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“Are ground-source heat pumps ready for decarbonizing residential heating and cooling?”

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Declaro, bajo mi responsabilidad, que el Proyecto presentado con el título

"Are ground-source heat pumps ready for decarbonizing residential heating and cooling?"

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Fdo.: Rodrigo Alonso Albertos Fecha: 1/ junio/ 2024

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“ARE GROUND-SOURCE HEAT PUMPS READY FOR DECARBONIZING RESIDENTIAL HEATING AND COOLING?”

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PROJECT SUMMARY

An analysis of Ground Source Heat Pump (GSHP) systems was thoroughly carried out, examining their efficiency parameters, operational dynamics, and economic aspects within various climates including Texas (hot humid), North Carolina (warm humid), and Massachusetts (cold humid). The influence of regional weather patterns, energy pricing, and specific GSHP system characteristics such as Coefficient of Performance (COP), and heating and cooling capacities, on their performance and cost-efficiency were also considered for an economic investigation. Comparative evaluations with other heating and cooling technologies were conducted, emphasizing the potential of GSHPs for facilitating the decarbonization of residential and commercial sectors.

Key words: Heat Pump, Grounds Source Heat Pump, Geothermic Heat Pump, Air Source Heat Pump, Cooling, Heating.

1. Introduction

The latest International Energy Agency roadmap claims that while most countries have pledged to reduce greenhouse gases emissions, the figure for these on a global scale do not seem to reach their upper limit, setting the stage for an in-depth analysis on the readiness of GSHP for decarbonizing residential heating and cooling. With the building sector being a major contributor to greenhouse gas (GHG), the rapid increase in global heat pump installations points towards a promising trend in sustainable building technologies. This thesis aims to explore the techno-economic aspects of GSHPs, their efficiency advantages over traditional systems, and their growing role in mitigating climate change.

2. Project definition

This project aims to rigorously evaluate the viability of GSHPs in mitigating residential carbon emissions within the context of global net-zero commitments and rising GHG emissions. By employing a combination of data analysis, advanced system modeling, and literature analysis, the study seeks to assess the techno-economic viability, operational efficiency, and market adoption rates of GSHPs, contrasted against traditional heating and cooling technologies. The anticipated outcome is a report that not only underscores the efficiency and potential environmental benefits of GSHPs but also provides strategic recommendations to enhance their adoption and implementation across diverse residential settings.

3. Model description

The model is designed to evaluate the efficiency and economic viability of GSHP systems across various residential settings. It incorporates dynamic simulations that account for regional climate variations, energy pricing, and system-specific parameters such as COP, heating and cooling capacities, and ground temperatures. The model calculates the energy consumption for heating and cooling based on actual meteorological data and simulates the operational costs by integrating current market rates for electricity and gas. Further, it considers installation costs, maintenance, and potential subsidies to provide a complete analysis of the cost-effectiveness of GSHP installations. This robust model enables a detailed assessment of GSHP performance over time, providing insights into their potential as sustainable solutions for residential environments

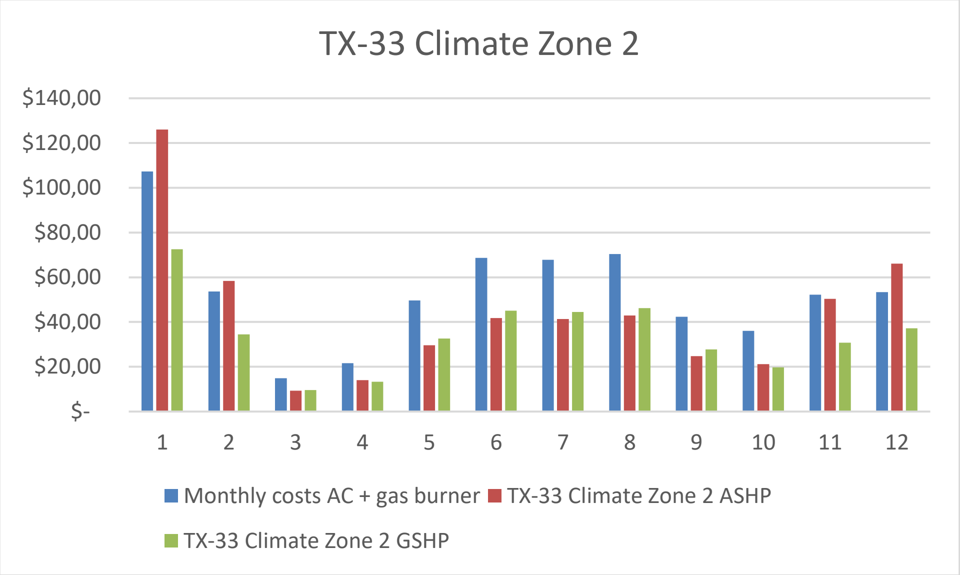

Figure 7. Estimations of monthly running costs for 2017 weather and energy demand of a 350 square meter house in Texas comparison of AC + gas burner system against ASHP and GSHP installations.

