of this study is to implement opensource data to ensure that the data is not biased and that this is independent research. The model will analyze various integration scenarios, including those that use aerothermal, geothermal, or a combination of both types of heat pumps, to identify their benefits for cities.

The methodology implemented requested three sources of data to model urban energy systems in the city of Oldenburg. The first dataset established the city's infrastructure, the second provided information on energy potential and locations for geothermal systems, and the third identified the relationship between variables in the model. The FlexiGIS tool was used to calculate the total area of buildings and estimate thermal energy consumption. The space occupied by different types of geothermal systems was assessed, and the coefficients of performance of aerothermal and geothermal heat pumps were used to estimate power and energy consumption for three scenarios. The first used aerothermal pumps, the second used geothermal pumps, and the third proposed a distributed and decentralized system using the maximum geothermal potential of a BHE to supply heat to nearby buildings.

The study concludes that GSHP using borehole heat exchangers (BHE) are the most suitable shallow geothermal systems for implementation in cities due to their efficiency, more minor space requirements, and less pressure on power distribution networks compared to air-source heat pumps. SGE can offer a more economical and environmentally friendly alternative to gas for space heat and hot water. However, implementing GSHPs faces challenges such as technical and non-technical barriers, environmental problems, and restrictions in historic buildings. Future studies should consider calculating heat consumption as a function of time to get more exact grid power requirements. The study also suggests a high potential for growth in German geothermal power capacities.

# Kurzfassung

Städtische Gebiete sind bedeutende Verbraucher von Primärenergie. Sie sind für einen großen Teil der globalen CO2-Emissionen verantwortlich, wobei der größte Teil des weltweiten Stromverbrauchs auf Gebäude entfällt und die Heizung in europäischen Wohngebäuden den größten Energieverbrauch darstellt. Es werden zwar Anstrengungen unternommen, um den CO2-Fußabdruck von Städten zu verringern, doch unvorhergesehene Ereignisse wie die Covid-19-Pandemie und internationale Konflikte können eine Herausforderung darstellen. Diese Ereignisse haben die Energiepreise in die Höhe getrieben, aber auch die Möglichkeit geschaffen, den Einsatz erneuerbarer Energien zu erhöhen. Der Einsatz von Wärmepumpen hat in jüngster Zeit zugenommen, um Alternativen zu herkömmlichen Heizsystemen auf der Basis fossiler Brennstoffe zu finden und die Energiematrix von Städten zu dekarbonisieren. In dieser Studie werden Erdwärmepumpen (GSHP) und aerothermische Wärmepumpen verglichen, da letztere zwar billiger und einfacher zu installieren sind, aber weniger effizient sind und das Stromnetz belasten könnten.

Durch die Einbeziehung der oberflächennahen Geothermie (SGE) können städtische Energiesysteme (UES) ihren durchschnittlichen Bedarf an Strom und elektrischer Energie aus den Stromnetzen für die Wärmeversorgung im Vergleich zum Einsatz von aerothermischen Wärmepumpen senken. Die Durchführbarkeit von oberflächennahen geothermischen Heizsystemen hängt jedoch vom Energiepotenzial des unterirdischen Gesteins und von der Abwesenheit jeglicher Einschränkungen im Zusammenhang mit der Verschmutzung des Wasserstroms am Standort ab. Daher zielt diese Studie darauf ab, mit Hilfe eines geografischen Informationssystems (GIS) und Open-Source-Daten ein Wärmeversorgungsmodell mit Hilfe von SGE zu entwickeln. Eines der Ziele dieser Studie ist die Verwendung von Open-Source-Daten, um sicherzustellen, dass die Daten nicht verzerrt sind und es sich um unabhängige Forschung handelt. Das Modell wird verschiedene Integrationsszenarien analysieren, darunter solche, die aerothermische, geothermische oder eine Kombination aus beiden Arten von Wärmepumpen verwenden, um deren Vorteile für Städte zu ermitteln.

Bei der angewandten Methodik wurden drei Datenquellen für die Modellierung städtischer Energiesysteme in der Stadt Oldenburg herangezogen. Mit dem ersten Datensatz wurde die Infrastruktur der Stadt ermittelt, der zweite lieferte Informationen über das Energiepotenzial und die Standorte für geothermische Systeme, und der dritte stellte die Beziehung zwischen den Variablen im Modell fest. Das FlexiGIS-Tool wurde verwendet, um die Gesamtfläche der Gebäude zu berechnen und den Wärmeenergieverbrauch zu schätzen. Der von verschiedenen Arten von geothermischen Systemen belegte Raum wurde bewertet, und die Leistungszahlen von aerothermischen und geothermischen Wärmepumpen wurden verwendet, um den Strom- und Energieverbrauch für drei Szenarien zu schätzen. Im ersten Szenario wurden aerothermische Pumpen verwendet, im zweiten geothermische Pumpen und im dritten Szenario wurde ein verteiltes und dezentrales System vorgeschlagen, das das maximale geothermische Potenzial einer BHE nutzt, um nahe gelegene Gebäude mit Wärme zu versorgen.

Die Studie kommt zu dem Schluss, dass sich Erdwärmepumpen mit Erdwärmesonden aufgrund ihrer Effizienz, ihres geringeren Platzbedarfs und der geringeren Belastung der

Stromverteilungsnetze im Vergleich zu Luftwärmepumpen am besten für die Anwendung in Städten eignen. Erdwärmepumpen können eine wirtschaftlichere und umweltfreundlichere Alternative zu Gas für Raumwärme und Warmwasser bieten. Die Einführung von KWP steht jedoch vor Herausforderungen wie technischen und nichttechnischen Hindernissen, Umweltproblemen und Einschränkungen in historischen Gebäuden. Künftige Studien sollten die Berechnung des Wärmeverbrauchs in Abhängigkeit von der Zeit in Betracht ziehen, um den Netzstrombedarf genauer zu ermitteln. Die Studie deutet auch auf ein hohes Wachstumspotenzial für die deutschen geothermischen Stromkapazitäten hin.

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# List of abbreviations

| Abbreviation | Meaning |
|---|---|
| Avg. | Average |
| Ag | Agricultural. Building category. |
| Co | Commercial. Building category. |
| BHE | Borehole Heat Exchanger |
| CityGML | OGC City Geography Markup Language |
| $CO_2$ | Carbon dioxide |
| COP | Coefficient of performance of a heat pump operating at the Carnot efficiency |
| DLR | Abbreviation of German words for: German Aerospace Center |
| Ed | Education. Building category |
| FLEXIGIS | Flexibilization in Geographic Information Systems |
| GIS | Geographic Information System |
| In | Industrial. Building category. |
| LBEG | Abbreviation of German words for: State Office for Mining, Energy and Geology of Lower Saxony |
| LGLN | Abbreviation of German words for: State Office for Geoinformation and Land Surveying of Lower Saxony. |
| Max. | Maximum |
| Min. | Minimum |
| OGC | Open Geospatial Consortium |
| OSM | Open Street Map |
| Re | Residential. Building category. |
| SGE | Shallow Geothermal Energy |
| UES | Urban Energy System |
| VDI | Abbreviation of German words for: Association of German Engineers |
| W | Watts |
| kW | Kilowatts |
| MW | Megawatts |
| TW | Terawatts |
| $W_{th}$ | Thermal watts |
| $kW_{th}$ | Thermal kilowatts |
| $MW_{th}$ | Thermal megawatts |
| $TW_{th}$ | Thermal terawatts |
| Wh/a | Watts hour annually |
| kWh/a | Kilowatts hour annually |
| MWh/a | Megawatts hour annually |

| | |
|---|---|
| TW h/a | Terawatts hours annually |
| $W_{th}$ h/a | Thermal watts hour annually |
| $kW_{th}$ h/a | Thermal kilowatts hour annually |
| $MW_{th}$ h/a | Thermal megawatts hour annually |
| $TW_{th}$ h/a | Thermal terawatts hour annually |
| WHG | Water Management Act |

# Nomenclature

| Symbols | Unit | Definition |
|---|---|---|
| $a_i$ | $m^2$ | Polygon area |
| $A_i$ | $m^2$ | Building area |
| $A_{ijk,\, bas,req}$ | $m^2$ | Area k of basket collector system for building i with heat consumption j |
| $A_{ijm,\, hor,req}$ | $m^2$ | Area m of horizontal collector system for building i with heat consumption j |
| $A_{ijn,\, BHE,req}$ | $m^2$ | Area n of vertical collector system (borehole heat exchangers) for building I with heat consumption n |
| $A_{district,\, bas}$ | $m^2$ | Area of district for basket collector systems |
| $A_{district,\, hor}$ | $m^2$ | Area of district for horizontal collector systems |
| $A_{district,\, BHE}$ | $m^2$ | Area of district for BHE |
| $A_{city,\, bas}$ | $m^2$ | Area of city for basket collector systems |
| $A_{city,\, hor}$ | $m^2$ | Area of city for horizontal collector systems |
| $A_{city,\, BHE}$ | $m^2$ | Area of city for BHE |
| $d_j$ | $\frac{kWth\,h}{m^2 * a}$ | Annual heat consumption per square meter, according to building's use (agriculture, commercial, education, industrial or residential). |
| $D_{ij}$ | $\frac{kWth\,h}{a}$ | Building's annual heat consumption |
| $h_i$ | $m$ | Building's height |
| $\dot{h}_{ik,bas}$ | $\frac{W}{basket}$ | heat extraction rate per basket k at building i |
| $\dot{h}_{ih_e,m}$ | $\frac{W}{m^2}$ | horizontal heat extraction rate m at building i |
| $\dot{h}_{iv_e,n}$ | $\frac{W}{m}$ | vertical heat extraction rate n at polygon i |
| $n_i$ | $number$ of storeys | Storeys per building i |
| $Q_{district,hp}$ | $W_{th}\frac{h}{a}$ | Annual heat consumption |
| $\dot{Q}_{district,hp}$ | $W_{th}$ | Building's thermal power requirement |
| $\dot{Q}_{ij,th}$ | $W$ | Building's thermal power requirement |
| $\dot{Q}_{ij,Pel\_ath}$ | $W$ | Average power demand of aerothermal heat pumps |
| $Q_{ij,e\_el\_ath}$ | $\frac{Wh}{a}$ | Electrical energy consumption of aerothermal heat pumps |

| | | |
|---|---|---|
| $Q_{ij,e\_el\_geoth}$ | $\frac{Wh}{a}$ | Electrical energy consumption of decentralized geothermal heat pumps |
| $\dot{Q}_{ij,Pel\_geoth}$ | $W$ | Average power demand of decentralized geothermal heat pumps |
| $\dot{Q}_{ij,\,Evap}$ | W | Evaporator power of the heat exchanger in heat pump of building i, with heat consumption j. |
| $\dot{Q}_{ij,Pel}$ | $W$ | Average power demand of aerothermal heat pumps and grid of decentralized geothermal heat pumps. |
| $Q_{ij,e\_el}$ | $\frac{Wh}{a}$ | Electrical energy consumption of aerothermal heat pumps and grid of decentralized geothermal heat pumps. |

# Chapter 1 Introduction

## 1.1 Motivation

According to the United Nations [1], urban areas consumes about 75% of global primary energy, and are also responsible of about 80% of global $CO_2$ emissions [2]. Expanding on the energy requirements of residential and commercial buildings, they consumed in 2018 about 60% of the global electrical energy [3]. In the case of Europe, from the total residential building's energy consumption, 80% was used for water and space heating [2], emitting 60% of the Europe's $CO_2$-emissions. Though, most of the global efforts are focused on getting the Net Zero Emissions by 2050 scenario [4], reducing the $CO_2$ footprint of cities, while they are sourced with sustainable energy [1], is a challenge that can easily be threatened by conjunctural situations, such as those produced by the Covid-19 pandemic and the recent war between Ukraine and Russia [5]. While these events have increased the prices of fossil fuels, they have also created a favorable situation to increase the deployment of renewable energies and decrease the dependency on fossil fuels. Thus, to keep energy market prices affordable for consumers, due to high prices affectations, as shown in figure Figure 1. Evolution and projected energy prices since 2018 until 2025. [6]., and foster energy security, some European countries have had to postpone nuclear plan decommission and maintain or increase imports of coal for power generation [5].

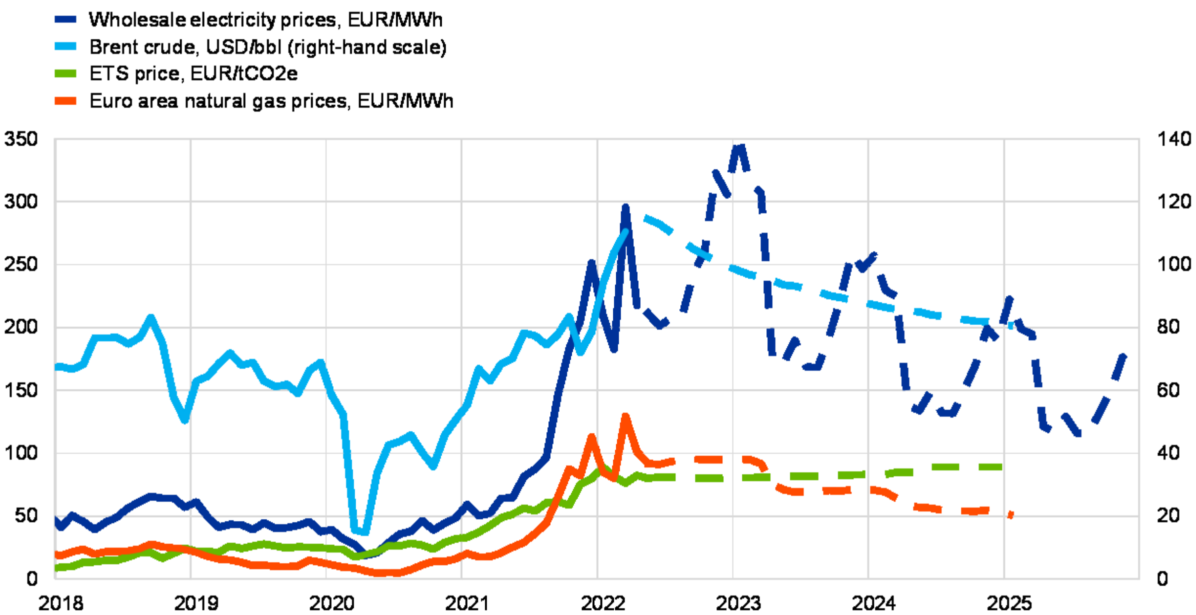



**Figure 1. Evolution and projected energy prices since 2018 until 2025. [6].**

In addition to the challenge of maintaining the focus on sustainability, all over the world, cities population is continuously growing. In 1990, there were just 10 cities with more than 10 million inhabitants, representing less than 7% of the global population [2]. By 2018, there were 33 large cities, growing the number of inhabitants in these types of cities summing up to 509 million [7]. Therefore, the role of renewable energies in facilitating the sustainable growth of cities is indispensable.

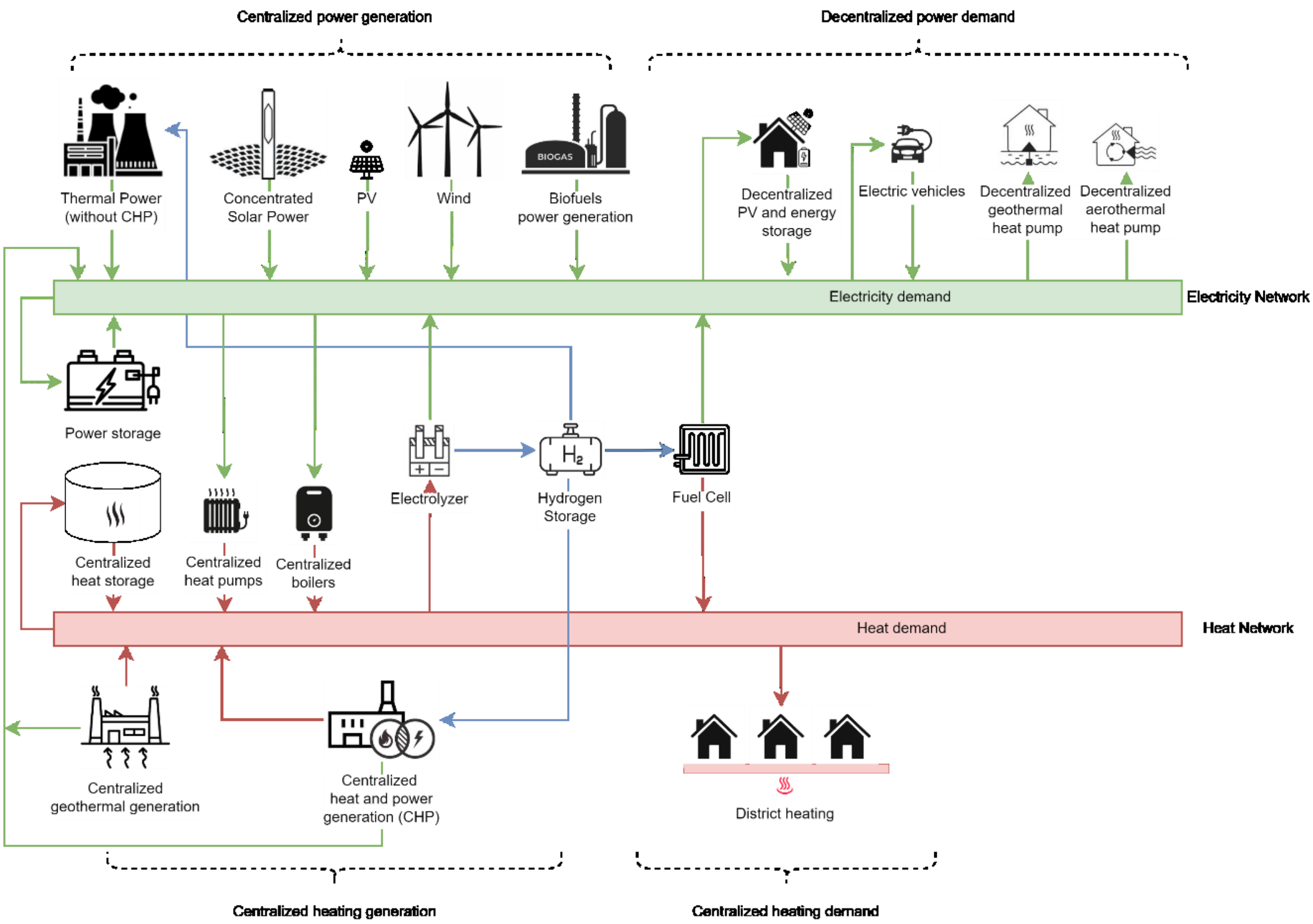



**Figure 2. Sector coupling of renewable energies**

As shown in Figure 2, current and future urban energy systems include the sharing of energy from centralized power plants, as well as the integration of solar and wind energy, concentrated solar power, or CHP plants, and other sources of renewable energy generation, into distributed generation systems, which has helped to make electricity generation more flexible, providing a solution to the decarbonization of countries' energy matrixes [8]. However, these solutions are insufficient to provide a sustainable solution to the city's heat consumptions. Therefore, identifying system-oriented solutions linking the electricity and heat network of a city, while helping in decarbonization and decentralization of urban energy systems (UES) are of high priority [9]. In this context, Ground Source Heat Pumps (GSHP), both horizontal (1.5–2 m deep) and vertical heat exchanger systems (usually 50 –150 m deep) [10], to urban energy systems, represent a big opportunity [11], even if involves considerable investments in the adaptation of grid and civil city's infrastructure [3].

The optimal integration of renewable energies into the UES requires a systematic approach, in which a model can be established and the different applicable restrictions can be considered. In this sense, while the management and control of urban infrastructure interventions for geothermal energy harnessing can be challenging, it also creates opportunities for the development of systems and platforms for appropriate modelling. Future energy systems that have the ability to consider the temporal dynamics of demand, generation and storage requirements of different forms of energy are likely to benefit from a spatial approach that considers the particular infrastructure and energy resource constraints of each city [12]. In the case of geothermal energy, like solar and wind energy resources, it can also be geolocated. This information can be exploited by a Geographic Information Systems (GIS), as it allows the temporal and spatial analysis of several variables. For instance, the polygons that comprise the infrastructure of a city [12], which can be used to analyze their interrelationship with particular geothermal energy variables such as the status and location of licensed wells, the geothermal energy potential in a given location at a specific depth, or city installing restrictions that may affect protected areas for archeological or environmental reasons. In this sense, the ability of public and private sector stakeholders and researchers to model and interpret the relationship of such information will be fundamental for the successful planning [13], regulation and construction of future UESs which integrates geothermal energy in their energy matrix.

Another challenge in UES planning is the access to transparent and open source information [9]. In several countries, information on electricity and thermal energy distribution networks belongs to private companies and is not of easy accessibility [3]. For this reason, it is intended to implement the FlexiGIS[1] model, which is a Geographic Information Systems GIS-based tool, that uses publicly available datasets like data from OpenStreetMap (OSM). The tool extracts, filters and categorizes geo-referenced urban energy infrastructure, simulates the local electricity consumption and generation from on-site renewable energy resources, and allocates the required decentralized storage in urban settings [14]. Thus, FlexiGIS allows to investigate different scenarios and apply characteristic roles of technologies in order to study the possibility of promoting the autonomy of UES. While FlexiGIS simulates the electricity requirements in UES, this study focuses on the heat sector. It aims to provide additional contributions to the field of applying GIS techniques for the assessment and analysis of different potential scenarios for the integration of geothermal energy heat pumps in urban settings.

### 1.2 Current state of scientific research

There are several models that have implemented GIS, in the field of renewable energy source potential analysis for urban energy systems. However, there is a higher proportion focused on solar and wind energy [12][15][16]. Indeed, in the specific field of GIS-Based urban energy models, with emphasis on geothermal energy, they are usually focused on realizing separated analysis of heat consumption [17] or heat potential estimation [18][19][20][21][22]. Other studies assess the capacity to supply the requested heat and the level of self-sufficiency that the heating network can obtain in cities [18][20]. However, it is done not considering infrastructure restrictions of a city, which is probably one of the most important elements for urban planning. Probably one of the most complete studies was developed in [23]. This study estimates the technical geothermal potential from ground source heat pumps for individual building-blocks on a regional scale [23]. Further, its energy potential is linked to the demand of building blocks, and additionally different restrictions for its installation, like those defined by the government or by law, are considered. However, the implemented solution does not use open source data, or is not documented as a free software solution. While these studies focus on shallow geological analysis and the calculation of their energy potential, they also highlight the possibility of getting in deep into the analysis of the feasibility of implementing different

[1] https://github.com/FlexiGIS

technologies, or the use of free data sources for the development of GIS modeling. This research will address this gap.

Additionally, there are other investigations already done with FlexiGIS, like the one for street lighting infrastructure [24], or the case study in the city of Philadelphia to analyze configurations of renewable power generation in cities [12], and the additional one over "allocation and optimization of distributed storage in urban energy systems [25]." FlexiGIS tool helps to promote the integration of local renewable energies resources in urban areas. This master thesis contributes to the further development of FlexiGIS and to identify different restrictions that may have the deployment of some types of technology for the use of shallow geothermal energy, the ability of this potential to meet the demand for thermal energy over time, and the technical and economic impact that could have the implementation of these technologies.

In this way, a comprehensive literature review related to GIS- based models of spatial and data assisted ground source heat pump potential analysis for urban energy systems is planned to be done, in order to contemplate best considerations that might help to develop the study defined in this master thesis.

### 1.3 Objectives and research questions of the thesis

Modelling energy necessities of cities involves a suitable characterization of requirements for energy consumption and generation potential. This master thesis aims to analyse the use of shallow geothermal energy with brine to water heat pumps and air to water heat pumps, using specific parameters of cities, such as space heat and hot water consumption by building type, usage and area per building, and heat extraction values for vertical, horizontal and basket heat exchangers.

The relevance of this study that it fills in a gap in the literature, namely modelling of heat supply system networks in UES using GIS open source data. It investigates scenarios to promote the implementation of shallow geothermal heat pump technology in order to allow cities to have a higher level of self-sufficiency of UES.

For the development of this master thesis, it was decided to use GSHP. This determination is because, although open geothermal systems could be considered for the development of the study, there is a significant limitation for the deployment of this technology, and it is due to not always is possible to find aquifers in the cities, which limits the implementation of this technology. For this reason, it has been decided to focus the study on using GSHP.

Regarding the systems to be developed, due to the available information on the VDI 4640 part 2, which was mainly consulted to do this study, this standard provides detailed technical information that was consulted for the development of the model using BHE, horizontal and basket collectors. It is also not intended to develop a mathematical model that performs a specific calculation of the internal variables of each geothermal system, such as the amount of cooling liquid mass, the design of the wells, and their heat exchange under the ground. It is also noted that the author understands that the assessment of the necessary adjustments to the network depends specifically on actual configuration of the grid, the maximum power that must currently be served and the type of load being served. In this sense, when the study specifies a value for the adaptations, this is done considering approximations developed by other studies and does not intend to delve into this matter.

In this sense, the scope of this study is mainly concentrated on an analysis of the possibility of GSHPs supplying heat to a city as well as their possible implications on the electricity grid. Consistently, the model development explained in this chapter does not consider at a detailed level the interrelationship of variables associated with the variation in the climate of the city in the case study, such as power and change in the efficiency of the equipment.

The research and modelling work are presented as a master's thesis, which aims to develop a model of heat supply with shallow geothermal heat pumps, using a GIS and open source data to analyse different integration scenarios and identify their benefits for cities.

Hence it is worthy to address the following research questions:

- Using open source data, how to evaluate the potential of geothermal energy in urban areas?
- To what extend can geothermal heat pumps contribute to high self-sufficiency in districts and cities?
- What type of shallow geothermal energy system (SGES) is most suitable for implementation in cities?
- Can the integration of geothermal heat pumps technologies in UES reduce the pressure on the distribution grids?
- What restrictions could we find in deploying different geothermal technologies?

### 1.4 Structure of thesis

The chapters of this master thesis were organized as follows:

- **Chapter 1: Introduction**
  It provides a framework to understand why introducing shallow geothermal energy may help urban energy systems to provide heat. It also explains the motivation, the main objectives and the research questions of the master thesis. Finally, it will provide an overview of the thesis structure.
- **Chapter 2: Shallow geothermal concepts**
  This chapter explains concepts related with geothermal energy and SGES.
- **Chapter 3: Methodology**
  It presents the research methodology and an approach for addressing the research problem discussed earlier. It provides an overview of the methods, calculations and tools utilized to accomplish the primary goal of the thesis.
- **Chapter 4: Modelling results**
  summarizes the results of the heating demand estimation, the requested area for the SGES investigated, and the scenario's average power demand and energy consumption.
- **Chapter 5: Results discussion**
  compares, discusses and analyses, the modelling results and infers the output of each scenario. It also does an economic analysis, and compares heat energy prices with current energy prices. It ends analysis the self-sufficiency that may bring geothermal energy to urban energy systems.

- **Chapter 6: Conclusions and outlook**
  concludes the research and provide further recommendations.
- **Chapter 7: Bibliography**
  state the sources of this master thesis.

# Chapter 2 Shallow geothermal concepts

Geothermal energy, originating from the heat within the Earth's core, is distinct from solar energy and arises from gravitational energy and the radioactive decay of unstable atoms. The vast amount of heat contained within the planet makes this energy source renewable, as human use cannot deplete the energy reservoir. The utilization of geothermal energy is sustained by renewal and replenishment from the internal planetary reservoir, rendering it practically unlimited if used sustainably. The sustainable use of renewable energy resources necessitates consumption rates that do not exceed the renewing process rate, which is notably fast in human timescales for renewable energy [26].

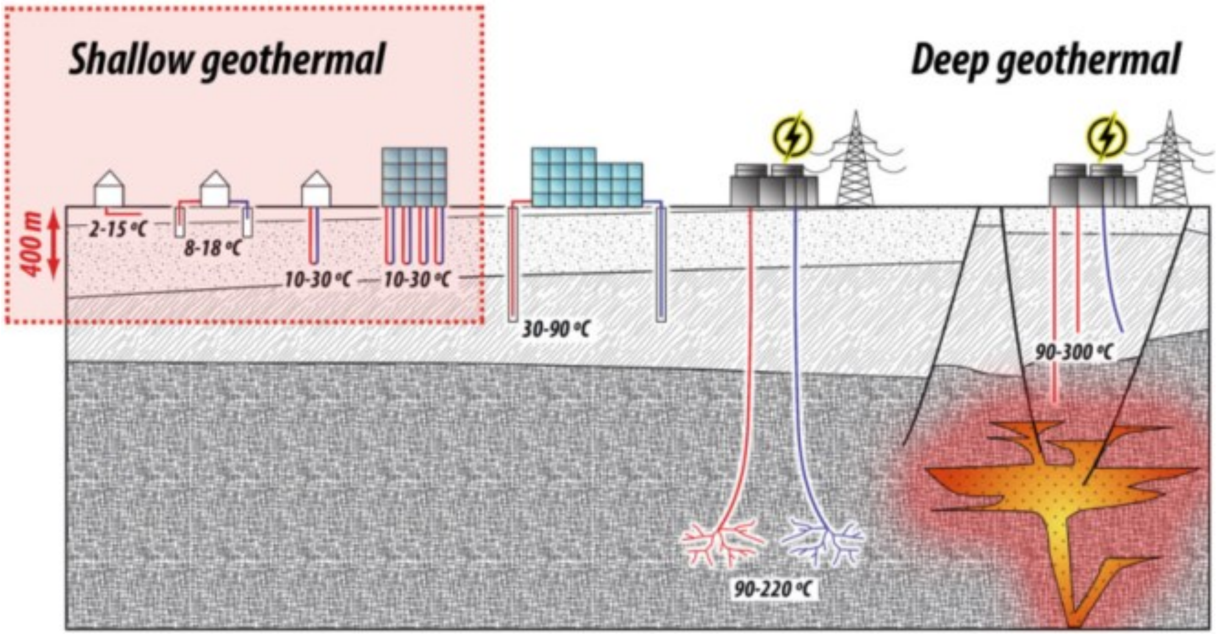


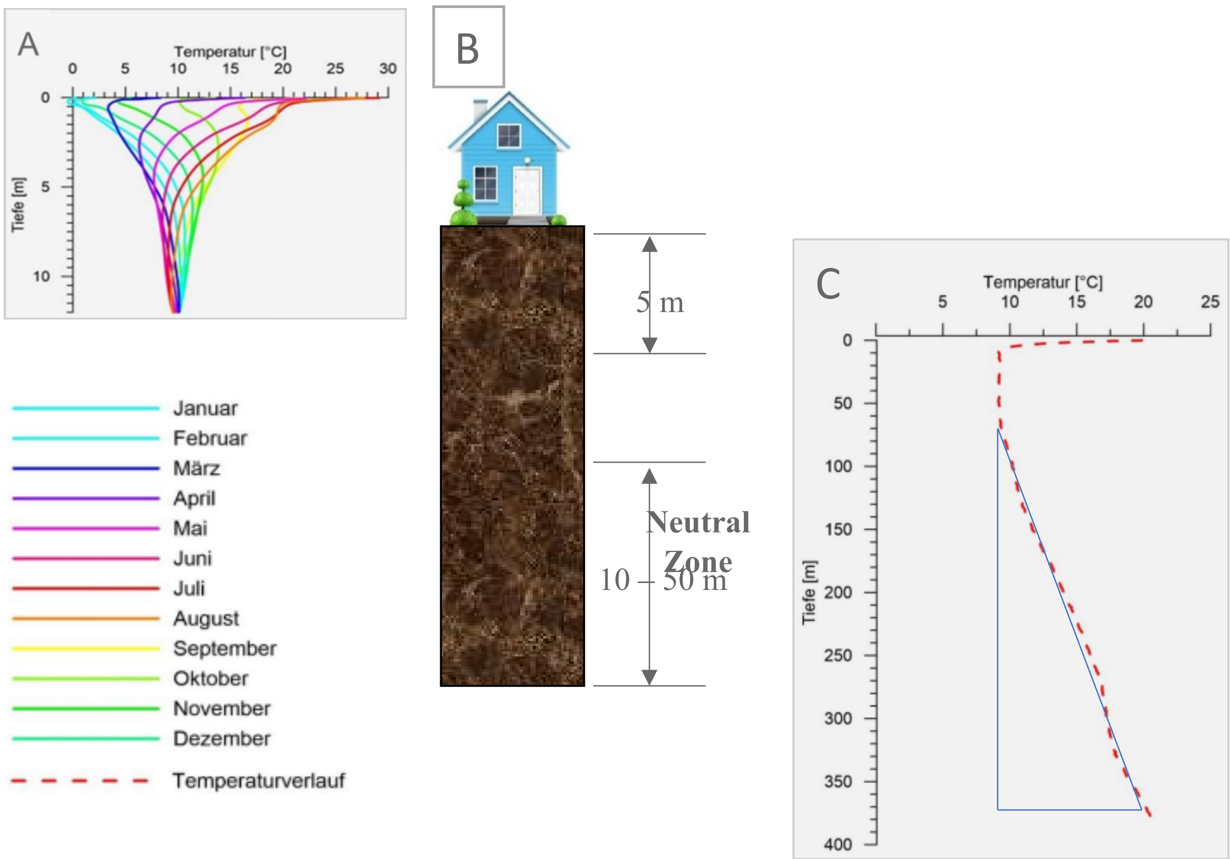

**Figure 3. Conceptual diagram of shallow geothermal energy and deep geothermal energy [27].**

Geothermal energy, also known as geothermal heat, refers to the thermal energy stored beneath the Earth's surface. Its utilization varies based on the depth at which it is extracted, with near-surface and deep geothermal energy systems offering distinct possibilities for usage. Therefore, geothermal heat can be categorized into two main types: shallow geothermal and deep geothermal energy systems [27]. A representation of the shallow and deep geothermal is shown in figure 3. The limit established by the standard VDI 4640 part 1 for SGE is 400 meters, where temperatures around 20° C can be found on average. Beyond this length, it is considered deep geothermal energy [28][27]. This study focuses on the capacity of a city to supply its heat consumption from SGE, the rest of the chapter will be focused on explaining related concepts to SGE.

## 2.1 Shallow geothermal energy

Regarding the earth's surface temperature, it is usually said to be around 14.5° C. This value is arrived at as a result of the balance of the solar energy incident on the earth, the reflected infrared radiation, and that which is trapped by the earth due to the greenhouse effect. In comparative terms, the thermal energy flowing from the earth's interior to the surface, approximately 0.05 $W/m^2$ to 0.12 $W/m^2$, versus that from solar radiation, 1000 $W/m^2$, is relatively small. Whenever the naturally mentioned balanced is disturbed, through heat injection or extraction, which is what can happen when installing a heat pump, the unbalanced amount of heat must be restored by heat transport. In geothermal energy, the thermal surplus or deficit must be rebalanced by heat transport, like conduction and convection, because heat constantly flows from hotter regions to cooler regions until there is no longer a temperature difference, a state known as thermal equilibrium.

**Figure 4. A: Mean annual variation of ground temperature using the example of the Potsdam secular station. B: Neutral zone. C: Temperature profile of borehole, measured in July 2014 [29].**




In the case of heat pumps that extract heat from the earth, it is desired that the rocks below ground have a high heat transport capacity so that the heat that comes in contact with the heat exchange well is efficiently supplied. The conductivity can describe a material's steady-state conduction heat transport capacity, $\lambda$ given in W/(m * K) and by the transit conditions for thermal diffusivity, $\alpha$ given in $W/m^2$. Now for convective heat transport, some rock factors can easily cause values of its heat transport capacity to vary even in rock types with similar chemical composition. These factors are the hydraulic conductivity, called permeability, which is measured in m/s, and the effective porosity, which is given in % of the rock. If there is no thermal conductivity measurement, reference tables established by the technical standards of each country are usually reviewed.

The amount of heat flow contributing to the underground heat balance varies significantly depending on the depth. In underground systems close to the surface, within the "neutral zone" of approximately 10 to 20 meters, such as those used in ground heat extraction, heat radiation and water percolation are the sole sources of energy used to offset any thermal deficit or surplus. As a result, the impact of geothermal heat flow must be considered. Only at depths ranging from 20 to 100 meters does the contribution of geothermal heat flow become more significant and predominantly influenced by it.

In this sense, the subsurface within the first 400 meters from the ground surface is a distinctive reservoir for storing and transferring thermal energy. This type of energy, either absorbed or dissipated as heat into this reservoir, is called shallow geothermal energy. The shallow subsurface is a significant source of ambient thermal energy along with surface water bodies and the atmosphere.

A further sub-classification is possible within these 400 meters into which SGE has been classified. First, a zone from the earth's surface to around 10 meters might be called shallow geothermal energy. In this Zone, seasonal temperature fluctuations influence it but diminish rapidly within a few meters underground. The average ground temperatures fluctuate slightly at a few meters' depth, as shown in Figure 4A. This fluctuation implies that geothermal energy from these shallow depths is already an appropriate heat source for heat pumps, providing stable source temperatures even during the primary heating period. Then, a zone called the Neutral Zone is found at a depth of around 10-20 meters, as represented in Figure 4B. There, the temperatures are near the annual average values of the mean air temperature, usually between 9°C and 10°C in most regions of northern Germany. Finally, below the Neutral Zone depth, the temperature in northern Germany rises at an average of about 3°C per 100 meters (Fig. 4C), called a geothermal gradient [29].

### 2.2 Shallow geothermal heat pumps technologies

Geothermal heat can be exploited for heat pump systems through closed or open geothermal systems. In closed geothermal systems, a heat transfer medium is circulated in pipes inserted into the ground through boreholes without directly contacting the ground. This method includes geothermal probes, collectors, and thermally activated green building components. The heat transfer medium absorbs the thermal energy from the ground and typically uses liquid mixtures of water and ethylene or propylene glycol as well as carbon dioxide or propane. Antifreeze and additives are often added to these liquid mixtures to prevent corrosion and biofilm growth.

In open geothermal systems, water is extracted from the ground through one or more well bores and then returned to the ground via additional bores or an infiltration system after extracting the heat. These are known as geothermal well systems. The hydraulic and chemical parameters of the subsoil are essential considerations for the effectiveness and sizing of an open geothermal system. Parameters such as the water permeability of the aquifer, distance to the groundwater table, and chemical composition of the water are crucial in this regard.

#### 2.2.1 Open geothermal system: geothermal well production systems

In Geothermal well production systems in shallow geothermal energy, like the one represented in figure 5, the depth of the wells depends on the aquifer's nature and the location of the groundwater surface. For efficient energy use, the ground level (the difference between the top of the ground and the groundwater level, as per DIN 4049-3) should not exceed 5-10 m at the site [29]. A minimum distance from the ground should be provided to allow the cooled water to drain, as the groundwater surface tends to rise around the absorption well. The subsoil's ability to absorb water determines the required floor distance. The technical data of the heat pump provides the necessary volume flow (the amount of water from the heat source). A pumping test is usually carried out to determine whether the water volume required for the heat pump is available. A yield of a few cubic meters of groundwater per hour is required for heating and cooling one to two-family homes. During construction, a sufficient distance must be maintained to prevent the cooled water from the absorption well from re-entering the production well area [29].

**Figure 5. geothermal well production system Credits to: Olymp [30][30].**

### 2.2.2 Closed geothermal system: ground source heat pumps

Ground source heat pumps (GSHPs) work by taking advantage of the ground's relatively constant temperature, typically between 10°C to 16°C year-round, to provide heating, cooling, and hot water for a building. GSHPs have three main components: the ground loop, the heat pump unit, and the system to distribute the gained heat.

Horizontal collectors are ground loop systems of pipes buried in the ground and filled with a water and antifreeze solution that circulates between the ground and the heat pump unit. The pipes can be installed vertically, called Borehole Heat Exchangers (BHE), or horizontally in the ground, and they will be called collectors. Depending on available space and the specific needs of the building, either horizontal or vertical collectors can be installed. The system of pipes absorbs heat from the ground during the winter months and rejects heat from the ground during the summer months.

The heat pump unit extracts heat from the ground loop and transfers it to the building as warm air, hot water, or radiant heat. In cooling mode, the heat pump unit reverses the process, extracting heat from the building and rejecting it to the ground loop.

The distribution system is how the heated or cooled air or water is distributed throughout the building. This can be in the form of air ductwork, radiators, underfloor heating for water, or a combination of both. Several factors can influence the efficiency and effectiveness of a GSHP system, including:

- The size and orientation of the building. The size and orientation of the building can affect the heating and cooling load, which in turn affects the size and capacity of the GSHP system required.
- The design and installation of the ground loop. The design and installation of the ground loop can affect its efficiency and performance. Proper sizing, depth, and spacing of the pipes are essential for maximizing the heat transfer between the ground and the heat pump unit.
- The efficiency of the heat pump unit. The efficiency of the heat pump unit can vary depending on the type and model. It is essential to choose a unit with a high coefficient of performance (COP) to ensure efficient operation.
- Climate and ground conditions. Climate and ground conditions can affect the performance of the ground loop. In areas with colder climates, the ground may freeze, which can affect the heat transfer process. Ground conditions such as soil type and moisture content can also affect the efficiency of the ground loop. In this sense, the heat consumption of a building can be satisfied with a geothermal system of different capacities. This variation depends on the location of the building and the underground type of rock.

### 2.2.3 Closed geothermal systems: probes or borehole heat exchangers

Geothermal probes or BHE, as shown in Figure 6, are closed pipe systems filled with a heat transfer medium that are inserted into a borehole and surrounded by filling material. There are three commercially available geothermal probes: single and multiple U-probes, coaxial probes, and direct evaporation probes. Single U-probes are U-shaped bent pipe loops, while multiple U-probes are bundled U-shaped pipe loops through which the heat transfer medium is circulated with a circulation pump. Coaxial probes are "tube-in-tube" systems consisting of an outer closed tube and a slightly shorter inner tube that is open at the bottom. Direct evaporation probes use a heat transfer medium that undergoes a phase change between liquid and gaseous inside the probe. Metal pipes are usually used for direct evaporation probes.

When planning a borehole heat exchanger system, it is essential to avoid undersized as it can reduce the system's efficiency and cause freeze-thaw cycles that damage the geothermal system and the environment. The quality of the borehole and the installation of the borehole heat exchanger, including the filling of the borehole annulus, are crucial for the efficiency of the system and groundwater protection. A high-quality filling material with high thermal conductivity should promote the system's efficiency and reduce the risk of undesired frost formation. When selecting a heat transfer fluid with low hazardous substances, groundwater protection should also be considered. The minimum distance between borehole heat exchangers should be at least 5 meters for systems with a heating capacity of up to 30 kWth, and the required distances for larger systems are calculated [29].

**Figure 6. Probes or borehole heat exchangers (BHE). Credits to: Olymp [30].**

### 2.2.4 Closed geothermal system: geothermal collectors

A geothermal heat collector, as depicted in Figure 7, is an underground closed pipe system containing a heat transfer medium, usually installed to a maximum depth of five metres below the frost penetration level. The pipe circuits of the geothermal collector are connected to a heat pump through collector pipes and a distribution shaft. Different types of geothermal heat collectors are available, such as area collectors, direct evaporation collectors, trench collectors, and spiral collectors. These collectors are placed in the soil zone where seasonal climatic changes significantly influence the temperature. The temperature range used in the annual cycle is larger than that of geothermal probe systems.

Horizontal collectors are leveled-laid pipe circuits made of materials such as PE-RC or PE-Xa, through which a heat transfer medium, usually called brine, circulates with the help of a circulation pump. The ground is excavated to a depth of 1.2-1.5 metres [29], and the pipe circuits are then laid horizontally on the subsoil in loops or compact absorber mats. The pipe spacing is usually between 5-80 cm [29], depending on the climate zone, soil, and construction type. The excavated soil is then replaced over the pipe circuits.

**Figure 7. Horizontal collector. Credits to: Olymp [30].**

Direct evaporation collectors use a heat transfer medium that undergoes a phase change between liquid and gaseous within the collector. The difference in density caused by the phase change initiates a circulation of the heat transfer medium in control mode without needing a circulation pump. Plastic-coated metal pipes (e.g., copper) with carbon dioxide ($CO_2$) or propane are usually used as the heat transfer medium [29].

For trench collectors, a trench is dug to a depth of up to 3 m, and the pipe circuits are mounted on the trench wall surfaces and the trench bottom. The trench is then backfilled with the excavated soil. In spiral collectors and geothermal baskets, the pipe circuit is wound into a cylinder or truncated cone, with diameters usually between 0.5 m and approximately 2 m. Due to their compact design, the area required for these collector types is smaller than for surface and trench collectors.

When designing a geothermal collector system, consulting with specialist companies, such as architects and heating and air conditioning specialists, is a good idea, considering several technical factors. The collector should not be built over or under structures, and the soil must be shaded, for example, by trees, to ensure complete soil regeneration. The range of the horizontal thermal influence is generally smaller than in the case of geothermal probe collectors, so a distance of one metre to the property line or other structures is sufficient for surface and trench collectors and a distance of two metres for spiral collectors and geothermal baskets.

Up to this point, the different shallow geothermal systems that can be implemented in urban systems have been explained. To summarize the information shared, table 1 mentions the type of technology, the depth at which they operate, the temperature underground with which the working fluid will interact, and the advantages and disadvantages of each technology.

**Table 1. Comparison of shallow geothermal heat pumps technologies [29].**

| Technology | Depth (m) | Underground operating temperatures | Advantages | Disadvantages |
|---|---|---|---|---|
| Horizontal Collectors | 1.2-1.5 | 3°C to 20°C, depending on the climate and soil conditions. | Are relatively easy to install and require minimal excavation work, which makes them more cost-effective compared to other systems. | Require a large amount of land for installation, which can be challenging in urban areas or on small properties. |
| Basket Collectors | 1.5-5.0 | typically operate at temperatures between 5°C and 15°C. | Are also easy to install, requiring much less area than horizontal collectors, and can be integrated into existing landscaping, making them a good choice for residential applications. | May require periodic maintenance to prevent clogging due to leaves or other debris. |
| Borehole heat exchangers | 40 - 400 | typically operate at temperatures ranging from 10 °C to 25°C, but can also reach higher temperatures of up to 35°C in cases, where the rock has good heat conduction properties and the BHE is exploiting its maximum heat potential. | Have a smaller footprint compared to horizontal collectors and basket collectors, and can be used in areas with limited space. They also provide higher heating and cooling efficiency due to the greater depth of the heat exchange pipes. | Can be more expensive to install due to the drilling process, which can also cause disruption to the surrounding area. Leakages might be difficult to find and handle. Additionally, the initial installation costs may be higher than other systems, but the long-term energy savings can offset the cost. |

### 2.2.5 Aerothermal heat pump systems

Due to this study will also cover a comparison between aerothermal and geothermal heat pump systems, fundamental principles of aerothermal heat pumps are covered in this section. Thus, an air-to-water heat pump is a type of heating system that extracts heat from the outdoor air and transfers it into the water for use in space heating and domestic hot water. A representation of an air/water heat pump system is depicted in figure 8.

The outdoor unit contains a compressor, a heat exchanger, and a fan. The fan draws in air from outside and passes it over the heat exchanger, which contains a refrigerant that absorbs heat from the air. The refrigerant is then compressed, which raises its temperature even further. The hot refrigerant is passed through a heat exchanger in the indoor unit, transferring its heat to the water circulated through the system. The water is then circulated through radiators or underfloor heating pipes to provide space heating and through a hot water cylinder to provide domestic hot water. The refrigerant, now cooled down, is passed through an expansion valve, which lowers its pressure and temperature, and it is then returned to the outdoor unit to begin the process again.

**Figure 8. Aerothermal heat pumps. Credits to: Olymp [30].**

The critical components of an air-to-water heat pump system include the following:

- Outdoor unit: This contains the compressor, heat exchanger, and fan that extracts heat from the air.
- The indoor unit contains the heat exchanger where the refrigerant transfers heat to the water.
- Distribution system: This includes radiators, underfloor heating pipes, and a hot water cylinder that circulate the heated water throughout the building.
- Controls: These manage the system's operation, including the compressor and fan speed, and can be programmed to optimize efficiency and comfort.

Air-to-water heat pumps are becoming an increasingly popular choice for heating homes and buildings, especially in areas with moderate winter temperatures. They are energy-efficient, quiet, and can provide both space heating and domestic hot water. However, they may not be suitable for very cold climates, as the system's efficiency decreases as the outdoor temperature drops.

# Chapter 3 Methodology

## 3.1 Model overview

In order to address the research questions, the implemented methodology follows four steps. Figure 10 is a summarized representation of each stage.

The first step is collecting data. It was mainly three sources. The first one was open-source map files with geographic information about the infrastructure of Oldenburg's city; the second one was LBEG data about the heat potential of the city and the water restrictions; and the third one was essential technical data from the related literature review.

The second step consists of geoprocessing the data for each district by employing an open-source data tool called FlexiGIS [9]. The tool stands for Flexibilization in Geographic Information Systems (GIS). FlexiGIS has a "plug-in" that can be added to the QGIS toolbar. Though FlexiGIS has many capabilities, this research helped establish the underlying urban energy infrastructure and simulate urban energy consumption. The first process is to download the raw OpenStreetMap (OSM) data from the OSM database for the city of Oldenburg. Then, implementing a java tool called "osmosis", OSM datasets are filtered for the 31 districts of the city, and the urban infrastructure is settled implementing different OSM elements like land use, buildings and highways, as depicted in

Figure 9, Figure 11 and Figure 12.

The OSM buildings are represented as polygons, while streets as lines. Buildings are categorized based on their portfolios and type of usage into five classes: agricultural, commercial, educational, industrial or residential.

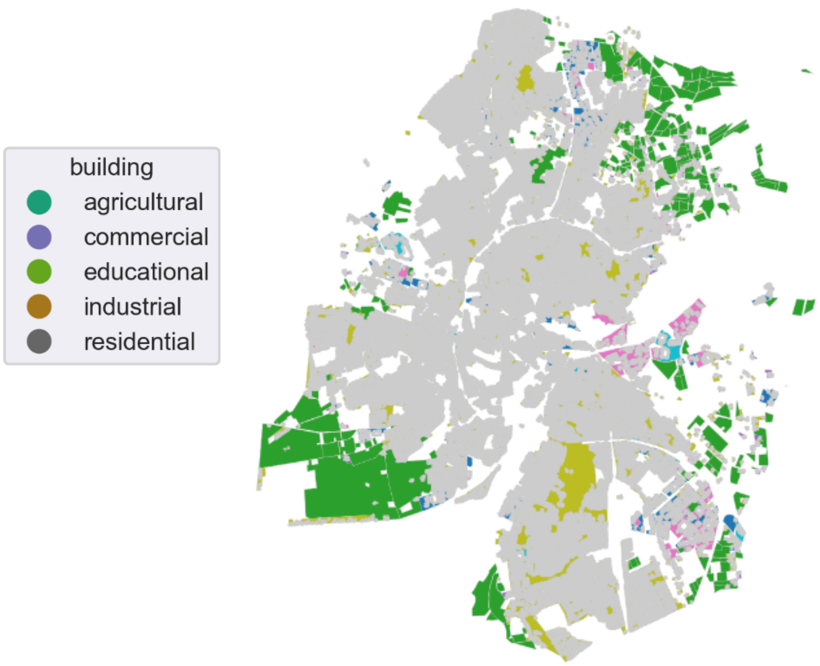



**Figure 9. Extracted OpenStreetMap land use datasets of Oldenburg's city [14].**

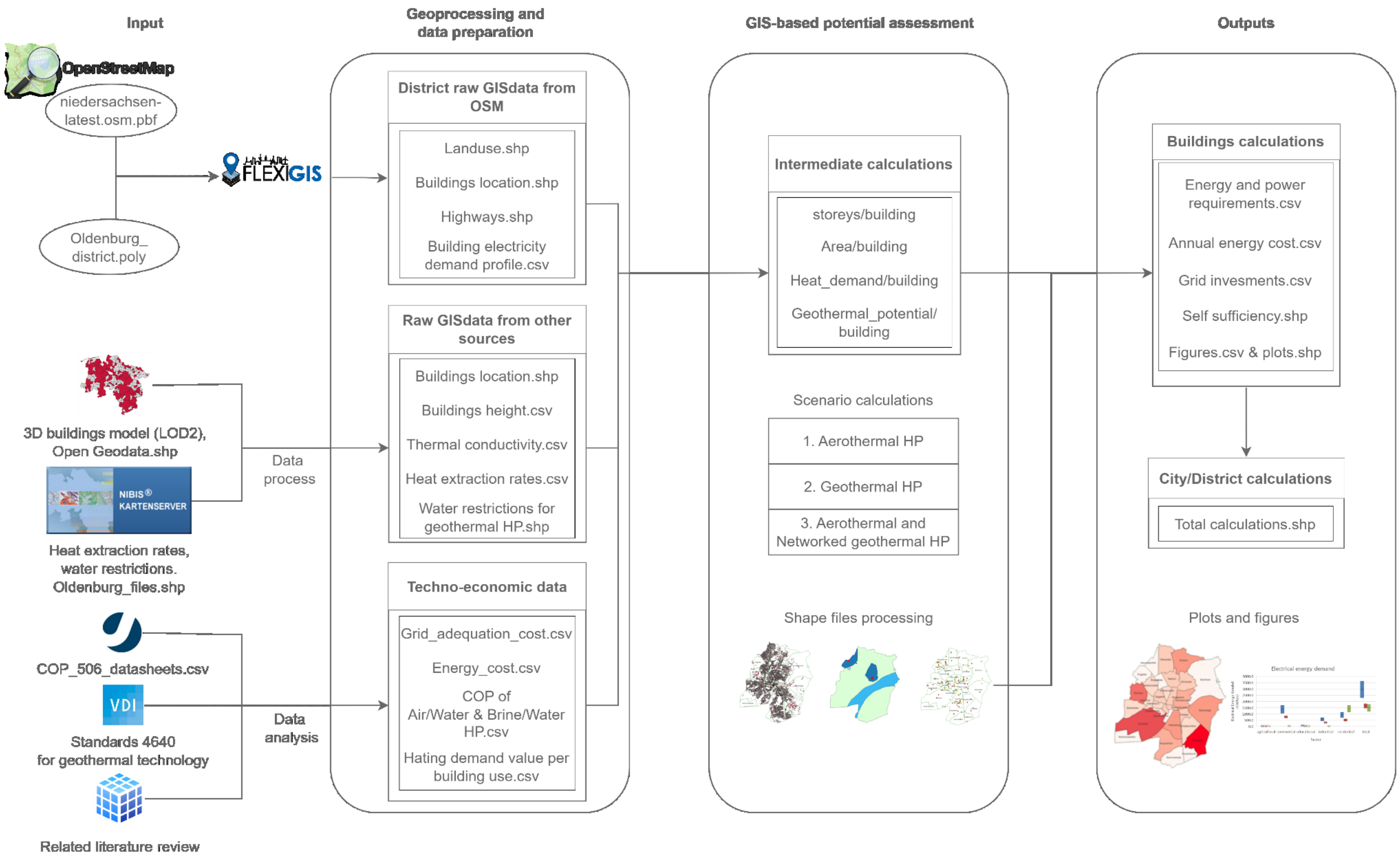



**Figure 10. Steps followed in the proposed Methodology**

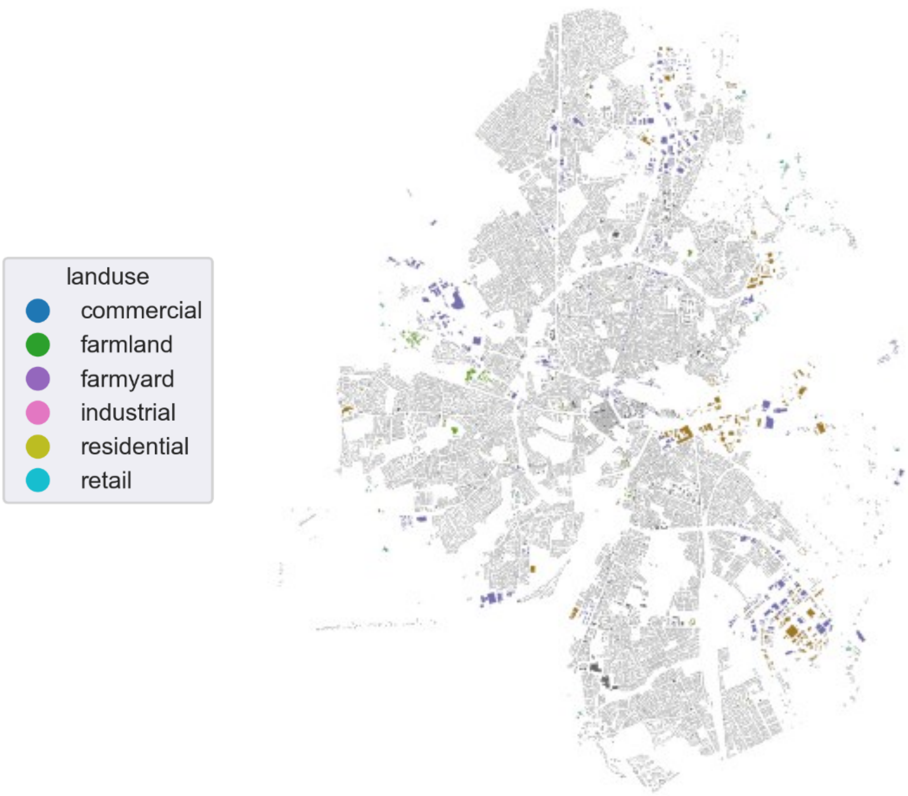



**Figure 11. Extracted OpentrStreetMap buildings infrastructures of Oldenburg city [14].**


**Figure 12. Extracted OpenStreetMap roads infrastructure of Oldenburg's city [14].**

Another important datasets are the 3D building models from the OpenGeoData [27]. It provides standardised roof shapes (gable roof, hipped roof) in Level of Detail 2 (LOD 2) [31]. Using this data it is possible to extract the height of each building and add it to the shape files that FlexiGIS generates.

Once the infrastructure of the city of Oldenburg has been established, using the shape files provided by LBEG, it is possible to proceed with adding data related to the thermal energy extraction potential in the area, as well as land use restrictions for implementing geothermal heat extraction technologies.

At this point, information is available about the geo-referenced position of all buildings in the city, the type of use of the building, its height, the heat extraction rate at its location, and whether the building is located in a place where a shallow heat collector cannot be installed.

The related literature review obtained vital information about the heat consumption values according to the type of building used. This information was relevant for assigning the estimated annual square meter demand to each building.

The third step stands for doing intermediate calculations to obtain heat energy consumption and geothermal potential per building. To obtain the heat consumption the first step is calculating the number of floors of the building [32], using the formula described in equation 3.1.

$$\boldsymbol{n_i[storey] = 0,32\left[\frac{storey}{m}\right] * (h_i - 2,5)[m]} \quad \textbf{[3.1]}$$

$n_i$ represents the number of floors per building. 0.32 is the result of dividing 1 over 3.125 meters, which corresponds to the average value per floor [32]; $h_i$ reflex the height of the building in meters; and 2.5 m corresponds to the value needed to correct the real height of the building without the roof. For the cases where the buildings were flat, it was necessary to filter out all buildings with flat roofs, according to the classification made by CityGML [33] and the 3D-Gebäudemodelle, Level of Detail 2 (LoD2) [34].

Due to the fact that in Germany any building with a height of less than 2.2 meters is not considered a building, all polygons with a height of less than 2.2 meters were discarded from the present study.

Once the number of storeys $n_i$ of the building $i$ is known, the value of the total area of the building $A_i$, is calculated by multiplying the number of storeys by the area of the polygon $a_i$, as specified in equation 3.2.

$$\boldsymbol{A_i = a_i[m^2/storeys] * n_i[storey]} \quad \textbf{[3.2]}$$

The heat consumption per building is calculated according to equation 3.3, by multiplying the annual heat consumption of the building according to its building category $d_j$[2], multiplied by the total building area $A_i$.

[2] Using as reference the consumption values (dj) developed by the University of Stuttgart's Institute of Economics and the Rational Use of Energy (IER) [46].

$$D_{ij}[kWth\ h] = A_i[m^2] * d_j\left[\frac{kWth\ h}{m^2 * a}\right] \quad [3.3]$$

According to VDI standard 4640 part 2, to supply space heat and hot water, an average heat pump operation of 2400 hours per year is required [35]. Hence, the calculation specified in equation 3.4. is considered to find the thermal power $\dot{Q}_{ij,\,th}$ required to supply the thermal energy

$$\dot{Q}_{ij,th}[kWth] = \frac{D_{ij}\left[\frac{kWth\ h}{m^2 * a}\right]}{2400\left[\frac{h}{a}\right]} \quad [3.4]$$

To calculate district or city values, a simple summation of the geolocated building heat consumptions per district, or of all buildings in the city is performed as indicated in equation 3.5.

$$\dot{Q}_{City/district,hp}[\ kW_{th}] = \sum \dot{Q}_{ij,th}[\ kW_{th}] \quad [3.5]$$

Then, considering that each building has a specific demand, it is possible to calculate the average electrical power of each building using the performance coefficient of the heat pump to be implemented, both for air-to-water heat pumps, $\dot{Q}_{ij,Pel\_ath}$, and for brine-to-water heat pumps $\dot{Q}_{,Pel_{geoth}}$, as shown in equation 3.6.

$$\dot{Q}_{ij,Pel\_geoth/ath}[W] = \frac{\dot{Q}_{ij,th}\ [kW]}{COP_{ij,geoth/ath}} \quad [3.6]$$

The concept of average power demand emphasises that the power required by the heat pumps has been calculated for stable operating points. The power demand at the starting operation points of each compressor motor has yet to be considered. For this reason, we speak of average power demand, which may have a minimum and maximum value depending on the COP used to do the calculation.

With the average power value of the heat pumps, it is possible to calculate the electrical energy consumed, over the suggested average running time period for space heat and hot water supply of 2400 hours per year, as shown in equation 3.7.

$$Q_{ij,e\_el\_geoth/ath}[Wh/a] = \dot{Q}_{ij,Pel\_geoth/ath}\ [W] * 2400\left[\frac{h}{a}\right] \quad [3.7]$$

Finally, the output variables, diagrams and plans corresponding to each scenario are established. At this point, it is important to clarify that the space required for its implementation was established as a criterion for selecting the geothermal energy extraction system. Since this study raises the possibility of installing geothermal heat pumps in urban areas, evaluating the space it would occupy and the fulfilment of the technical requirements for its installation is of high relevance.

To calculate the required area for each type of installation per building, it is requested to calculate the heat exchanger thermal power $\dot{Q}_{ij,\,Evap}$ per building $i$, with heat consumption $j$ from the average thermal power $\dot{Q}_{ij,\,th}$ demanded, and the performance coefficient of the geothermal heat pump. For this purpose, equation 3.8 is used.

$$\dot{Q}_{ij,\,Evap} = \dot{Q}_{ij,\,th}\left(1 - \frac{1}{COP_{ij,geoth}}\right) \quad [3.8]$$

As mentioned in the scope of the study, this research covered three heat exchange technologies: Basket, horizontal and vertical heat collectors or borehole heat exchangers (BHE). The next section will explain how to estimate requested areas for these systems.

### 3.1.1 Calculation of area for basket collector systems

To find the area of the baskets, according to the specifications mentioned in VDI 4640 part 2 [35], there must always be a distance between their centroids of at least 4 meters, as shown in figure 13. A bigger or smaller basket depends mainly on the heat potential underground. What varies for each system is the heat extraction rate $\dot{h}_{ik,bas}$ per basket $k$ at building $i$, which depends mainly on the ambient temperature, considering that it is a technology that is at most 2 meters underground[3], the number of operating hours per year, and the type of rock. The values to be implemented in equation 3.9 to estimate the system area consider typical values of the heat extraction rate per basket for a system located in northern Germany [35].

$$A_{ijk,\,bas,req}[m^2] = 4\left[\frac{m^2}{basket}\right] * \left(\frac{\dot{Q}_{ij,\,Evap}[W]}{\dot{h}_{ik,bas}\left[\frac{W}{basket}\right]}\right) \quad [3.9]$$

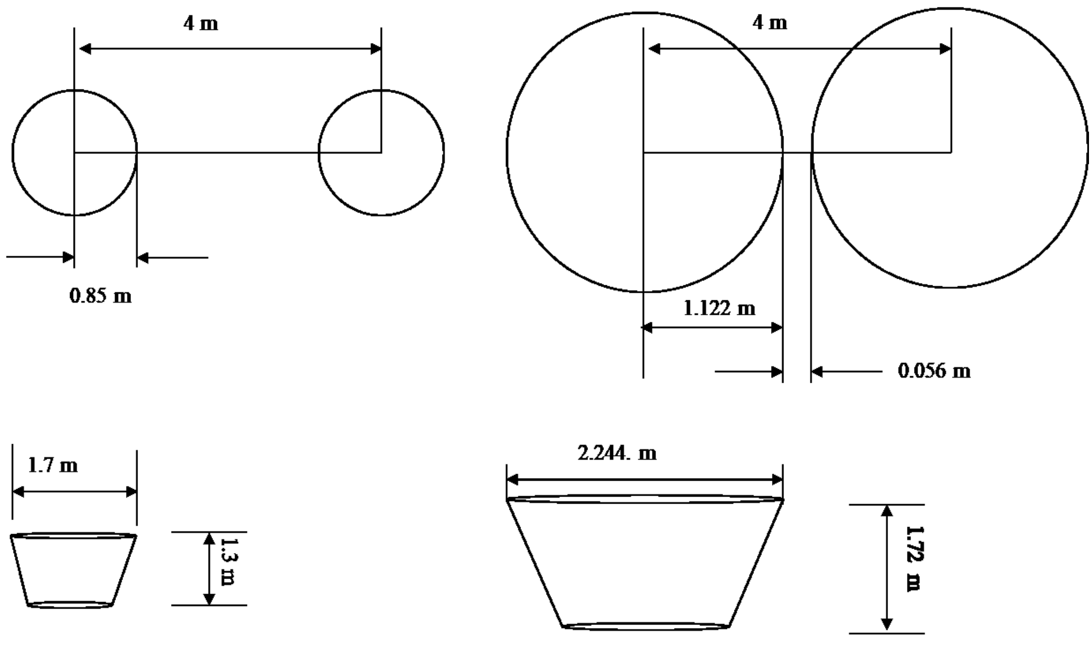



**Figure 13. Basket collector geometry. Left: Possible Geometry and (right) maximum geometry of a basket collector (2023).**

[3] Installing geothermal baskets up to 5 meters depth is possible, but in this study, the 5 m depth is not considered because the study is specifically using VDI 4640 part 2 values, as reference values.

### 3.1.2 Calculation of area for horizontal collector systems

In the case of horizontal heat collectors, the shape files shared by LBEG [36], have information about the heat extraction rate $m$ per square meter $\dot{h}_{ih_e,m}$ in a geo-referenced way. Thus, to calculate the required area for a horizontal system, equation 3.10 is implemented, where dividing the evaporator thermal power $\dot{Q}_{ij,\,Evap}$ over the heat extraction rate, the area of the system is estimated.

$$A_{ijm,\,hor,req}[m^2] = \frac{\dot{Q}_{ij,\,Evap}[W]}{\dot{h}_{h_e,m}\left[\frac{W}{m^2}\right]} \qquad \textbf{[3.10]}$$

### 3.1.3 Borehole heat exchanger systems

Several parameters should be considered to design the required area for BHE. Using VDI 4640 part 2 as a reference, such design requirements are listed below:

- To avoid thermal interaction with other BHE in the immediate vicinity, for heat pumps with a heating capacity of up to 30 kW, the minimum distance among boreholes heat exchangers should be at least 5 m to boreholes of the same system, 10 m to the nearest system, and 6 m distance among BHE for capacities of more than 30 kW.
- For systems with heat pumps of 30 kW or more, the maximum number of BHEs is 5.
- Near-surface geothermal energy goes to a depth of up to 400 m.
- BHE diameters are usually between 30-150 mm.

A schematic representation of the mentioned requirements is depicted in Figure 14.

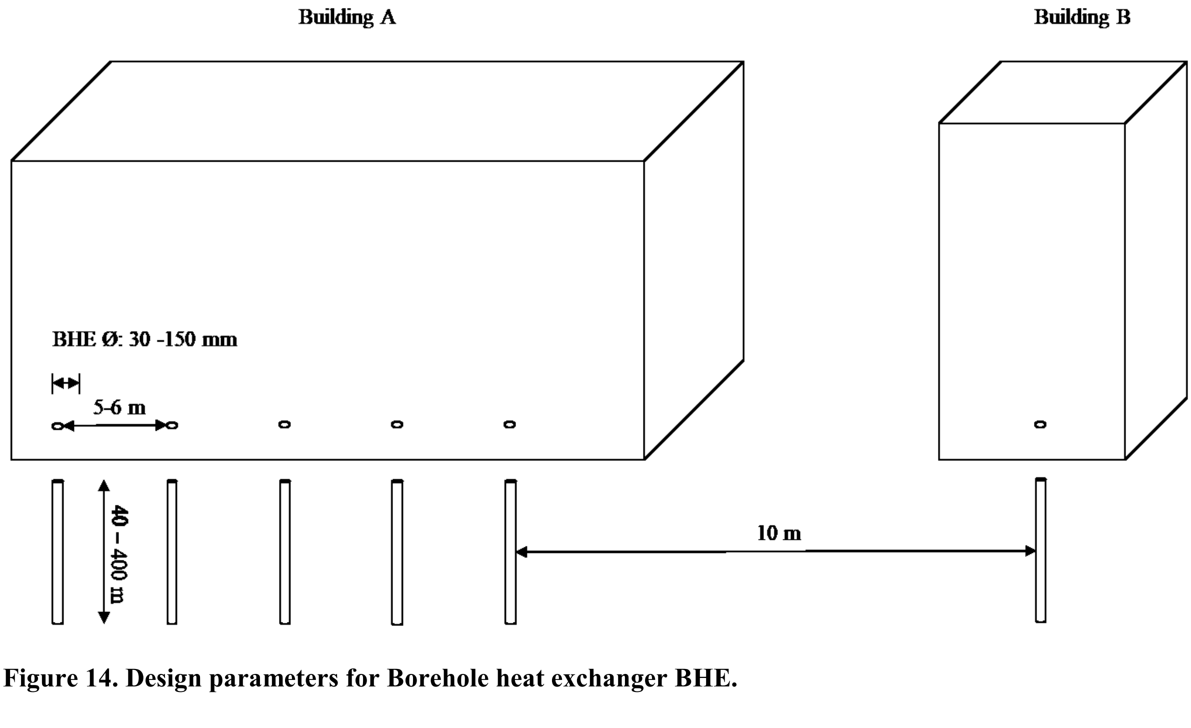



**Figure 14. Design parameters for Borehole heat exchanger BHE.**

A top view of these requirements, like the one presented in Figure 15 allows for identifying an ellipse footprint of the requested area for BHE systems. In this sense, the calculation of the area implies considering a maximum number of up to 5 BHE per system, with a maximum BHE diameter $\O_{BHE}$ of 150 mm, and distances of 6 meters between BHE requiring the implementation of heat pumps of more than 30 kW, as well as a distance of 10 meters to the nearest system. These variables are represented in equation 3.11.

$$A_{ijn,\,BHE,req}[m^2] = \pi * (5 + \varnothing_{BHE})[m] * \left(5\frac{d_{bh,ij}[m]}{400[m]} + 1 + \varnothing_{BHE}\right)[m] \quad \textbf{[3.11]}$$

Where the area required $A_{ijn,\,BHE,req}$ for the system of building $i$, with heat consumption $j$, whose installation would require heat to be extracted from a depth $d_{bh,ij}$. However, because only shallow geothermal generation projects are considered, this depth should be divided by 400 m, and the reference value used as the heat extraction rate at 400 m, at the building location, to determine the number of wells that will need to be considered in the system at the building location with a heat extraction rate $\dot{h}_{ijv_e,n}$.

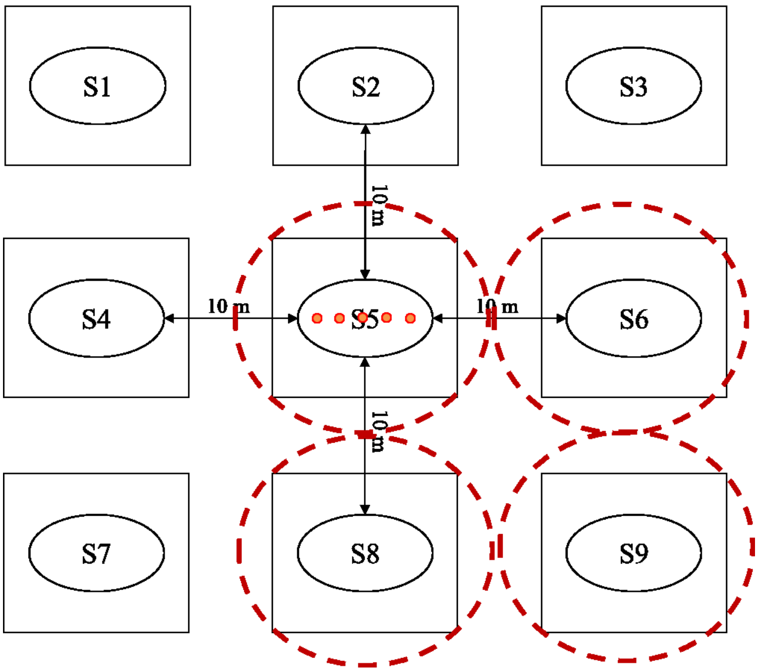



**Figure 15. Top view of BHE systems.**

Equation 3.11 considers the use of the depth $d_{bh,ij}$ of the borehole required to supply the heat consumption $d_{ij}$. To estimate this value, an interpolation of the heat extraction rate $\dot{h}_{ijv_e,n}$ in the district where building $i$ is located has been defined as in equation 3.12.

$$\dot{h}_{ijv_e,n} = \frac{h_{er2} - h_{er1}}{d_{m2} - d_{m1}} * (d_{bh,ij} - d_{m1}) + h_{er1} \quad \textbf{[3.12]}$$

Considering that the LBEG shape files provided geo-referenced information of the heat extraction rate $n$, at depths between 40 and 100 meters, the value of the heat extraction rate at longer depths is estimated using as reference the heat extraction rate at 40 m $h_{er1}$, and the heat extraction rate at 100 m $h_{er2}$, or an estimated value to 100 m, using a thermal energy gradient of 3 W/100 m [4].

[4] The temperature gradient is 3°C/100 m, and considering the linear relation between heat and the temperature delta, $Q = c * m * \Delta T$, this approach was considered to apply at the possible heat to be found underground.

Thus, taking as a reference the equation for estimating the power in the evaporator $\dot{Q}_{ij,\,Evap}$, using heat extraction rate $\dot{h}_{iv_e,n}$, it is possible to identify the depth of the borehole through equation 3.13.

$$\dot{\boldsymbol{Q}}_{\boldsymbol{ij},\,\boldsymbol{Evap}} = \boldsymbol{d}_{\boldsymbol{bh,ij}} * \dot{\boldsymbol{h}}_{\boldsymbol{iv_e,n}} \qquad [3.13]$$

However, as $vh_{ej}$ is also unknown, it is possible to estimate this value by using equation 3.14.

$$\dot{\boldsymbol{Q}}_{\boldsymbol{ij},\,\boldsymbol{Evap}} = \boldsymbol{d}_{\boldsymbol{bh,ij}} * \frac{\boldsymbol{h}_{\boldsymbol{er2}}-\boldsymbol{h}_{\boldsymbol{er1}}}{\boldsymbol{d}_{\boldsymbol{m2}}-\boldsymbol{d}_{\boldsymbol{m1}}} * \left(\boldsymbol{d}_{\boldsymbol{bh,ij}} - \boldsymbol{d}_{\boldsymbol{m1}}\right) + \boldsymbol{h}_{\boldsymbol{er1}} \qquad [3.14]$$

From Equation 3.14 by solving for $d_{bh,ij}$, as shown in Equation 3.15, it is possible to obtain the depth required to satisfy the heat consumption of building $i$.

$$d_{bh,ij} = -\left(\frac{-d_{m1}+h_{er1}\frac{d_{m2}-d_{m1}}{h_{er2}-h_{er1}}}{2}\right) + \sqrt{\left(\frac{-d_{m1}+h_{er1}\frac{d_{m2}-d_{m1}}{h_{er2}-h_{er1}}}{2}\right)^2 + \dot{Q}_{ij,\,Evap} * \frac{d_{m2}-d_{m1}}{h_{er2}-h_{er1}}} \qquad [3.15]$$

### 3.1.4 Exemplary calculations and contrast with real values

In order to exemplify and give clarity to the calculations that have been made here, the following is a step-by-step explanation of the calculations that we have made for a 150 square meters polygon, with a height of 9 meters, and a roof type with a hipped roof, located in a residential area.

The first step is estimating the number of storeys of the building according to equation 1. To this purpose, it is used the height of the building, and the roof classification:

$$n_i[storey] = 0{,}32\left[\frac{storey}{m}\right] * (9 - 2{,}5)[m] = 2.08 \approx 2\ storeys$$

The result, means the house would have 2 storeys. The height of 2.5 m above the two storeys and the decimal values obtained when calculating the number of levels belongs to the roof structure.

Subsequently, the value of the total area of the building $A_i$, is calculated according to equation 3.2, by multiplying the number of storeys $n_i$ by the area of the polygon $a_i$:

$$\boldsymbol{A}_{\boldsymbol{i}} = \boldsymbol{a}_{\boldsymbol{i}}\left[\frac{\boldsymbol{m}^{\boldsymbol{2}}}{\boldsymbol{storeys}}\right] * \boldsymbol{n}_{\boldsymbol{i}}[\boldsymbol{storey}] = \boldsymbol{150}\,\frac{\boldsymbol{m}^{\boldsymbol{2}}}{\boldsymbol{storeys}} * \boldsymbol{2}[\boldsymbol{storey}] = \boldsymbol{300m^2}$$

Because the polygon is described for being a residential building with 150 m$^2$, with 2 storeys, and is a building not located in the historical center of the city, where usually buildings have the worst isolation, the assigned heat consumption would be: 62.6 $\frac{kWth\,h}{a}$ [32].

Then, using equation 3.3, the heat consumption of the whole building is calculated:

$$D_{ij}[kWth\,h] = 300m^2 * 62.6\frac{kWth\,h}{m^2 * a} = 18{,}780\frac{kWth\,h}{m^2 * a}$$

With the heat consumption, it is also possible to find the average thermal power $\dot{Q}_{ij,\, th}$ required to supply the thermal energy, as stated in equation 3.4:

$$\dot{Q}_{ij,th}[kW_{th}] = \frac{18{,}780 \left[\frac{kW_{th}\, h}{m^2 * a}\right]}{2400 \left[\frac{h}{a}\right]} = 7.8\ kW_{th}$$

Once the heat consumption is calculated, it is possible to estimate the requested area for each type of system investigated in this master thesis. To do that, the first step is assigning an estimated COP value for the heat pump. Because, the requested heat has a value with less than 10 $kW_{th}$, from the data base of COP [37], it is possible to consider an average value for the range of heat pumps from 1 to 10 kW of 3.1. Then, it is possible to calculate the heat capacity in the evaporator, according to equation 3.8, as follows:

$$\dot{Q}_{ij,\,Evap}[kW_{evap}] = 7.8kW_{th}\left(1 - \frac{1}{3.1}\right) = 5.2kW$$

From this point, it is possible to estimate the area of the three systems:

- Basket collector area: Calculated according to equation 3.9. Here the heat extraction rate per basket $\dot{h}_{ik,bas}$ has been selected assuming the rock underground is Sandy Clay.

$$A_{ijk,\,bas,req}[m^2] = 4\frac{m^2}{basket} * \frac{5.2kW}{0.5\left[\frac{kW}{basket}\right]} = 40\ m^2$$

- Horizontal collector: Calculated according to equation 3.10. Assuming the same type of rock, then the maximum heat extraction rate per square meter $h_{\dot{he},m}$ according to LBEG will be applied.

$$A_{ijm,\,hor,req}[m^2] = \frac{5.2kW}{40\left[\frac{W}{m^2}\right]} = 130m^2$$

- Borehole heat exchanger: The first step is, consistent with equation 3.15, finding how deep the borehole of the system should be in order to cover the heat consumption. To this aim, two heat extraction rates at different depth will be assumed from the district with the best heat extraction rates in Oldenburg.

$$d_{bh,ij} = -\left(\frac{-40m + 0.03\frac{W}{m}\frac{(100-40)m}{(0.04-0.03)\frac{W}{m}}}{2}\right) + \sqrt{\left(\frac{-40m + 0.03\frac{W}{m}\frac{100m-40m}{(0.04-0.03)\frac{W}{m}}}{2}\right)^2 + 5{,}2kW\frac{(100-40)m}{(0.04-0.03)\frac{W}{m}}}$$

$$d_{bh,ij} = -70m + \sqrt{(70m)^2 + 31.200m^2} = 120m$$

If the depth of the BHE would be deeper than 400 m, this value should be divided by 400 m, so that, the number of BHE required to cover the heat consumption.

In this example the heat consumption would be covered by a BHE of 120 m. Using this value, it is possible to estimate the area of the system by using the equation 3.11.

$$A_{ijn,\,BHE,req}[m^2] = \pi * (5 + 0.150)m * \left(5\frac{120m}{400m} + 1 + 0.15\right)m = 4{,}93m^2 \approx 5.0m^2$$

As final results, the following areas were estimated:

- Basket collector: 40 $m^2$
- Horizontal collector: 130 $m^2$
- Borehole heat exchanger: 5 $m^2$

These areas will help the owner of the project to consider which system will fix better in her (his) case.

Then, the specification of the heat pumps is also possible to be estimated. To do that, the first step is calculating the heat pump power. Because there are two possibilities, aerothermal or geothermal heat pumps, the example will start by aerothermal heat pumps, and then for geothermal heat pumps.

- Aerothermal heat pumps: $\dot{\boldsymbol{Q}}_{\boldsymbol{ij,Pel\_ath}}[\boldsymbol{W}] = \frac{\dot{Q}_{ij,th}\,[kW]}{COP_{ij,ath}} = \frac{7.8kW}{2.1} = \mathbf{3.7}\boldsymbol{kW}$
- Geothermal heat pumps: $\dot{\boldsymbol{Q}}_{\boldsymbol{ij,Pel\_geoth}}[\boldsymbol{W}] = \frac{\dot{Q}_{ij,th}\,[kW]}{COP_{ij,geoth}} = \frac{7.8kW}{3.1} = \mathbf{2.5}\boldsymbol{kW}$

With the average power value of the heat pumps, it is possible to calculate the electrical energy consumed, over the suggested average running time period for space heat and hot water supply of 2400 hours per year as follows:

- Aerothermal heat pumps: $Q_{ij,e\_el\_ath}[Wh/a] = \dot{Q}_{ij,Pel\_ath}\,[W] * 2400\left[\frac{h}{a}\right]$

$$Q_{ij,e\_el\_ath}[Wh/a] = 3.7\ kW * 2400\frac{h}{a} = \frac{8.9MWh}{a}$$

- Geothermal heat pumps: $Q_{ij,e\_el\_geoth}[Wh/a] = \dot{Q}_{ij,Pel\_geoth/}\,[W] * 2400\left[\frac{h}{a}\right]$

$$Q_{ij,e\_el\_geoth}[Wh/a] = 2.5\ kW * 2400\frac{h}{a} = \frac{6MWh}{a}$$

As a result, it has been found that to supply the same heat, a geothermal pump may require 2.5 kW, while an aerothermal heat pump may require 3.7 kW. It means less grid power, about 1.2 kW, and energy savings of 3.9 MWh/a. With these estimations, somebody interested in implementing heat pumps to meet the heat consumption of their household can best define the type of system, considering energy savings and installation costs. In the case of an aerothermal system, the whole installation may be are around 10,000 to 20,000 euros less expensive than geothermal systems. However, the lifetime of geothermal systems can reach up to 50 years, while aerothermal systems last between 10 and 15 years.

### 3.2 Scenarios definition and case study


**Figure 16. Oldenburg city and limitation of its 31 districts.**

In order to answer the research questions posed in section 1.4, as a case study three scenarios in the city of Oldenburg will be analyzed. The city of Oldenburg is located at coordinates 53°08′38″N 8°12′50″. By December 2022 had a population of 173,987 inhabitants, with an area of 10,321 Ha [38], with 31 districts distributed as depicted in Figure 16.

The scenarios to be investigated in this master thesis are represented in Figure 17 and explained in detail as follows:

- **Scenario 1:** Heat supply to buildings with decentralized aerothermal heat pumps.
- **Scenario 2:** Heat supply to buildings with decentralized geothermal heat pumps.
- **Scenario 3:** Heat supply with aerothermal heat pumps, in restricted areas for installing geothermal heat pumps, and networked geothermal heat pumps.

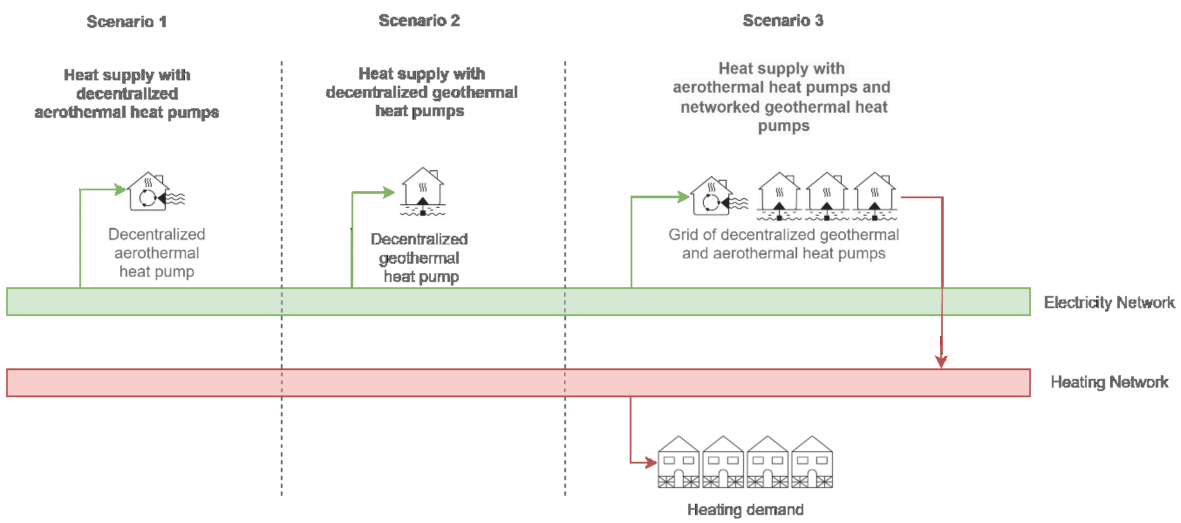



**Figure 17. Scenarios to be investigated**

### 3.2.1 Scenario 1: Heat supply to buildings with decentralized aerothermal heat pumps

The first scenario, which will be used as a comparative reference, corresponds to the supply of heat to buildings in the city through aerothermal heat pumps. The main reason to consider this scenario is the high popularity of this technology in Europe in recent years. According to the numbers mentioned by the IEA [39], as shown in Figure 18, in 2021, heat pump sales increased by more than 13% globally". The European Union was the region with the most significant proportion increase, and the most major markets were France, Italy and Germany, with sales growing around 35% yearly and exceeding 2.2 million units.

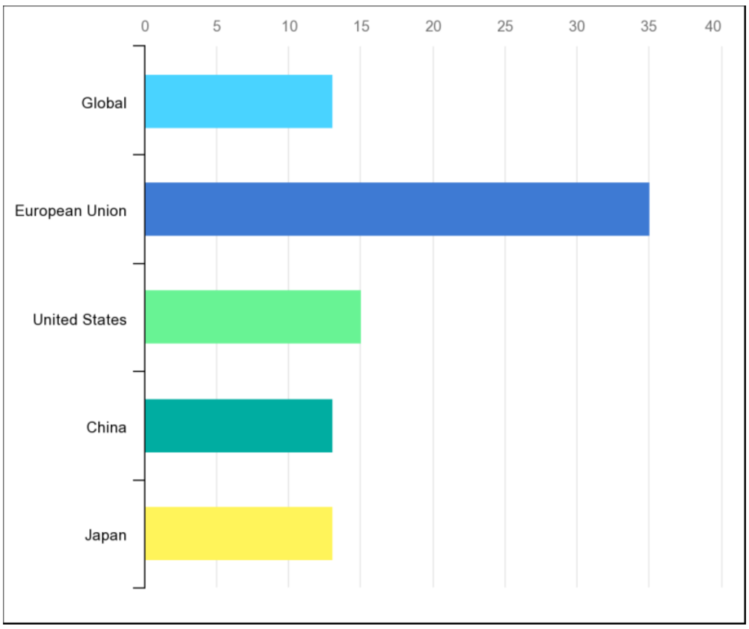



**Figure 18. Increase in heat pumps sales in selected regions, 2021 relative to 2020**

Additionally, Air to water heat pumps is the majority of sales globally, with a market share of more than 60% in 2021 [39]. Due to the high prices and the risk of gas shortages in the German energy matrix in the near future, thermal improvement projects for buildings and new constructions are implementing aerothermal heat pumps because they are easier to install and more economical than geothermal heat pumps. However, these heat pumps are less efficient than ground-source heat pumps, so we intend to analyze the average power and electrical energy that would be added to the distribution network of Oldenburg. This extra demand will allow us to estimate the increased energy and the required investments for grid adaptations to implement this solution.

### 3.2.2 Scenario 2: Heat supply to buildings with decentralized geothermal heat pumps

The second scenario will focus on implementing decentralized brine/water heat pumps. This scenario will analyze three technologies that allow taking advantage of shallow geothermal energy. The three heat exchanger technologies are basket collector systems, horizontal collector systems, and BHE. For this scenario, it is particularly relevant to analyze the possible restrictions that may result from the use of underground water according to the German Water Management Act (WHG) in conjunction with the federal state Water Acts and the derived administrative regulations that apply. For this purpose, the data provided by LBEG on land use restrictions for the installation of BHE or thermal energy collectors will be reviewed. Additionally, possible restrictions for the use of technologies according to the Guide to the use of geothermal energy in Lower Saxony Legal and technical principles [40] and the restrictions mentioned by VDI 4640 part 2 [35], where it mentions that for systems with heat pumps of more than 30 kW, a maximum of 5 BHE can be installed, with a depth of up to 400 m, will be considered. Implementing this scenario will allow essential conclusions to be drawn about the relief to the electricity grid that implementing this solution would imply compared to aerothermal heat pumps.

### 3.2.3 Scenario 3: Heat supply with aerothermal heat pumps, in restricted areas for installing geothermal heat pumps, and networked geothermal heat pumps

The third scenario proposes to analyze the optimal implementation of aerothermal heat pumps installed in those places where, due to WHG regulation, it is not possible to SGE in conjunction with a network of decentralized geothermal heat pumps with BHE that exploit the maximum potential they could have, at a depth of 400 m, and with the capacity to supply thermal energy to neighbouring buildings. As a result of this scenario, full coverage of the city's energy consumption is expected, a heat supply coupled to the electricity grid, with lower investment requirements in the distribution network, as well as the ability to provide a high percentage of self-sufficiency in the city's thermal energy supply.

It is emphasized that these are decentralized heat pumps to avoid confusing this solution with the implementation of thermal districts, where a single system, usually fueled by fossil fuels or with a cogeneration system (CHP), is responsible for heat generation, and heat distribution to the buildings is carried out through a network of pipes that transport hot water. The solution proposed here considers several shallow wells, i.e. up to 400 meters deep, distributed throughout the city, which will supply heat to the nearest neighbouring buildings.

### 3.3 Data collection

The present study requires the provision of three types of information, urban geo-datasets that facilitate the establishment of the infrastructure of the city of Oldenburg; heat extraction potential of the Oldenburg's city; and relevant information on shallow heat pump technology that will allow the establishment of the calculations necessary to answer the research questions.

#### 3.3.1 Urban geo-datasets

i. **OpenStreetMap (OSM) data [14]:** is open source data, free to use for any purpose, with the conditions of properly crediting OpenStreetMap and its contributors. Based on OSM data, FlexiGIS extracts and classify the data to be used in the next steps.

ii. **Open Geodata from Niedersachsen [27]:** Open sourced data, with a 3D building model with LOD2 of the city of Oldenburg. According to the CityGML Conceptual Model, explained by OGC in the 3.0 Conceptual Model Users Guide [41], buildings are represented differently. Each way of representing buildings differs in the level of detail of the building. As the level of detail increases, the number of objects considered to describe the building rises. Two-dimensional drawings represent the LOD0. LOD1 is represented only by three-dimensional volumes, but without considering the shape of the roof of each building. The LOD2 considers the height of the roofs and their shapes. LOD3 has a higher level of detail than LOD2, representing windows, doors, and roof shapes. For a better interpretation of the above LODs, see the Figure 19.

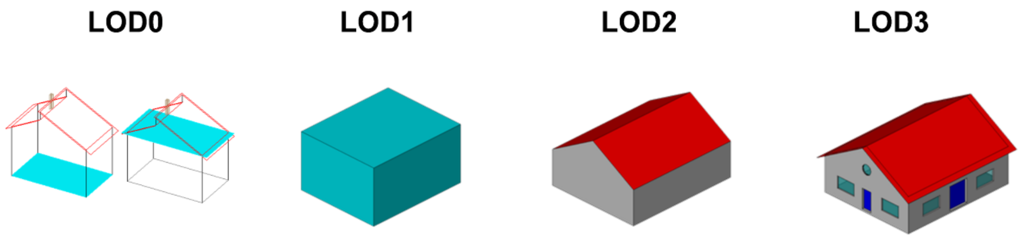



**Figure 19. Representation of buildings according to Levels of details 0-3 (© OGC) [41].**

Figure 20 displays the 45,973 3D buildings in the city of Oldenburg. It should be noted that, according to German regulations, only buildings that exceed a height of 2.2 m are considered buildings [42].

- The most critical information from this dataset is the height of the building, which is a 3D measurement data representing the height points of the building roof from a laser scan point cloud or matching point cloud. This variable will be added to the extracted data from FlexiGIS.

#### 3.3.2 Datasets of heat potential coming from the LBEG

Similar studies usually develop the geothermal profile of the rock below ground, using the information on the rock type classification, the thickness, and the maximum capacity that can be reached in the rock, ensuring compliance with regulations for installing shallow geothermal heat pumps. To establish the heat extraction rate of the rocks beneath Oldenburg, the LBEG was contacted to request files with geo-referenced information on geothermal potential measurements in shallow depths up to 5 meters, and in boreholes at 40, 60, 80, and 100 meters below ground level.

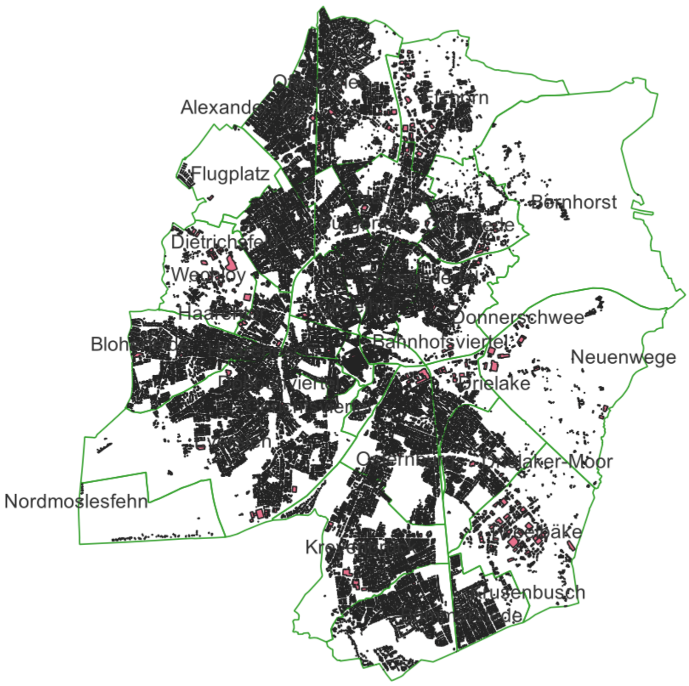



**Figure 20. 3D-building model, LOD2. Credits: OpenStreetMap and FlexiGIS**

Here it is essential to highlight the achievement of this information because it gives us accurate information on measurements that LBEG has carried out and that it usually shares with interested persons or companies in exchange for an established value for this service. Through its contribution, was possible to develop the analysis and discussions in this research that can be of benefit to the city of Oldenburg and the development of knowledge in general about the implementation of geothermal heat pump technology.

Regarding the procedure to apply for obtaining permission to install an SGE, the following is a summary taken from the Legal and technical basis for ground-coupled heat pump systems [29]. Where LBEG knows the reasons for restriction, or even in areas where the restriction is unknown, the competent Lower Water Authority will check whether the conditions for constructing geothermal collectors or BHE systems are fulfilled.

- In areas where LBEG is unaware of any restrictions, the competent Lower Water Authority checks if any additional reasons need to be evident on the LBEG map. If there are no reasons to restrict the implementation of the project, the project is allowed to be constructed.
- In the case of BHE's projects, the requirements for construction and operation for using geothermal energy described in the guideline "Use of geothermal energy in Lower Saxony" (Annex 1a) must be observed.
- In the case of collectors' projects, the requirements for construction and operation for using geothermal energy described in the guideline "Use of geothermal energy in Lower Saxony" (Annex 1b) must be observed.

- In areas where restrictions are known to the LBEG, according to the Guideline "Geothermal energy use in Lower Saxony", Location factors chapter 6, the Lower Water Authority first checks if the restrictions mentioned apply to the intended project, or if, for some reason, they do not apply to it, because the reason for the restriction occurs at depths more significant than the design depth of the intended geothermal installation. In these cases, because the restriction does not affect the project, the Lower Water Authority reviews whether there is additional information to that presented on the LBEG map, and if there is no basis for restricting the project, it can be constructed. If the project considers a BHE or a collector, the requirements for construction and operation for the use of geothermal energy described in the guideline "Use of geothermal energy in Lower Saxony" Annex 1a or Annex 1b, respectively, must be observed.

If the project is affected by restriction grounds, the notice submitted by the company interested in developing the project is considered an application for a permit under the water law, explicitly mentioning this consideration in its application. In the permit application, the Lower Water Authority determines under which context of each case the water law assesses whether and under which conditions the installation of a geothermal energy project is possible. Additionally, in case of permit applications, the Lower Water Authority determines which conditions beyond the general requirements of the guidelines are to be imposed within the framework of §§ 8, 9 WHG. If the permit is approved, the applicant receives a permit from the Lower Water Authority with specific project implementation provisions.

In cases where the implementation of a project cannot be defined based on the map, or if there are other local indications of conditions influencing the use of SGE, the Lower Water Authority or, if necessary, the LBEG assists based on an application.

- In cases where a geothermal energy project is planned to be built in a not permitted area, the use of geothermal energy is prohibited due to the proximity to a water extraction plant. In these areas, the implementation of a geothermal project is usually prohibited.

Though the data contained in maps for heat collector systems or BHE, serve as a support and guide to the conditions for the implementation of a collector or a BHE project in advance, LBEG always recommends the review of the "Guidelines for the use of geothermal energy in Lower Saxony" [29], which contains thermal and legal information to understand the planning process of a geothermal project. The shape files shared by LBEG are presented below in the following literals.

### i. Conditions of use of shallow geothermal energy for geothermal heat collectors [36] (up to 5 m depth).

The map "Terms of use for near-surface geothermal energy - geothermal heat collectors" shows a classification of geothermal heat use by geothermal heat collectors into three area categories.

- The LBEG is not aware of any reasons for restricting the use of geothermal energy,
- reasons for restriction known to the LBEG for the use of geothermal heat,
- use of geothermal energy not permitted.

Although the information contained in Figure 21 and Figure 22 does not provide technical information about the possibility of developing a geothermal energy project, the information classified by “Legend” -no known reasons for restrictions, reasons for restriction known, and not permitted areas- summarizes the information available from the state of Lower Saxony for shallow heat extraction with collectors, which can go down to a depth of 5 meters.

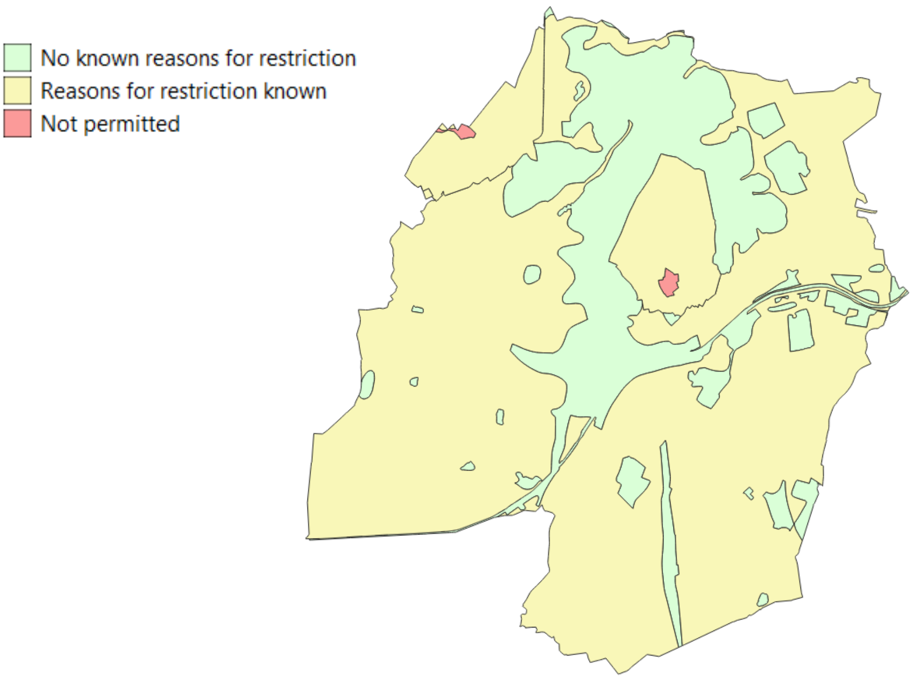



**Figure 21. Conditions for shallow geothermal energy for geothermal heat collectors. Credits to LBEG.**

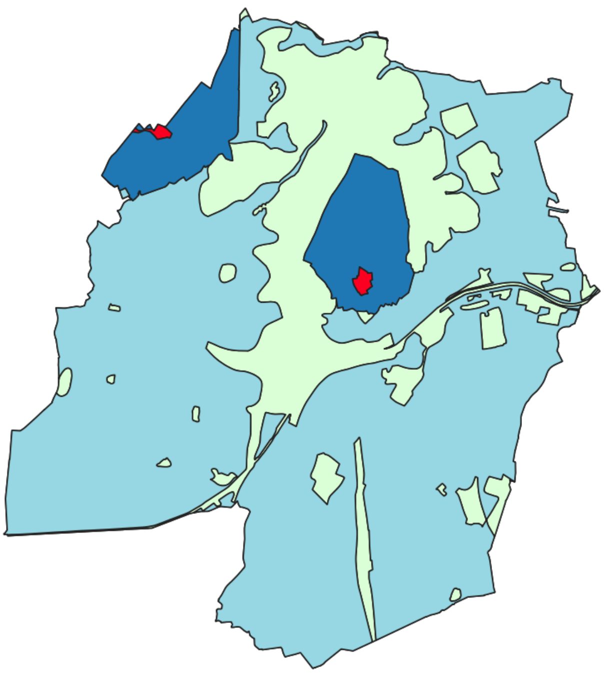


**Figure 22. Restriction reasons of shallow geothermal energy for geothermal heat collectors. Credits to LBEG.**

No known reasons for restriction
Reason for restriction: Drinking water or medicinal spring protection area (protection zone 3, 4, 5, 6, B, D or no indication).
Reason for restriction: low groundwater flow distance
Unauthorised, drinking water or medicinal spring protection area (protection zone 1, 2 or A)

### ii. Conditions of use of shallow geothermal energy for BHE (up to 100 m depth) [43].

Like the map in figures Figure 23 and Figure 24, the map conditions of use of shallow geothermal energy for BHE shows a classification into three categories of areas for the use of geothermal energy by borehole heat exchangers:

- LBEG is not aware of any reasons to restrict the use of geothermal borehole heat exchangers,
- LBEG is not aware of any known reasons to restrict the use of geothermal energy,
- use of geothermal energy not permitted.

There are several reasons why a specific area might be restricted to install a geothermal energy system. The reasons for the restrictions known are:

- Drinking water or medicinal spring protection area (protection zone 3, 4, 5, 6, B, D or no indication).
- Groundwater salinization area.
- Hazard area due to artesian groundwater conditions.

And not permitted areas where by no reason a project will be allowed to be constructed:

- Drinking water or medicinal spring protection area (protection zone 1, 2, or A).

This classification is according to the guidelines of the "Geothermal energy use in Lower Saxony". The map is based on information available for the state of Lower Saxony and summarizes all issues applicable to boreholes up to 100 m deep.

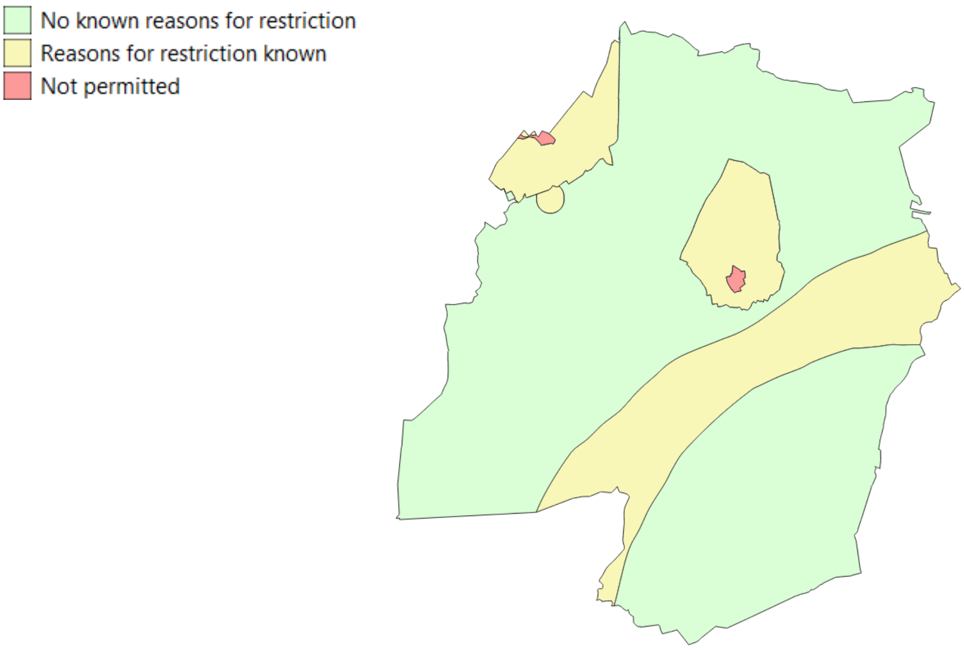



**Figure 23. Conditions for shallow geothermal energy for BHE. Credits to LBEG.**

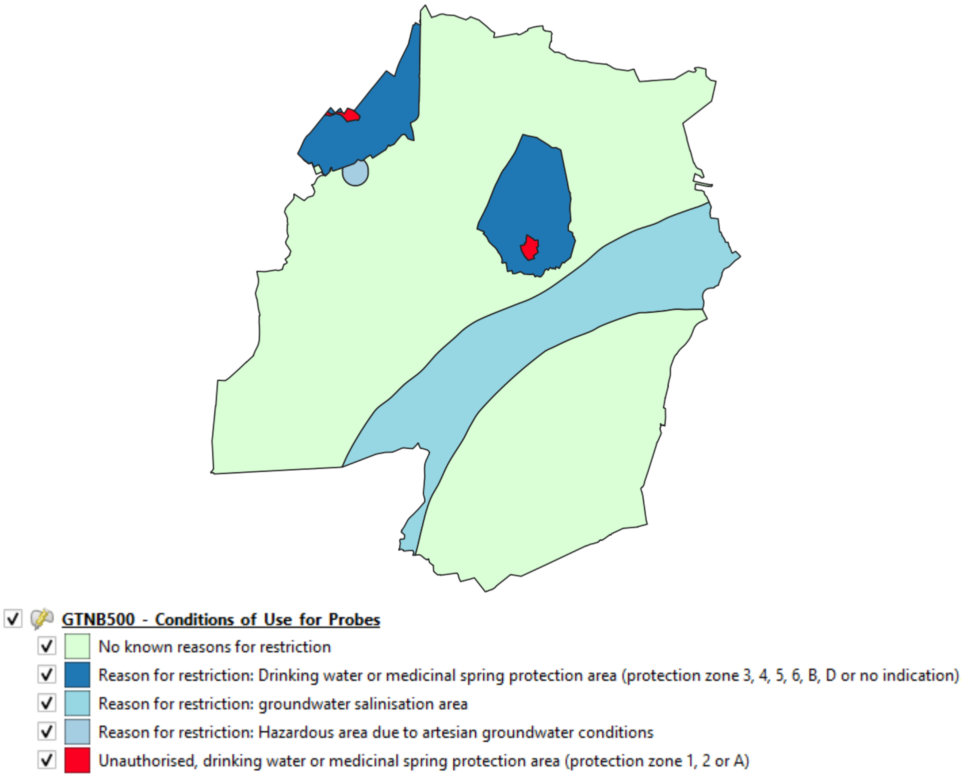



**Figure 24. Restriction reasons of shallow geothermal energy for BHE. Credits to LBEG.**

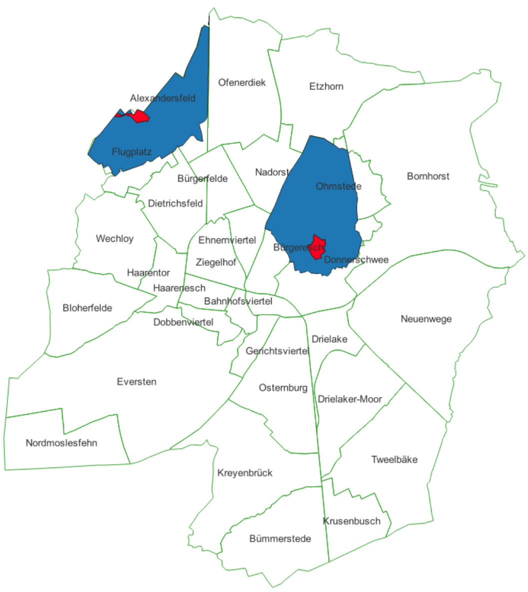



**Figure 25. Map of restricted areas for GSHP according to LBEG reported information and considered to be filtered for the purpose of this master thesis. Credits to LBEG.**

For this study, the areas displayed below in Figure 25 Figure 1and classified as Drinking water or medicinal spring protection area (protection zone 3, 4, 5, 6, B, D or no indication) and Drinking water or medicinal spring protection area (protection zone 1, 2, or A) have been considered as restricted areas, and the geothermal energy potential will not be investigated in this area. Other areas were assumed feasible, considering that it is always possible to verify with LBEG if it is possible to have the authorization to implement the GSHP project.

### iii. Potential site suitability of sites for geothermal collectors [44] (installation depth 1.2-1.5 m).

The map "Potentially suitable locations for horizontal heat exchangers (installation depth of 1.2 - 1.5 m)", presented in Figure 26 differentiates four categories, though for the city of Oldenburg, there are only 3 of them:

- well suitable,
- suitable,
- less suitable,
- unsuitable (hard rock).

The soil classification found on this map is based on the description of the geological rock profile, information about the groundwater table, and a rating of the thermal conductivity of soil and complex rock types. The map represents an initial estimate of geothermal potential. However, the georeferenced data may differs from a detailed investigation of local ground conditions.

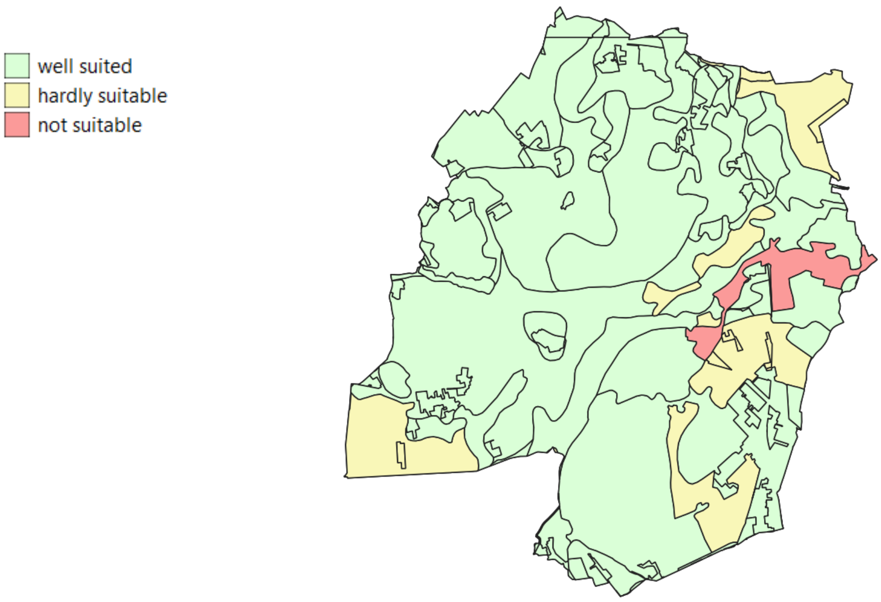



**Figure 26. Potential site suitability of sites for geothermal collectors. Credits: LBEG.**

### iv. Thermal conductivities for BHE systems up to 30 kW capacity and borehole lengths of 40 m, 60 m, 80 m, or 100 m [45].

The map in Figure 27 represents average thermal conductivities for selected boreholes, which are based on values from the VDI 4640. They are a mix of measured values and values from the nationally standardized product catalogue for the economic application of near-surface geothermal data. In case a project is in a location close to a measurement point, proven that the rock type is comparable, the values expressed on the map can serve as an orientation to estimate the average value of the thermal conductivity for a borehole length of 40 m, 60 m, 80 m or 100 m. In representing an initial estimate of thermal conductivity, the data on this map does not replace a review of local ground conditions.

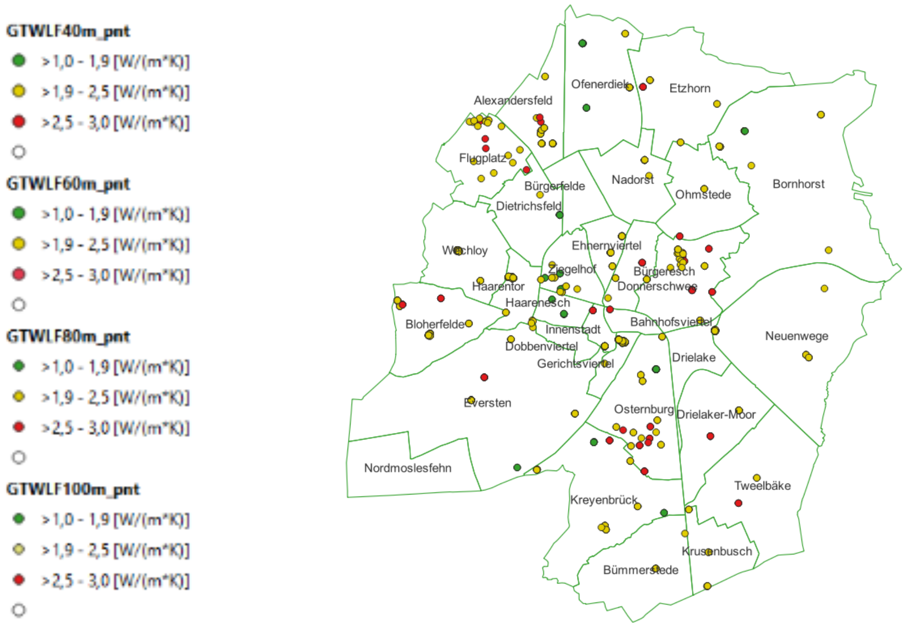



**Figure 27. Estimated average value of the thermal conductivity for a borehole length of 40 m, 60 m, 80 m or 100 m. Credits: LBEG.**

### 3.3.3 Most relevant data coming from the literature review

Many sources were consulted, but the techno-economic information from the literature review was the most relevant information. As a technological source, a database of 506 models of heat pumps developed by the Jülich institute [37] was consulted in order to get data about their Coefficient of Performance. The database is sourced from the results of test labs measurements from the mark certification process of the European Heat Pump Association (EHPA).

**Table 2. COP values, according to categories of demanded average power**

| COP - For Heat Pumps which work with ambient temperature of -7 °C, output to 52°C | | | | | | |
|---|---|---|---|---|---|---|
| **Heat Pump power category** | | **0-10 (kW)** | **10-20 (kW)** | **20-30 (kW)** | **30 - 48.9 (kW)** | **Average COP** |
| Brine/Water | Min. | 2.5 | 2.6 | 2.9 | 3.0 | 2.73 |
| | Avg. | 3.1 | 3.0 | 3.2 | 3.2 | 3.12 |
| | Max. | 3.6 | 3.6 | 3.5 | 3.5 | 3.54 |
| Air/Water | Min. | 1.5 | 1.6 | 1.6 | 1.6 | 1.58 |
| | Avg. | 2.1 | 2.1 | 1.9 | 2.0 | 2.03 |
| | Max. | 2.6 | 2.7 | 2.4 | 2.4 | 2.53 |

From all the models in the COP database, this study considered only Outdoor Air/Water and Brine/Water heat pumps because they are the ones part of the scope of the study. Considering that Oldenburg is a city that, during the last 30 years, had ambient temperatures of -20 °C to 34

°C [46], the filtered COPs of heat pumps selected for this study were those with a starting working ambient temperature at -7 °C, and output to 52°C, to supply not only space heating but also water heating.

In order to get some approximation of the natural values of the COP for a given range of requested electrical power, they were organized into four groups, as described in Table 2, highlighting the minimum, average and maximum COP of each category.

Another essential source to document and identifies appropriate calculations was the family standards of the Thermal use of the underground VDI 4640. They are listed below:

- VDI 4640 Blatt 1 (2010-06-00): Thermal use of the underground - Fundamentals, approvals, environmental aspects.
- VDI 4640 Blatt 1 Berichtigung (2011-12-00): Thermal use of the underground - Fundamentals, approvals, environmental aspects, Corrigendum concerning guideline VDI 4640 Part 1:2010-06.
- VDI 4640 Blatt 2 (2019-06-00): Thermal use of the underground - Ground source heat pump systems.
- VDI 4640 Blatt 2 Berichtigung (2020-04-00) Thermal use of the underground - Ground source heat pump systems, Corrigendum concerning standard VDI 4640 Part 2:2019-06.
- VDI 4640 Blatt 3 (2001-06-00) Utilization of the subsurface for thermal purposes - Underground thermal energy storage.
- VDI 4640 Blatt 4 (2004-09-00) Thermal use of the underground - Direct uses.
- VDI 4640 Blatt 5 (2020-07-00) Thermal use of the underground - Thermal response test (TRT).

From these standards, the "Guidelines for the use of geothermal energy in Lower Saxony" [29] and the paper written by [32], the formulaic collection described in section 3.1 was deduced, and implemented to develop the mathematical model described in this chapter. Additionally, for the second and third scenarios, the following data described in Table 3, was implemented in order to assign a heat extraction rate, considering two input reference values, the thermal conductivity data provided by LBEG [45] and the type of rock [10], **Error! Reference source n ot found.**[25] in the district to where the project belongs to.

**Table 3. Thermal conductivity according [28].**

| Category | Thermal Conductivity [W/(m*K)] | $vh\_e_i$ Extraction rate [W/m] |
|---|---|---|
| Very Low | ≤ 1,0 | 20 |
| Low | 1,0-1,9 | 30 |
| Average | 1.9-2,5 | 40 |
| Good | 2,5-3,0 | 50 |
| Very Good | ≥3,0 | 60 |

Furthermore, the complementary data source for the development of this study, provided by [32], was the one presented in table 4, where based on the study developed by [47]. They provide typical values of annual heat consumption by the type of building used. These data were used to estimate the heat consumption of the identified polygons in Oldenburg.

Two parameters will be considered to develop an economic analysis of the implementation of heat pumps for the thermal energy supply of the city of Oldenburg. First, using the electrical power value calculated for each type of scenario, the cost of upgrading the electrical network to supply the new electrical power requirement from the distribution network will be estimated. For this purpose, a referenced value of 0.18 €/W from [48], will be considered. At this point, it is essential to mention that a network expansion requirement has a non-linear dependence on several factors, like the actual network structure, nature of supply and capacity of renewable installations.

For this study, given that the objective of this study is not to assess impacts of using heat pumps on the electricity network and its particularities for growth concerning the current demand, the investment cost to grow the network will be estimated, assuming that each kW of power for the implementation of the scenarios described in 3.2 is required for its proper functioning. In a second instance, the cost of electricity that the new aggregated demand that each scenario might have will be reviewed, making use of updated values from an energy contract that promotes the installation of heat pumps in Germany [49]. It considers an annual contract value of 44.39 €/year, summed with the consumed energy multiplied by 0.265 €/kWh.

**Table 4. Typical heating demand values per settlement type [32].**

| Settlement type | Description | $kWh/m^2a$ |
|---|---|---|
| ST 1 | Terraced houses | 62,6 |
| ST 2 | Apartments in Agriculture areas | 111.6 |
| ST 3 | Services or other buildings in Agriculture areas | 207,1 |
| ST 4 | Small apartment buildings | 130,9 |
| ST 5 | Small and medium apartment buildings | 181.1 |
| ST 6 | Large public buildings | 207,1 |
| ST 7 | Commercial and service buildings | 913,7 |

Additionally, using the information that FlexiGIS on the electricity consumption of all buildings in the city, it will be proceeded to identify, versus the estimated scenarios, the percentage of electricity that would be required per year to implement each one. Finally, the city's self-sufficiency in supplying thermal energy provided by geothermal energy will be reviewed using the resulting best-case scenario data.

# Chapter 4 Modelling results

This chapter describes the research analysis of the model developed for the three scenarios conducted for the city of Oldenburg using the methodology described in chapter 3. The first section will present the results obtained for the heat consumption according to 3.1. In the second section of the analysis, the area required for each shallow geothermal energy technology will be reviewed, assuming that in each scenario, 100% of the city's heat consumption will be supplied. In the third section, the results obtained will be reviewed in detail, and a comparative analysis will be made between the results of the scenarios.

## 4.1 Heating demand

The first aspect being addressed is the thermal energy requirement of the city of Oldenburg and its different districts.

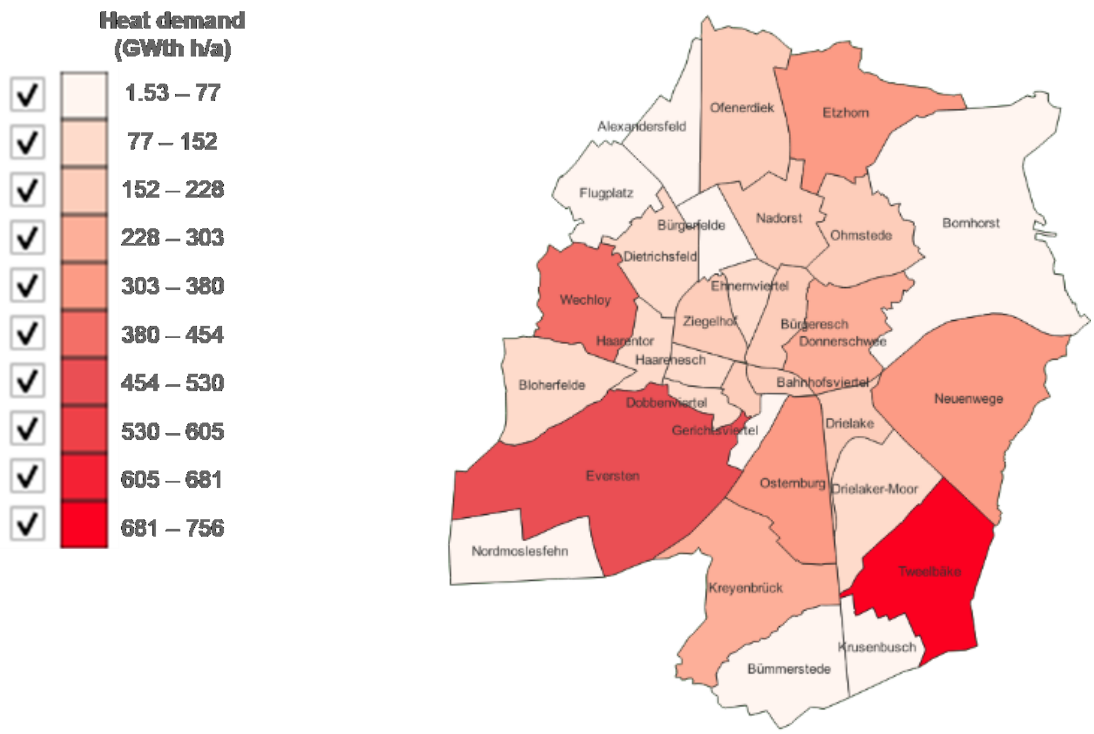



**Figure 28. Heating demand by district in Oldenburg city.**

The average thermal power demand per year would be 2.34 GWth, which means a thermal energy consumption of 5.6 TWth h/a, considering the value suggested by VDI 4640 part 2 of 2400 operating hours per year of heat pumps for space heating and hot water supply.

From Figure 28, it can be seen that the three districts with the highest electricity demand are Wechloy (408 GWth h/a), Eversten (474 GWth h/a) and Tweelbäke (756 GWth h/a). The reason why these districts have the highest demand is due to the density of buildings with the highest consumption, as can be seen in Table 5.

**Table 5. Calculated heat consumption, area, buildings and buildings density per district.**

| Name | Calculated_heat_demand ($GW_{th}$ h/a) | Area (Ha) | Buildings | Buildings density (Buildings/$m^2$) |
|---|---|---|---|---|
| Alexandersfeld | 74.4 | 243.3 | 3,015 | 12.4 |
| Bahnhofsviertel | 209.4 | 51.8 | 244 | 4.7 |
| Bloherfelde | 101.7 | 319.8 | 2,609 | 8.2 |
| Bornhorst | 18.2 | 1246.8 | 182 | 0.1 |
| Bümmerstede | 65.4 | 388.9 | 2,748 | 7.1 |
| Bürgeresch | 210.1 | 144.1 | 1,606 | 11.1 |
| Bürgerfelde | 61.0 | 140.1 | 977 | 7.0 |
| Dietrichsfeld | 89.8 | 244.8 | 2,373 | 9.7 |
| Dobbenviertel | 94.3 | 64.7 | 586 | 9.1 |
| Donnerschwee | 250.3 | 336.9 | 1,277 | 3.8 |
| Drielake | 165.6 | 137.1 | 550 | 4.0 |
| Drielaker-Moor | 119.6 | 349.8 | 1,993 | 5.7 |
| Ehnernviertel | 90.0 | 98.5 | 1,113 | 11.3 |
| Etzhorn | 325.7 | 507.8 | 1,123 | 2.2 |
| Eversten | 474.5 | 1147.1 | 6,325 | 5.5 |
| Flugplatz | 8.7 | 261.9 | 59 | 0.2 |
| Gerichtsviertel | 54.4 | 65.9 | 408 | 6.2 |
| Haarenesch | 80.1 | 76.4 | 747 | 9.8 |
| Haarentor | 99.6 | 123.9 | 950 | 7.7 |
| Innenstadt | 163.8 | 46.5 | 689 | 14.8 |
| Kreyenbrück | 252.4 | 555.6 | 3,410 | 6.1 |
| Krusenbusch | 23.0 | 187.1 | 1,255 | 6.7 |
| Nadorst | 160.0 | 257.9 | 1,518 | 5.9 |
| Neuenwege | 343.2 | 808.5 | 239 | 0.3 |
| Nordmoslesfehn | 1.5 | 317.7 | 90 | 0.3 |
| Ofenerdiek | 212.8 | 464.7 | 3,153 | 6.8 |
| Ohmstede | 196.2 | 308.5 | 1,324 | 4.3 |
| Osternburg | 342.4 | 398.1 | 3,135 | 7.9 |
| Tweelbäke | 756.4 | 546.0 | 477 | 0.9 |
| Wechloy | 408.6 | 328.1 | 477 | 1.5 |
| Ziegelhof | 178.2 | 153.4 | 1,312 | 8.6 |
| Total | 5631.3 | 10321.7 | 45964 | 4.5 |

In the case of Eversten, this would be the district with the highest density of buildings per square metre. Eversten would account for 13.76% of the city's buildings, 14% of the residential buildings, 10.8% of the buildings in the agriculture sector and 10.6% of the buildings in the education sector. These buildings would represent a heat consumption of 8.43% of the city's total demand.

The case of Tweelbäke, the district that would have the highest thermal energy consumption, has two particularities. First, it is a district that would have only 1% of the city's buildings. However, 16% of the buildings in the industrial and agricultural categories are located in this district. These buildings would account for 13% of the city's total thermal energy consumption. Wechloy is one of the three districts with the highest demand, it is the smallest district, with a location of 1% of the total number of buildings. However, this district has buildings in the commercial and industrial sectors, which have a sizeable built-up area and are characterized by high consumption. In total, 7.26% of the electricity demand of the city of Oldenburg is concentrated in this district.

The case of Wechloy, a district with 328 Ha and a building density of 1.5 Buildings/Ha, is interesting because in comparison to other larger districts, e.g. Borhnhorst 1.246 Ha, which has a building density of 0.14 Buildings/Ha, or a smaller district with a higher density of built-up area such as Harrenesch 9.7 Buildings/Ha in an area of 76 Ha, its energy consumption is the third highest in the city. This result justifies, to some extent, the introduction of scenario number 3 considered in this study, where shallow geothermal energy systems, exploiting their maximum allowable potential, can supply heat to neighbouring buildings.

### 4.2 Requested area for shallow geothermal heat exchangers

The total area of the city of Oldenburg is approximately 10,322 ha. However, only 922 Ha are occupied by buildings in the 31 districts that make up the city of Oldenburg.

Although, according to Figure 29, there is 40.6% of non-constructed area, 3,77% belongs to water reservoirs, rivers or lakes, and only 36.8% of the city could be used to implement geothermal energy systems with a basket or horizontal heat collectors. Hence, it is essential to review what area would be required for this type of system, as these types of systems have specific requirements for their implementation.

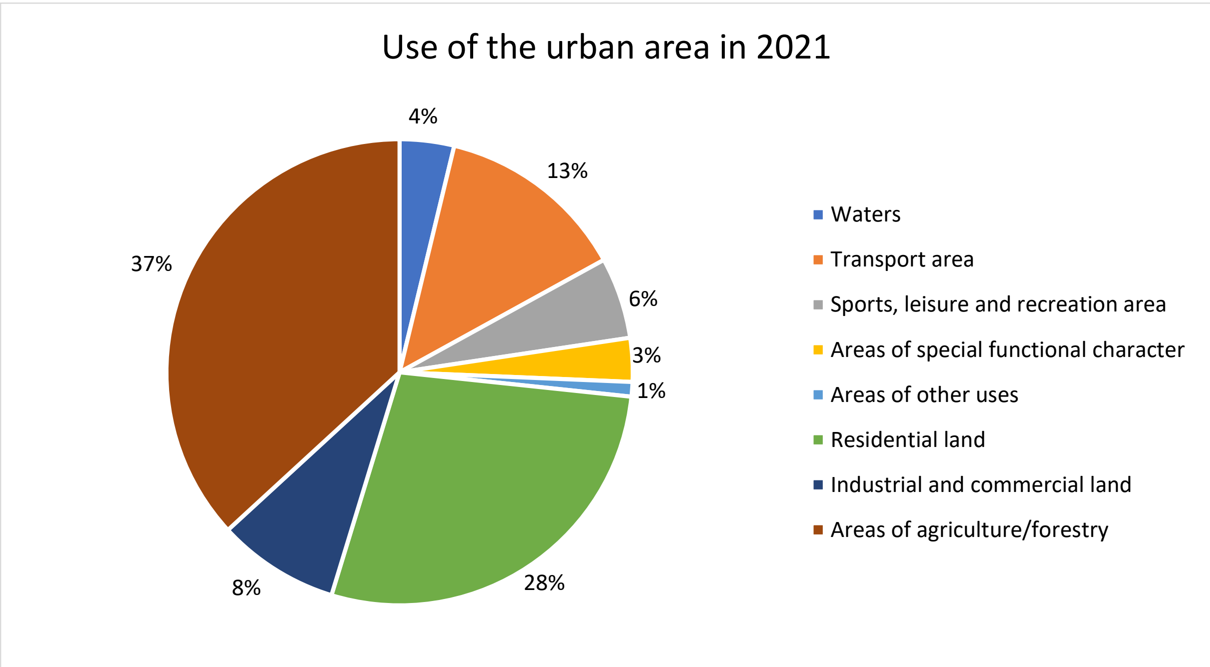



**Figure 29. Used of urban area in Oldenburg's city [50].**

The results obtained are summarized in table 6. In the case of horizontal collectors, if it were necessary to supply the thermal energy of Oldenburg with this technology, at least 56.97% of the total city would be occupied to implement this solution. This area is a substantial figure, and this solution can be applied in areas with lower densities of buildings per hectare. Perhaps it is feasible in districts like Nümmerstede, Kruschenbusch, Borhorst, Nordmoslesfehn or Bürgefelde, where there is sufficient area for such a facility. However, two critical factors discourage the deployment of this technology. The first is to ensure that no projects are built on this type of system, no trees are planted, or no shadows are cast. The second aspect being considered is the availability of land. As this is a linked system that requires the availability of land, the cost per square meter of the installation site would be relevant, as, on average, in the city of Oldenburg, approximately 25 $m^2$/kWth would be required.

**Table 6. Area of systems to provide Heating demand of the city of Oldenburg**

| Building type | Area of systems (Ha) | Building's area (Ha) | Proportion | Oldenburg area (Ha) | Proportion |
|---|---|---|---|---|---|
| Horizontal | 5,880 | 922 | 638.06% | 10,322 | 56.97% |
| Basket | 1,116 | | 121.10% | | 10.81% |
| BHE | 525 | | 56.95% | | 5.08% |

The case of basket-type collectors is more feasible, as the heat collection of this type of system optimises the use of space to supply the same amount of heat. A rough calculation of the area required per kW of thermal energy supplied indicates that about 4.76 $m^2$/kWth would be required, one-fifth of the area required for horizontal collectors. Basket collectors would require 1,116 Ha to supply the total thermal energy consumption of the city of Oldenburg. This area represents approximately 10.8% of the city's total area, which suggests that it would be a more viable option for implementation than a horizontal system where the cost per square meter of the urban area is a constraint.

Furthermore, concerning vertical collectors, or BHEs, this technology would require the least space per kW of thermal energy generated. While each well would have a maximum diameter of 150 mm, the wells of a system must be 5 meters apart, and the systems must be 10 meters apart. By meeting this requirement, it would be possible to supply the city's thermal energy in areas where it is possible to implement the technology, occupying only 2.24 $m^2$/kWth. This value results in a footprint of less than 6% of the total unbuilt area of the city and less than 57% of the total area where the city's buildings are currently located. This last proportion highlights that this type of installation can be deployed within the built-up area, i.e. without affecting unbuilt spaces or spaces that do not belong to the property. Also, as there is no need to cast shadows on it or to have no restriction on what is built on the BHE, this type of system is more feasible than horizontal or basket-type collectors. In summary, geothermal systems with BHE are more suitable for urban installations with a high concentration of buildings, where the cost per square meter can be a differentiator for installing a geothermal system. Figure 30 shows in terms of footprint, the proportion from the city, which would be required to supply the whole heat consumption, using one of the three types of heat collector systems.

**Figure 30. Space required to supply the whole heat demand per shallow geothermal technology. From left to right. Left: Footprint of horizontal systems. Center: Footprint of basket collectors. Right: Footprint of BHE.**

Under the results obtained in this section, the scenarios will be analyzed considering the collection of shallow geothermal heat through the BHE type system.

### 4.3 Modelling results

This section will review the electricity consumption results and each scenario's average power demand.

#### 4.3.1 Scenario 1: Heat supply to buildings with decentralized aerothermal heat pumps.

Table 7 summarizes the results obtained for scenario 1. It presents the maximum and minimum average power demand and electrical energy consumption.

**Table 7. Electrical power and energy consumption of scenario 1.**

| | Category | Min power demand **MW** | Max power demand **MW** | Min energy consumption **GWh/a** | Max energy consumption **GWh/a** |
|---|---|---|---|---|---|
| Aerothermal heat pumps | Agricultural | 10.2 | 15.95 | 24.48 | 38.29 |
| | Commercial | 446.33 | 694.04 | 1071.2 | 1665.7 |
| | Education | 21.15 | 32.91 | 50.75 | 78.98 |
| | Industrial | 187.78 | 291.99 | 450.67 | 700.78 |
| | Residential | 295.02 | 473.17 | 708.06 | 1135.6 |
| | Total | **960.48** | **1508.06** | **2305.16** | **3619.35** |

Since scenario 1 proposes the installation of an air/water pump heat supply system for each building, the result shows a distribution of electrical energy consumption directly proportional to the heat consumption that each building would have. For this reason, the charts in Figure 31 and Figure 32 show a power demand range of 960 MW to 1508 MW, and an energy consumption of 2305 GWh/a to 3619 GWh/a. Under this scenario, the sector that would demand the most power is the commercial sector, with an average power between 446 MW and 694 MW, consuming energy between 1071 GWh/y and 1665 GWh/y. This sector is followed by the residential sector, due to its large number of buildings, and the industrial sector, which, although it has a significant heat consumption, this study does not consider the additional heat consumptions for the development of its industrial processes, which could significantly increase the estimated value in this study. The sectors with the lowest power demand and electricity consumption would be education and agriculture. The main reason for this distribution is the consumption of the building type and the number and size of buildings by category.

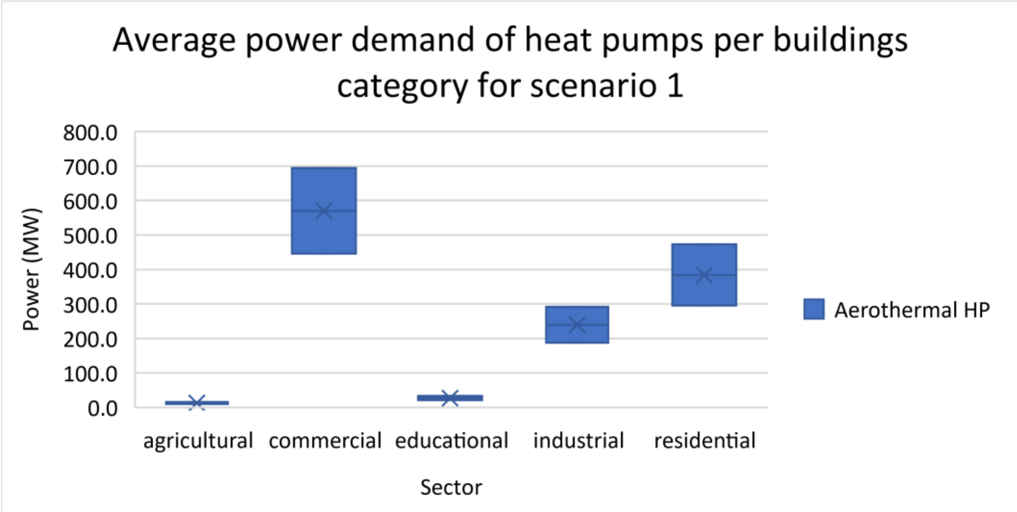



**Figure 31. Average power demand of heat pumps per buildings category for scenario 1.**

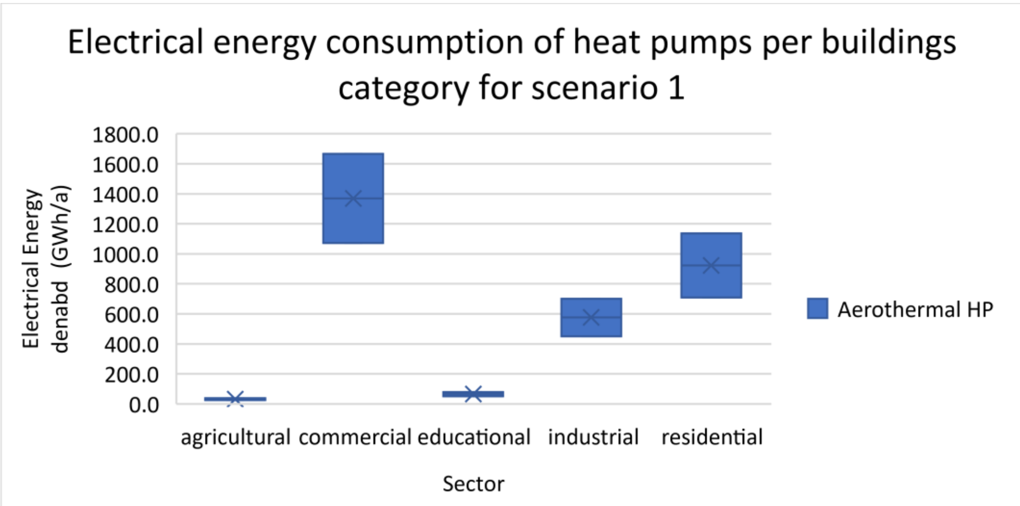



**Figure 32. Electrical energy consumption of heat pumps per buildings category for scenario 1.**

Since this is a theoretical approximation of the implementation of air-to-water heat pumps, the estimated size of the heat pumps is independent of the real possibility of supplying a heat pump of the size mentioned in Table 8. For example, in the commercial category, some buildings require systems with a heat pump with a capacity of 30 MW. For this reason, in order to interpret this result, it is suggested to consider the installation of several heat pumps that, in total, add up to the required capacity.

**Table 8. Average rated power of aerothermal heat pumps per building category for scenario 1.**

| Row Labels | Average of Ath_Pel_min (kW) | Average of Ath_Pel_max (kW) | Min of Ath_Pel_min (kW) | Max of Ath_Pel_max (kW) |
|---|---|---|---|---|
| Agricultural | 34 | 53 | 0.703 | 867 |
| Commercial | 361 | 562 | 0.025 | 30,562 |
| Education | 97 | 152 | 1.904 | 2,164 |
| Industrial | 418 | 650 | 0.022 | 20,991 |
| Residential | 7 | 11 | 0.002 | 2,823 |

Moreover, heat pump specifications, which on average would be required to supply thermal energy to the Oldenburg buildings, are close to reality. Heat pumps between 7 and 11 kW are values usually found among the references of the products of different manufacturers [37].

### 4.3.2 Scenario 2: Heat supply to buildings with decentralized geothermal heat pumps.

Scenario 2 aims to supply thermal energy through GSHP using BHE systems. Regarding this scenario, it is essential to mention that according to VDI 4640 part 2, in those systems where a heat pump of more than 30 kW is required, a maximum of 5 wells may be installed. Out of a total of 45,964 buildings, there would be 1966 buildings requiring 6 or more BHE. Though few, these buildings represent 73.6% of the total thermal energy consumption. This high percentage is because they are buildings that have the highest consumption, commercial, industrial, education and large districts for highly dense residential units. Therefore, the analysis would imply difficulties of comparing this solution with scenarios 1 and 3 established, which is why the analysis of the results will address the possibility of supplying electricity independently of the required number of BHE. It means that systems with up to 1,900 BHE are considered, which would not be feasible. Table 9 shows the results obtained for scenario 2. It presents the maximum and minimum electrical power demand and electrical energy consumption by building use category.

**Table 9. Average electrical power demand and energy consumption of heat pumps per building category scenario 2.**

| | Category | Min power demand **MW** | Max power demand **MW** | Min energy consumption **GWh/a** | Max energy consumption **GWh/a** |
|---|---|---|---|---|---|
| Geothermal heat pumps | Agricultural | 6.61 | 8.21 | 15.85 | 19.7 |
| | Commercial | 288.67 | 346.68 | 692.81 | 832.03 |
| | Education | 13.52 | 16.35 | 32.45 | 39.23 |
| | Industrial | 117.78 | 141.44 | 282.68 | 339.46 |
| | Residential | 184.37 | 244.29 | 442.48 | 586.29 |
| | Total | **610.95** | **756.96** | **1466.27** | **1816.7** |

Although this scenario represents the implementation of supplying the total heat consumption of the city through heat pumps using decentralized and independent BHE, the solution is capable of supplying only 92.3% of the city's demand because there are areas where heat supply has not been considered, because their location is over a restricted area for the installation of BHE with reasons known by the LBEG as explained in 3.3.2.

Figure 33 and Figure 34 facilitate the identification of the categories of buildings with the highest power demand and energy consumption. Similar to scenario 1, the sectors of buildings with the highest average power demand would be commercial, with a range of 289 MW to 347 MW, followed by residential, 184 MW to 244 MW and industrial, with a range of 118 MW to 141 MW.

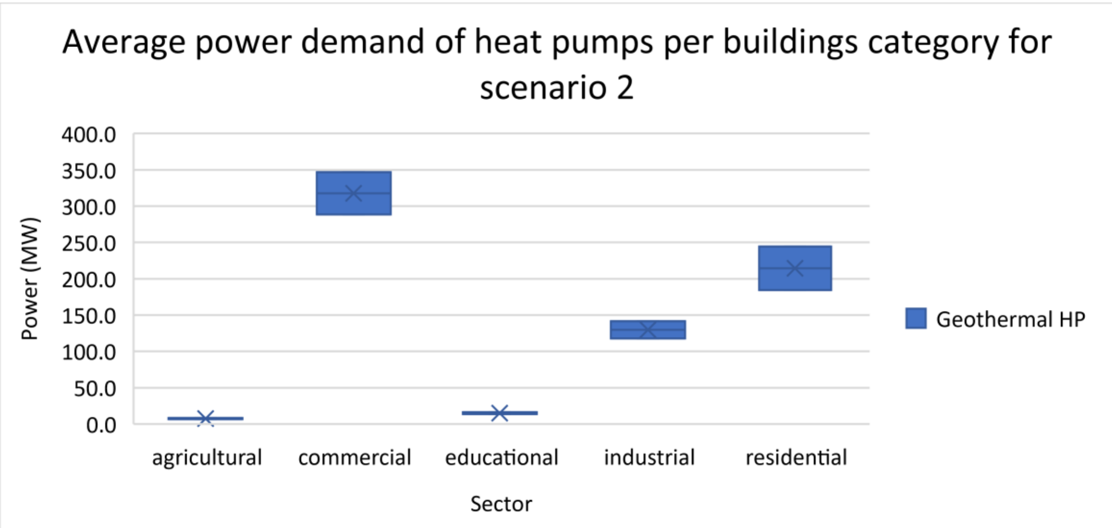



**Figure 33. Average power demand of heat pumps per buildings category for scenario 2.**

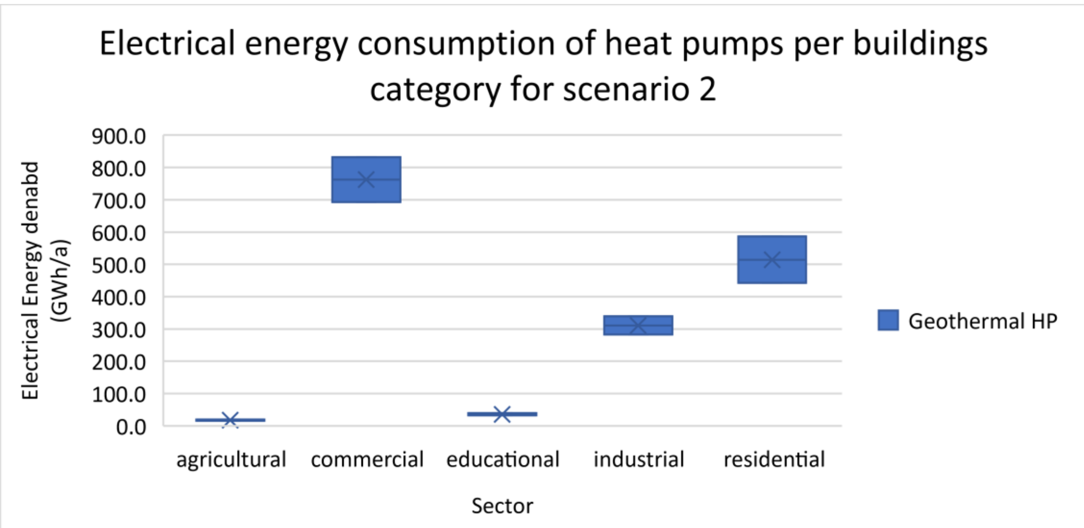



**Figure 34. Electrical energy consumption of heat pumps per buildings category for scenario 2.**

The critical issue in this scenario is the reduction in power demand and energy consumption compared to scenario 1, which will be discussed in chapter 5.

As detailed in Table 10, there would also be a significant reduction in heat pumps specifications. Since the mean value of the average power demand that might be considered in geothermal energy systems would significantly decrease. In the case the residential buildings category, a reference sector to verify the data obtained, an average pump demand of 5 kW minimum and 6 kW maximum is observed. These are usual values for geothermal heat pump to be install in the residential sector. Even so, because this scenario contemplates the development of systems, which may require even 1900 BHE, there are heat pump requirements of up to 16 MW in the commercial sector and 11 MW in the industrial sector. Naturally, these would not represent the reality of a heat pump capacity to be installed in the commercial category. It would mean the installation of several heat pumps to complete the requested power capacity.

**Table 10. Average rated power of aerothermal heat pumps per building category for scenario 2.**

| Row Labels | Average of Geoth_Pel_min (kW) | Average of Geoth_Pel_max (kW) | Min of Geoth_Pel_min (kW) | Max of Geoth_Pel_max (kW) |
|---|---|---|---|---|
| Agricultural | 24 | 29 | 0.5182 | 455 |
| Commercial | 246 | 295 | 0.0181 | 16058 |
| Education | 67 | 80 | 1.4043 | 1137 |
| Industrial | 285 | 342 | 0.0160 | 11029 |
| Residential | 5 | 6 | 0.0013 | 1483 |

#### 4.3.3 Scenario 3: Heat supply with aerothermal heat pumps, in restricted areas for installing geothermal heat pumps, and networked geothermal heat pumps.

In order to visualize better how would look scenario 3, Figure 35 represents Haarenesch district implementing at least 1 BHE per building, and sharing the heat capacity to the nearest building.

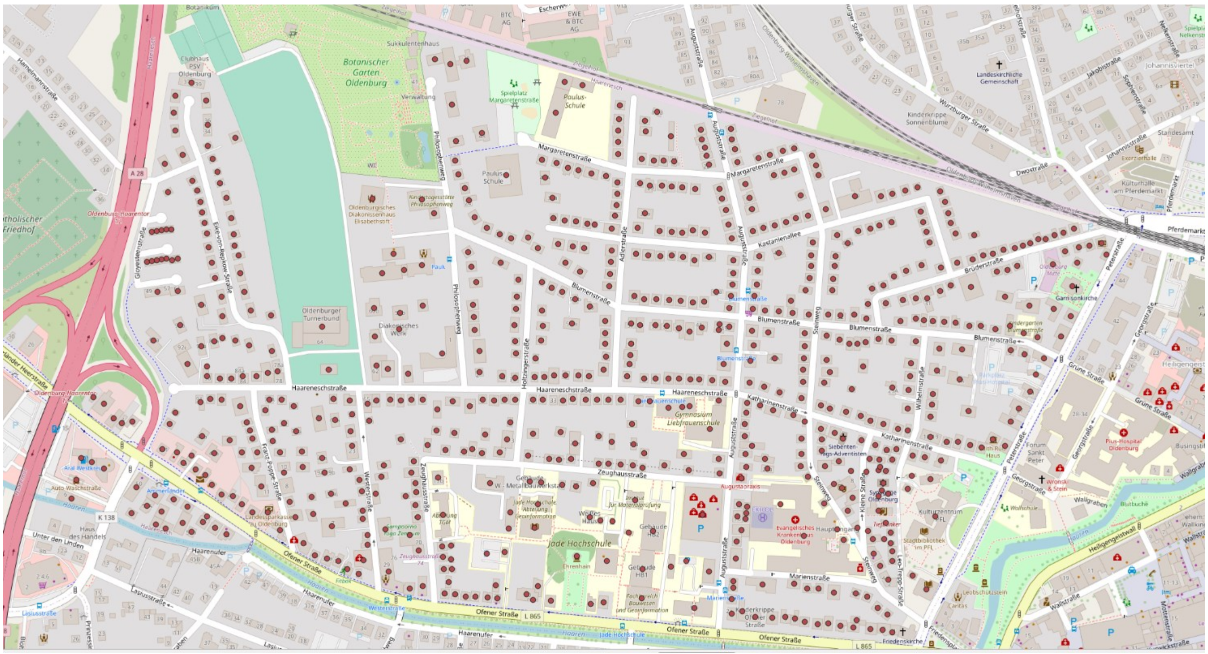


**Figure 35. GIS-based distribution of 1 BHE per building in Haarenesch district.**

One of the most relevant results of this scenario is that to supply the total heat consumption of the city, at least 40,386 systems would be required, of which at least 24,481 would have to have two BHE per system, and the rest only 1 BHE. In total, 70,444 wells of up to 400 meters would be required. Additionally, since 12% of the total number of buildings are located in areas where it is not possible to install a geothermal system, this demand would be met by aerothermal systems.

**Table 11. Average electrical power demand and energy consumption of heat pumps per building category scenario 3.**

| | Category | Min power demand MW | Max power demand MW | Min energy consumption GWh/a | Max energy consumption GWh/a |
|---|---|---|---|---|---|
| Network of geothermal and aerothermal heat pumps | Agricultural | 3.70 | 5.45 | 8.89 | 13.09 |
| | Commercial | 35.19 | 53.24 | 84.46 | 127.78 |
| | Education | 4.15 | 6.08 | 9.95 | 14.59 |
| | Industrial | 18.85 | 28.90 | 45.25 | 69.35 |
| | Residential | 511.59 | 738.76 | 1227.83 | 1773.03 |
| | Total | **573.49** | **832.44** | **1376.37** | **1997.84** |

Table 11 reports the results obtained for scenario 3. It indicates the maximum and minimum electrical power demand and electrical energy consumption by building use category. It should be noted that, in this result, the requirements of the area served by geothermal pumps and those served by aerothermal pumps are added together.

In this scenario, it is important to highlight two aspects: the residential category where most geothermal systems would be located and the maximum and minimum power range for implementing the scenario. Figure 36 and Figure 37 show that at least 95% of the systems would be installed in the residential sector, while only 2.6% would be located in the commercial sector. The minimum average power required for scenario 3 to supply the city's heat would be a minimum of 573 MW and a maximum of 832 MW.

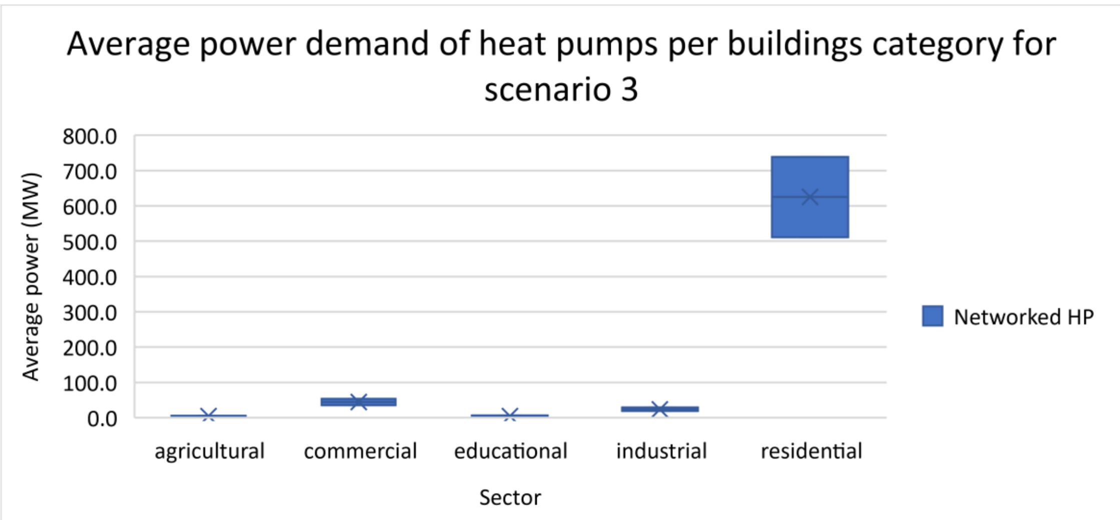



**Figure 36. Power demand for implementation of scenario 3.**

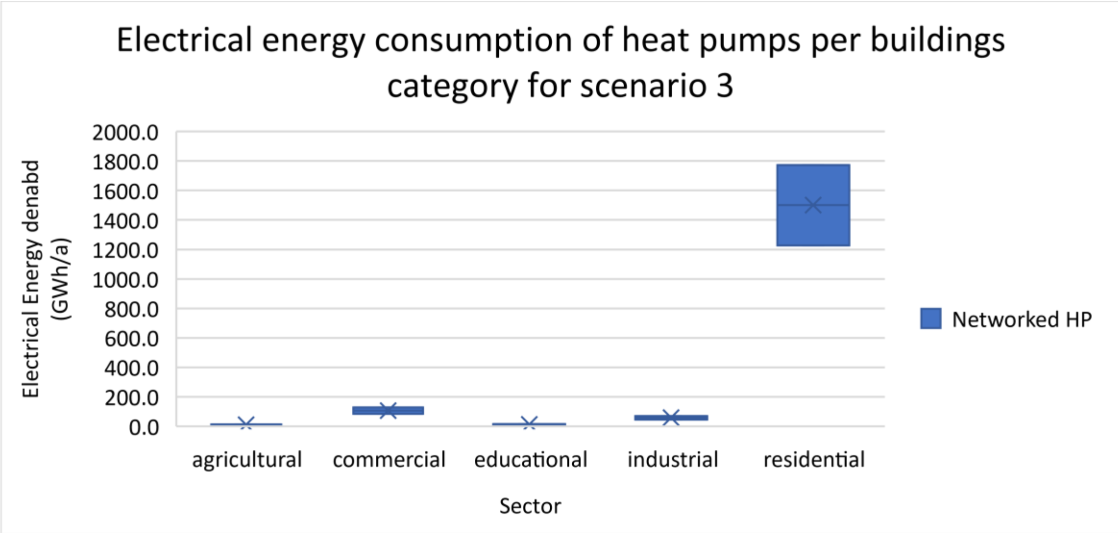



**Figure 37. Electrical energy consumption for implementation of scenario 3.**

Regarding the type of geothermal pumps required to operate these systems, table 12 shows an average of heat pumps between 7 and 11 kW, with minimum values of 6 kW and a maximum of 20 kW. The difference between these results is that, although all the systems will have a BHE of up to 400 meters in depth, their location may be in areas with less or more geothermal potential, and there is not precisely and optimization of the use of districts with higher heat potential according the rock underground.

**Table 12. Average, maximum and minimum power of brine/water heat pumps for scenario 3.**

| Row Labels | Average of Geoth_Pel_min (kW) | Average of Geoth_Pel_max (kW) | Min of Geoth_Pel_min (kW) | Max of Geoth_Pel_max (kW) |
|---|---|---|---|---|
| Agricultural | 7 | 10 | 6 | 12 |
| Commercial | 7 | 11 | 6 | 20 |
| Education | 8 | 11 | 6 | 20 |
| Industrial | 7 | 10 | 6 | 15 |
| Residential | 8 | 11 | 6 | 20 |

# Chapter 5 Results discussion

This chapter focus on analysing the results explained in Chapter 4. For this purpose, Section 1 will compare the results obtained; Section 2 will discuss the way scenario 3 would attend to the heat consumption; Section 3 will review how the obtained results affect the costs associated with upgrading distribution networks and the impact of the increase in energy costs by building type; and Section 4 will present how geothermal heat pumps contribute to the self-sufficiency of heat supply in the investigated case study of the city of Oldenburg.

## 5.1 Requested area for shallow geothermal heat exchangers

The values in table 13 were obtained by dividing the requested area of each shallow geothermal heat exchanger technology to the power heat demand requested to the whole city. These values suggest that to deploy SGE in high density of buildings in urban areas, the best solutions are basket collectors and BHE because they can offer the same power capacity of 1 kW, in 4.76 $m^2$ and 2.24 $m^2$, respectively. These values are considerably lower than the area requested by horizontal collectors, which may require around 25 $m^2$/kW.

**Table 13. Relationship of area requested to supply 1 kW of heat per shallow geothermal technology**

| Shallow geothermal heat exchanger technology | Requested area, per kW of heat supplied ($m^2$/kW) |
|---|---|
| Horizontal collector | 25.07 |
| Basket collector | 4.76 |
| Borehole heat exchanger | 2.24 |

## 5.2 Scenario analysis of power demand and electrical energy consumption of heat pumps for different building categories

Figure 38 compares the average power demand of the three scenarios. From this figure, two aspects stand highlighted. Firstly, the distribution of demand by building category, and secondly, the power demand value that would be required to implement the scenario.

Regarding the distribution of demand by building category, when thermal energy is supplied by aerothermal heat pumps, as in scenario 1, or by geothermal heat pumps, as in scenario 2, the electrical power demand, as explained in equation 3.6, is inversely proportional to the COP of the type of heat pump to be implemented. As geothermal heat pumps perform better than aerothermal pumps due to their possibility to put the working fluid in contact with the shallow earth, which has a more stable temperature, and with values that generate a lower temperature difference than aerothermal ones, the potential electrical demand of the geothermal heat pump will always be lower than that of the air/water heat pump, for the same weather conditions and same requested temperatures in buildings. For this reason, to supply the thermal energy of the city of Oldenburg, scenario 1 requires much more power than scenario 2, and additionally, in both scenarios, the electrical power demanded by the heat pumps is distributed proportionally per building category. In contrast to scenarios 1 and 2, in the case of scenario 3, the power demand of the heat pumps would be distributed primarily on residential buildings, where it is possible to install a geothermal system, according to the LBEG requirements.

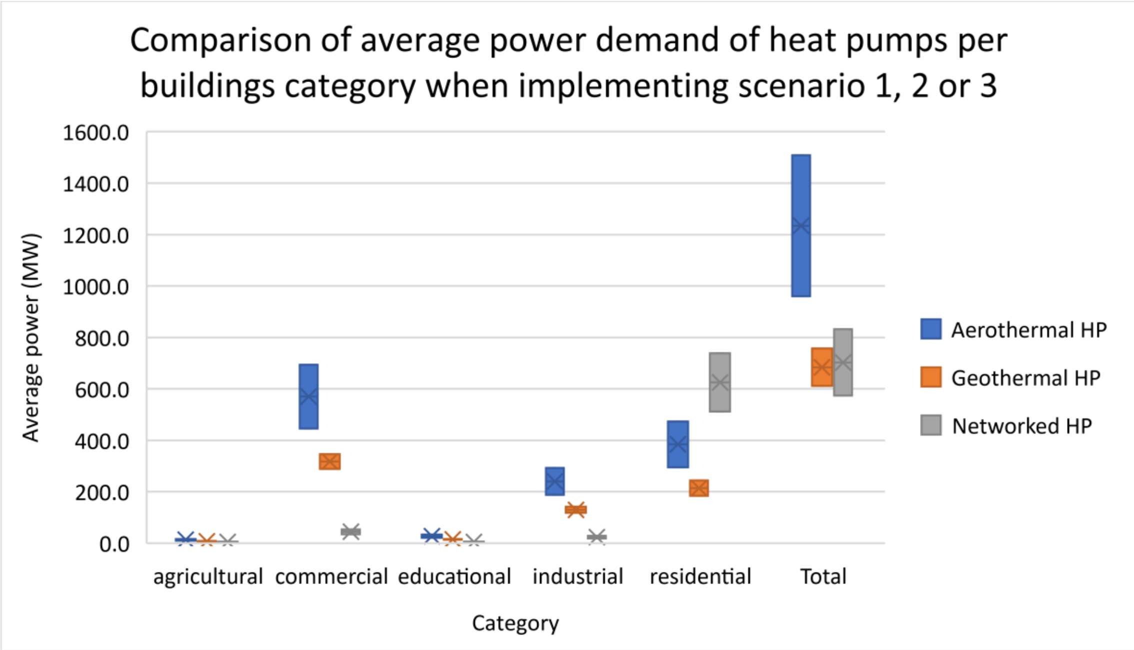



**Figure 38. Comparison of average power demand of heat pumps per buildings category when implementing scenario 1, 2 or 3.**

Figure 38 and Table 14 presents the results of the minimum and maximum values of the average power demand and electricity consumption. The last column of the table shows the percentage that the scenario can cover of the total need of the city. In the case of scenario 1, the aerothermal pumps can cover 100% of the demand, mainly because they can be installed anywhere without restriction. In scenario 2, it is considered that there are areas with restrictions for deploying this technology, which is why they only cover 92.29% of the city's heat consumption. Finally, scenario 3 can supply the total heat consumption because it takes full advantage of the potential of the BHE and because in places where the use of geothermal heat pumps is restricted, the installation of aerothermal heat pumps is assumed.

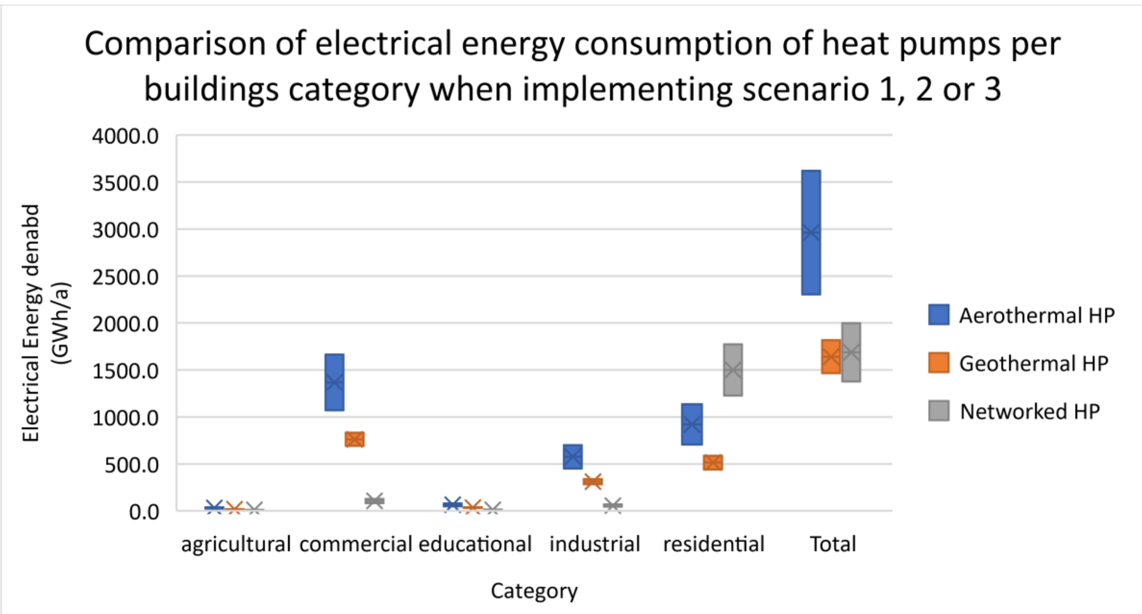



**Figure 39. Comparison of electrical energy consumption of heat pumps per buildings category when implementing scenario 1, 2 or 3.**

Figure 39 presents the average power demand of the three scenarios and shows similar behaviour to that mentioned in Figure 38, where the average power demand was provided. However, from this diagram, it is vital to highlight the power demand values that would imply implementing these solutions. In the case scenario 1 is implemented, the air/water heat pumps would consume between 2.3 and 3.6 TWh/year. This amount of energy is a high value, compared to the electrical energy required by the buildings currently in Oldenburg, of 0.9 TWh/a, according to the data extracted by FlexiGIS and presented in Table 14.

**Table 14. Average electrical power demand and energy consumption of heat pumps per building category for scenarios 1, 2 and 3.**

| Scenario | Category | Min power demand [MW] | Max power demand [MW] | Min energy consumption [GWh/a] | Max energy consumption [GWh/a] | Heat consumption % |
|---|---|---|---|---|---|---|
| **Scenario 1** Aerothermal heat pumps | agricultural | 10.2 | 15.95 | 24.48 | 38.29 | 100.00% |
| | commercial | 446.33 | 694.04 | 1071.20 | 1665.70 | |
| | educational | 21.15 | 32.91 | 50.75 | 78.98 | |
| | industrial | 187.78 | 291.99 | 450.67 | 700.78 | |
| | residential | 295.02 | 473.17 | 708.06 | 1135.60 | |
| | Total | **960.48** | **1508.06** | **2305.16** | **3619.35** | |
| **Scenario 2** Geothermal heat pumps | agricultural | 6.61 | 8.21 | 15.85 | 19.70 | 94% |
| | commercial | 288.67 | 346.68 | 692.81 | 832.03 | 95% |
| | educational | 13.52 | 16.35 | 32.45 | 39.23 | 94% |
| | industrial | 117.78 | 141.44 | 282.68 | 339.46 | 92% |
| | residential | 184.37 | 244.29 | 442.48 | 586.29 | 88% |
| | Total | **610.95** | **756.96** | **1466.27** | **1816.70** | 92% |
| **Scenario 3** Network of geothermal and aerothermal heat pumps | agricultural | 3.70 | 5.45 | 8.89 | 13.09 | 54% |
| | commercial | 35.19 | 53.24 | 84.46 | 127.78 | 11% |
| | educational | 4.15 | 6.08 | 9.95 | 14.59 | 31% |
| | industrial | 18.85 | 28.90 | 45.25 | 69.35 | 12% |
| | residential | 511.59 | 738.76 | 1227.83 | 1773.03 | 289% |
| | Total | **573.49** | **832.44** | **1376.37** | **1997.84** | **100.%** |

For scenarios 2 and 3, the energy consumption values may be less than double the energy consumed, with similar values for each scenario, totalling between 1.4 and 1.8 TWh/a in the case of scenario 2 and between 1.4 and 2.0 TWh/a in the case of scenario 3. According to the values presented in Table 15, these values would represent an increase in electricity consumption of buildings in Oldenburg from 151.6% to 187.9% in the case of scenario 2 and from 142.3% to 206.6% in the case of scenario 3. Due to the use of more distributed thermal power generation in the city in residential areas, in places where there may be a higher geothermal potential, scenario 3 would provide a better minimum performance than that perceived in scenario 2.

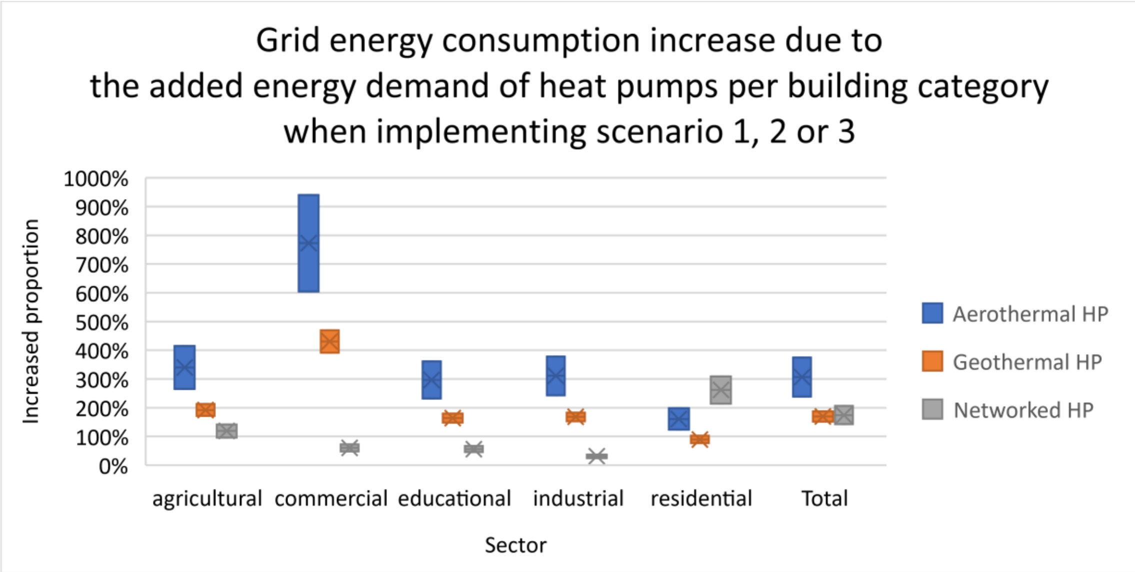



**Figure 40. Grid energy consumption increase due to the added energy demand of heat pumps per building category when implementing scenario 1, 2 or 3.**

**Table 15. Increase of electrical energy consumption in Oldenburg's city due to the added energy demand of heat pumps per building category when implementing scenario 1, 2 or 3.**

| Scenario | Category | District El_en demand [GWh] | Min % | Max % |
|---|---|---|---|---|
| Aerothermal heat pumps | agricultural | 9.24 | 265.0% | 414.4% |
| | commercial | 177.15 | 604.7% | 940.3% |
| | educational | 21.87 | 232.0% | 361.1% |
| | industrial | 185.27 | 243.3% | 378.3% |
| | residential | 573.42 | 123.5% | 198.0% |
| | Total | **966.95** | **238.4%** | **374.3%** |
| Geothermal heat pumps | agricultural | 9.24 | 171.5% | 213.2% |
| | commercial | 177.15 | 391.1% | 469.7% |
| | educational | 21.87 | 148.3% | 179.4% |
| | industrial | 185.27 | 152.6% | 183.2% |
| | residential | 573.42 | 77.2% | 102.2% |
| | Total | **966.95** | **151.6%** | **187.9%** |
| Network of geothermal and aerothermal heat pumps | agricultural | 9.24 | 96.2% | 141.6% |
| | commercial | 177.15 | 47.7% | 72.1% |
| | educational | 21.87 | 45.5% | 66.7% |
| | industrial | 185.27 | 24.4% | 37.4% |
| | residential | 573.42 | 214.1% | 309.2% |
| | Total | **966.95** | **142.3%** | **206.6%** |

Figure 40 shows the proportion of increased energy in the electric power supply circuit concerning current consumption by building category. As previously mentioned, while for scenarios 1 and 2, electric energy consumption would increase proportionally to thermal energy consumption by building category, scenario 3 would not increase energy consumption proportionally in all buildings. Scenario 3 would distribute the installation of shallow geothermal systems in the residential sector in places where LBEG does not provide information about possible restrictions and generates an average energy consumption growth in the residential building category of 261.65%.

### 5.3 Heat supply geographic distribution of scenario 3.

To better visualize what was explained in Section 5.1, Figure 41 and Figure 42 are presented to identify how the heat consumption and supply are distributed. Although the highest estimated energy consumption is concentrated in Eversten, Twelbäke and Wechloy, the energy supply would not exactly come from these districts due to the category, number and size of the buildings present there. In the case of the Wechloy district, which has a high thermal energy consumption, this could be supported by neighbouring systems installed in the districts of Bloherferde and Dietrichfeld, which are not characterized by high consumption but do have a higher geothermal potential than Wechloy itself, complying with the installation restrictions mentioned in [35].

The same case occurs with the district of Twelbäke, which concentrates the highest energy consumption among all the districts, but as it has few buildings, its demand can be met by nearby systems that could be installed in Bümmerstede and Drielaker-Moor. Regarding Drielaker-Moor, Figure 42 shows that it has the potential to support Twelbäke and the Neuenwege district, which has a high demand but a low supply due to its low building density. Eversten is perhaps one of the districts with the highest demand and high potential to be served self-sufficiently. With most buildings, it could serve itself with a network of interconnected shallow geothermal pumps.

Ofenerdiek stands out as one of the districts with the highest geothermal potential for one main reason: this district has a high density of buildings and a low heat consumption, so it has a great potential to support the energy supply in the Etzhorn district. Finally, districts in LBEG-restricted locations, such as Alexandersfeld, Ehnernviertel, Bürgerbusch, or Donnerschwee, have a high heat supply value because they would implement aerothermal heat pump technologies.

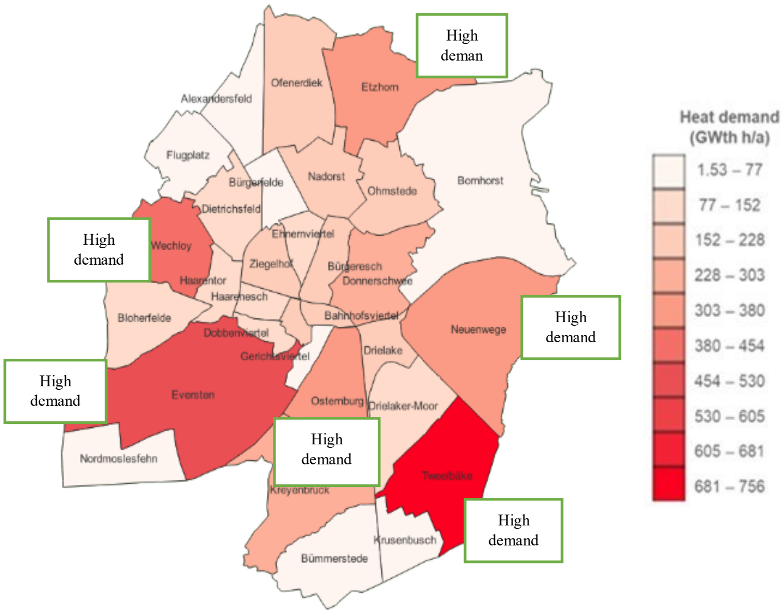



**Figure 41. GIS-based distribution of heat consumption.**

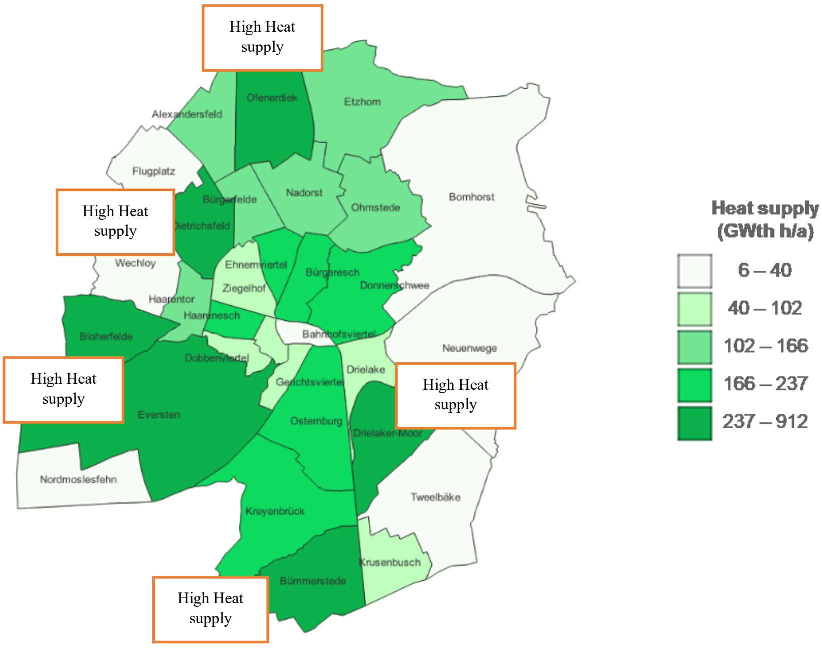



**Figure 42. GIS-based distribution of heat supply using available SGE, and aerothermal heat pumps, according to scenario 3.**

## 5.4 Economic analysis

So far, the pressure on the growth of the distribution network facilities that may result from implementing each scenario and the associated electricity consumption has been reviewed. In this section, an analysis will focus on reviewing the costs of implementing each scenario from the point of view of the cost associated with increasing the capacity of the electrical network to implement each scenario, as well as the cost of the electrical energy involved in its operation.

**Table 16. Cost of upgrading the grid to implement scenarios 1, 2, and 3.**

| Demand level | Scenario | Grid adaptation cost (Mill. of €) |
|---|---|---|
| Max power demand | Scenario 1: Aerothermal HP | 271 € |
| | Scenario 2: Geothermal HP | 136 € |
| | Scenario 3: Networked HP | 150 € |
| Min power demand | Scenario 1: Aerothermal HP | 173 € |
| | Scenario 2: Geothermal HP | 110 € |
| | Scenario 3: Networked HP | 103 € |

Table 16 presents the cost of increasing the power grid's capacity to implement each scenario. Since the estimate of this cost is directly proportional to the value of the estimated demand, scenario 1, which requires a higher average power, with values between 960 and 1508 MW, the adaptation would imply an investment of between 103 and 271 million euros. The value of 0.18 €/W corresponds to the figure of increasing the capacity of the distribution network to allow the flow of electricity that would be delivered by an installation with an average power of 128 GW of renewable energy by 2032 [48]. Assuming a German population as of September 2022 of 84,270,625 [51], the population of Oldenburg would be 0.21% of the total. Assuming that the consumption of thermal energy can be distributed proportionally with the number of inhabitants, this would mean that of the 128 GW of additional power required in Germany, only 264 MW would correspond to the growth in the power of the city of Oldenburg. Therefore, implementing scenario 1which would request between 960 and1508 MW is not only a high cost for the estimates made in that study, but it would also be a value five times outside the proportional estimates made with numbers in [48].

Likewise, for the case of scenario 2, implementation costs vary between 110 million euros and between 103 and 150 million euros for the case of scenario 3. In the best scenario, which would be the minimum cost of implementing scenario 3, i.e. 103 million, it is a value that, compared to implementing scenario 1, is close to one-third of the maximum value of scenario 1, 271 million euros. Likewise, considering scenario 3, the minimum value of power growth in the distribution network of 573 MW, compared to the 264 MW that was estimated according to the proportion of inhabitants of the city of Oldenburg, would mean that under the results that have been estimated here, the growth of the network should be 117% higher than mentioned in that study.

Although the values arrived at in this research seem high compared to the estimates made by [48], it is essential to consider that previously heat supply from 100% renewable sources was not estimated, ruling out the use of gas for heat supply altogether. In this sense, this study contributes to the knowledge of the implementation of this technology, explaining the benefits at the level of self-sufficiency in heat supply, but also warning that the spread of this technology implies tremendous pressure on the distribution network to be updated, and means essential investments that must be considered in the growth scenarios of the distribution networks.

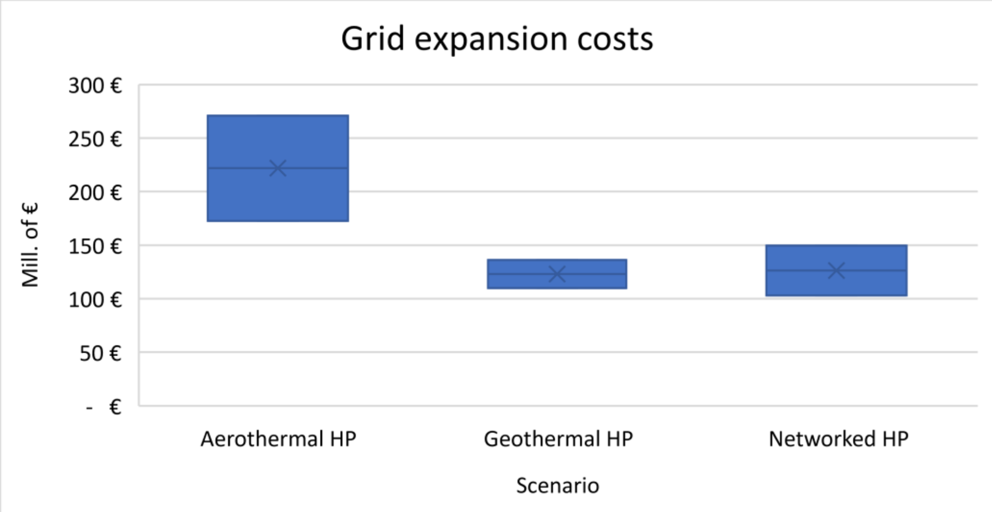



**Figure 43. Grid expansion costs of scenarios 1, 2 and 3.**

Figure 43 represents the comparison of implementing the three scenarios. Thus, if a city has the possibility of generating the heat required in winter using geothermal systems, this study can help utilities to orient their efforts to find solutions for implementing geothermal systems in such a way that they can reduce the need to increase the capacity of the electrical grid to support the implementation of this technology.

Although the average values of the grid growth cost are similar for the geothermal and networked heat pump scenarios, the uncertainty for the networked heat pumps is higher. This occurs mainly, because of two reasons. First, because in the networked heat pumps scenario it is pretended to cover the 100% heat demand of the city, and second because the scenario uses also a small portion of aerothermal heat pumps, and because they are wider efficient range, they add uncertainty to the grid expansion costs estimated.

Using the cost of electric energy obtained for each scenario and dividing it by the value of thermal energy, the values of the Table 17 are obtained. This table is relevant because it allows a comparison of the values obtained with the cost in Cents of €/kWh of the current gas market.

When consulting the website of the energy supply company of Oldenburg SWO [52], the following values for the price per kWh of gas can be found. As of February 18, 2023, the price is 12 cents/kWh of gas for anyone using it for private purposes, heating water with a gas boiler, heating, cooking, or other purposes. If the gas is used in a thermal district, the cost is 9.5 cents/kWh. When analysing these two prices, the fairest value that should be used for comparison with those obtained in Table 17 should be the offered one by SWO for use in thermal districts. When comparing the value obtained by scenario 1, the maximum value per kWh of 17 cents/kWh is high, even at a time when gas prices are high. However, the minimum price in scenario 1 of 10.9 cents/kWh is only 1.4 cents/kWh above the price set by SWO. In the case of scenarios 2 and 3, both offer a maximum and minimum cost of lower than 9.5 cents/kWh. This result not only suggests the economic viability of shallow geothermal systems for users in terms of the cost they would pay per kWh but since geothermal energy is a renewable energy source, it contributes significantly to the objectives of decarbonising the energy matrix of the UES.

**Table 17. Heat cost of scenarios 1, 2 and 3.**

| Demand level | Scenario | Heat cost [Cents of €/kWh] |
|---|---|---|
| Max energy cost | Scenario 1: Aerothermal HP | 17.0 |
| | Scenario 2: Geothermal HP | 8.6 |
| | Scenario 3: Networked HP | 9.4 |
| Min energy cost | Scenario 1: Aerothermal HP | 10.9 |
| | Scenario 2: Geothermal HP | 6.9 |
| | Scenario 3: Networked HP | 6.5 |

### 5.5 Self-sufficiency heat contribution of geothermal technologies considering results in scenario 3

This section will analyse the contribution of self-sufficiency to the city's thermal energy supply using scenario three as a reference. Starting from the concept of autarky is explained by [53], which means the ability of a region not to import energy resources, electricity as well as heat, from other regions so that it can instead use its local resources to meet the needs of its energy system. In this section, we will perform a simple calculation in which we will identify, from 100% of the energy required for energy consumption, how much corresponds to electrical energy coming from the grid and to energy provided by the geothermal and aerothermal systems as defined in scenario 3.

Table 18 summarizes the self-sufficiency values that Oldenburg could obtain to meet its heat consumption in case scenario three is implemented. Maximum self-sufficiency of 75.5% means that to supply the 100% of heat consumption in Oldenburg's city, the electric grid would supply 24.5% of the thermal energy, and the remaining 75.5% of the thermal energy could be supplied by a combination of 12.8% aerothermal systems and 87.2% shallow geothermal systems. The maximum value would occur when the systems with the best COP are installed. Likewise, when heat pumps with the lowest COP are installed, a self-sufficiency of 64.5% could be achieved.

**Table 18. Self-sufficiency provided to the UES of Oldenburg by scenario 3.**

| Self-sufficiency provided by scenario 3 to the city of Oldenburg | | |
|---|---|---|
| Total Heating demand (GWth h/a) | | 5,629 |
| Min Energy Consumption | Max Self-sufficiency (%) | 75.5% |
| | Min Energy Consumption GWh/a | 1,376 |
| | Proportion of Self-sufficiency coming from Aerothermal Systems (%) | 12.8% |
| | Proportion of Self-sufficiency coming from Shallow Geothermal Systems (%) | 87.2% |
| Max Energy Consumption | Min Self-sufficiency (%) | 64.5% |
| | Max Energy Consumption (GWh/a) | 1,998 |
| | Proportion of Self-sufficiency coming from Aerothermal Systems (%) | 14.0% |
| | Proportion of Self-sufficiency coming from Shallow Geothermal Systems (%) | 86.0% |

This result is significant from the point of view of the possibility of supplying 100% of the thermal energy consumption by the city of Oldenburg using renewable energy sources. Although gas is currently the primary energy source for providing heat, it could be replaced by an optimal mix of SGE and aerothermal energy. In addition, if the city's thermal energy supply became 100% self-sufficient, the remaining 24.5 to 35.5% of the electricity grid could be generated by renewable sources such as wind and solar energy. At this point, it is recalled that scenario 3 has a proportion of thermal energy supplied by air/water heat pumps in those places where it is not allowed to install BHE, according to the information provided by LBEG. Thus, the self-sufficiency presented here is obtained by combining heat supply from geothermal and aerothermal systems. Figure 44 is a graphical representation of the results obtained in Table 18.

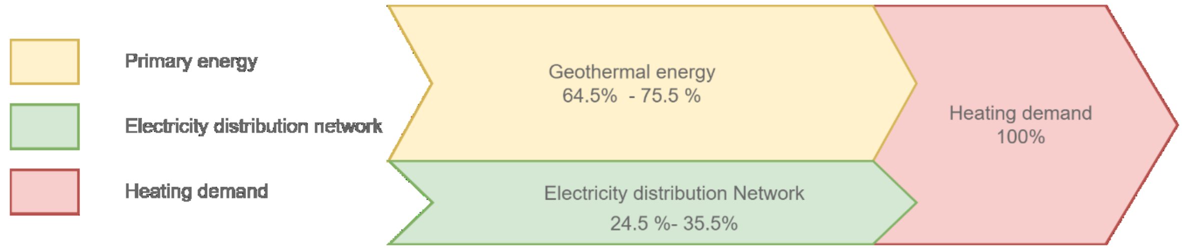



**Figure 44. Graphic representation of Self-sufficiency provided by scenario 3 to supply heat to the city of Oldenburg.**

# Chapter 6 Conclusions and outlook

Integrating shallow geothermal systems allows Urban Energy Systems (UES) to have a lower average power and electrical energy requirement from the power grids to supply heat than if aerothermal heat pumps were implemented. However, the deployment of shallow geothermal heat systems depends on the heat energy potential at the respective geographical area, and having a condition of no restrictions at the site related to the possible contamination of water streams. Using the city of Oldenburg as a case study, this research developed a model to compare the area required for the deployment of shallow geothermal heat extraction systems and to estimate the power and electrical energy consumption of three possible scenarios, in which aerothermal, geothermal, or a combination of the two type of heat pumps could be implemented.

This work responds to the research questions stated in section 1.3. In order to solve them, the researcher started by reading related literature and previous studies. The information consulted identified the most relevant variables and data sources needed to develop a mathematical model to infer the answers to the questions formulated. Then, using information provided by State Office for Mining, Energy and Geology of Lower Saxony (LBEG) on the geothermal potential and water flow restrictions in the city, three geothermal systems were compared: horizontal collectors, basket-type collectors, and Borehole Heat Exchangers BHE, to identify which one could be the most suitable for implementation in urban systems.

In the first scenario, aerothermal heat pumps would meet the heat demand. In the second scenario, it was considered that the demand would be completed by geothermal heat pumps, wherever a geothermal system could be installed, regardless of the number of wells required to supply the thermal energy needed for each building. In the third scenario, it was defined that the city's heat consumption would be met by geothermal heat pumps, using its maximum shallow geothermal potential, in wells up to the total allowable 400 meters long. The results of these scenarios allowed us to identify the average power demand of the shallow geothermal systems, their energy consumption, and their contribution to the self-sufficiency of the energy system of the city of Oldenburg.

The results indicate that Ground Source Heat Pumps (GSHP) using BHE are more suitable for implementation in cities because they use less area per heat power delivered than the basket and horizontal collectors. While BHE used 2.24 $m^2/kW$, other shallow geothermal systems require the double or even times bigger areas to supply the same amount of heat.

It was also possible to deduce that geothermal systems exert less pressure than aerothermal systems on the power supplied by distribution networks because geothermal heat pumps perform better than aerothermal pumps. The coefficient of performance (COP) measures the heat pump's efficiency, defined as the ratio of heat output to electrical input. A higher COP indicates a more efficient heat pump. Geothermal heat pumps typically have a COP of 3 to 6, producing three to six units of heat for every unit of electrical energy used to power the heat pump. In comparison, aerothermal heat pumps typically have a COP of 2 to 4, producing two to four units of heat for every unit of electrical energy used. The better performance is because the temperature difference between the ground and the refrigerant is smaller and more constant than the temperature difference between the air and the refrigerant. This means less energy is required to transfer heat between the two mediums.

Using updated energy contract values to extract energy prices for geothermal heat pumps and gas supply contracts, was possible to identify that Shallow Geothermal Energy (SGE) could offer more economical alternative prices than aerothermal heat pumps and even than gas in thermal districts. In this sense, there are several economic benefits to implementing geothermal systems. First, the grid operators will benefit because they must invest less in the networks, between 70 and 121 million of € when implementing SGE through the networked heat pumps scenario instead of aerothermal heat pumps. Second, consumers find an economically comparable alternative to the current gas price which is around 9.5 Cents of €/kWh for thermal districts. For the same kWh of heat, they could pay between of 6.5 to 9.4 Cents of €/kWh when sourced from geothermal systems as the ones simulated in scenarios 2 and 3. Thirdly, is the environment, which can benefit from reducing the carbon footprint by having between 65 and 75% of the heat supply coming from a renewable source. However, this proportion can be even higher if the remaining percentage depending on the electrical energy coming from the grid, is coupled with renewable energy sources.

The results obtained in this study have been based on opensource data, which allows the independent character of the research development of any little interest. Though, other studies like the one in [32], have gotten deviations of around -4% and 16% to the real heat consumption, it is intended to share with the interested people in this research that developing studies that support the planning of UES from the use of open source data is possible, and you may get good approximations to the real heat consumption values.

For implementing shallow geothermal heat pumps in cities, it is essential to consider all possible challenges of this technology. In this study, the constraints known to LBEG have been considered, and they were mainly related to the potential contamination of water streams. Though only 4% of Oldenburg's city corresponds to lakes and rivers, and it is understood as restricted areas to install SGE, according to the LBEG, 24.6% of the town has areas marked with known reasons to do not allow installation of SGE, and where please check before with the LBEG if a project can be installing, and under which conditions the facility should be done.

The recent gas shortage and the need to diversify the energy matrix basket have led to a consideration of future growth scenarios for power grids, which may require the implementation of deep geothermal systems and centralized thermal districts. Deep geothermal energy has already grown significantly in Germany since 2003, with 250 MW of total installed capacity for geothermal heat production in 2013 [54], but there is still a high potential for growth and integration into urban energy systems. Deep geothermal energy is a more stable source of renewable energy compared to solar and wind energy and may be enough to cover the full heat consumption of a city. However, it is not emission-free and may release greenhouse gases during the combustion process [55], which could counteract its benefits as a renewable source. Furthermore, concerns exist regarding structural alterations due to hydraulic fracking implemented as a deep drilling technique. Despite these challenges, the potential for growth in the German geothermal power sector remains high.

Regarding the current digital energy market in Germany, Geothermal energy has the potential to play an essential role. The digital market is a complex system that aims to make energy production and consumption more efficient and sustainable by integrating renewable energy sources and digital technologies. It implements smart meters and energy storage systems, critical elements of the digital energy market in Germany that allow for more accurate billing, pricing, and balancing of the supply and demand of electricity; and virtual power plants (VPPs), which can sell excess renewable energy back into the grid [56]. In this way, Geothermal energy might provide a reliable and sustainable source of heat that can support the integration of variable renewable energy sources and help meet the energy consumptions of a growing population. The predictability of geothermal energy makes it well-suited for supporting the integration of renewable energy sources and can be further optimized by digital technologies to enhance its performance and efficiency.

The study recommends developing a model that evaluates the effect of climate on heat consumption and its impact on the instantaneous power demand of geothermal pumps. By doing so, researchers can approximate these solutions' maximum power demand and electrical energy consumption, leading to better-informed decisions regarding their implementation.

To conclude with some recommendations:

- Further improvements can be made to the model by developing a time and temperature dependant modelling to find the heat consumption calculation.
- By making a time-dependent model, it would be possible to better couple thermal energy with other renewable energy systems, so as to integrate them into additional analyses in the digital energy market.
- Additional model accuracy can be achieved by including estimated hot water transportation losses in SGE with sufficient potential to supply nearby buildings.
- By coupling shallow geothermal energy (SGE) to an electrical grid that utilizes other renewable energy sources, such as solar and wind energy, it is possible to model the totality of urban energy requirements using tools like FlexiGIS. This modelling allows for the identification of the optimal mix of each renewable energy source to achieve greater self-sufficiency for the system.
- Improvements to the model in terms of greater accuracy of the geothermal potential of different city areas can be made by implementing geographic extrapolations, which are different from the subject of this study.
- It could be possible to develop the calculation of an optimal scenario of SGE implementation for a city based on a network that intensifies the use of areas with more significant geothermal potential than others and establishing, from them, distributed thermal districts that can serve a city.
- Utilities should review the legal instruments to develop distributed SGE with the capacity to supply heat to several buildings and to reduce the costs of adapting electricity grids.

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