4. Results

First, total energy demands reflect regional climate influences, with Texas having a higher cooling demand (9021kWh) compared to heating (7129kWh), which contrasts with North Carolina (12502kWh heating, 2505kWh cooling) and Massachusetts (17221kWh heating, 2739kWh cooling). These figures underscore the predominance of heating in colder states and cooling in warmer states, indicating a clear thermal imbalance across the regions.

Second, these thermal imbalances on the GSHPs' efficiency, noting that persistent imbalances could alter the ground temperatures around the BHEs, potentially decreasing the system's COP over time. In Texas the modelled COP drifted from 5 to 4.99, while in North Carolina the system changed from a COP of 4.6 to 4.57; in Massachusetts these numbers were of 4.1 and 4.06 in the span of one year. A linear correlation is used to model these temperature changes, providing insights into how prolonged deviations in thermal input and output could affect the GSHP's performance.

Third, although the model offers an approximation rather than precise predictions, it serves as a critical tool for assessing the long-term sustainability and efficiency of GSHP installations in varying climatic conditions. We observe that costs in TX, scenario where cooling is predominant, yearly operational costs for AC and gas burner, ASHP, and GSHP systems were $638, $526, and $413, respectively, highlighting significant savings with GSHPs due to their superior efficiency in cooling. In a heating-focused scenario in North Carolina, GSHPs again showed lower annual costs at $413 compared to $580 for AC and gas burner systems and $613 for ASHPs, underscoring the GSHP's ability to reduce heating costs effectively. In Massachusetts, where heating is crucial, the GSHP system's annual running costs were $620, significantly lower than $1,027 for AC and gas burner and $812 for ASHPs, translating to a 42% cost reduction if only heating were considered. These figures demonstrate the substantial savings and increased efficiency GSHPs offer over both traditional and alternative heating systems

5. Conclusions

In the analysis of GSHP, it is clear that their viability heavily relies on the fluctuating costs of electricity and gas, with economic factors significantly affecting their operational expenses. GSHPs are particularly beneficial in commercial settings due to their high COPs and the substantial long-term energy savings that offset the initial high installation costs, leveraging economies of scale more effectively than in residential applications. The industry's rapid growth and scaling capabilities suggest a promising future for GSHP technology, enhancing its affordability and accessibility as unit costs decrease.

Our findings confirm that GSHPs are well-suited for widespread decarbonization efforts. Through comparative analysis, GSHPs show superior energy efficiency and environmental benefits over traditional heat pumps and fossil fuel-based systems. Furthermore, the modeling of GSHPs within a residential context demonstrates their practical efficiency and the ability to handle complex installation dynamics. With increasing installation rates and ongoing advancements, GSHPs are poised to significantly contribute to a sustainable energy transition. This study supports a bright outlook for GSHP technology, driven by both economic and environmental advantages, as it moves towards greater adoption and impact.

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CHAPTER 1. INTRODUCTION.

"The number of countries that have pledged to reach net-zero emissions by mid-century or soon after continues to grow, but so do global greenhouse gas emissions" opens the latest IEA roadmap for the Global Energy Sector which offers its scrutiny of trends and technology for their 2050 Roadmap. A bold yet true statement that will be the lightguide and late motif of the following thesis: "Are ground-source heat pumps ready for decarbonizing residential heating and cooling?".

In charting a course towards a sustainable future, the onus of emissions reduction has significantly fallen on the choices consumers make. An estimated 55% of the cumulative emissions reductions are attributed to consumer choices like opting for electric vehicles and (retro)fitting homes with energy-efficient and decarbonized technologies like the installation of heat pumps. In comparison, a mere 4% is credited to behavioral changes. Among the myriads of sustainable options available to consumers, ground-source heat pumps (GSHPs) emerge as a front runner for numerous reasons. As it is clearly demonstrated in [9_1].

The building sector, directly accounting for about 7% of the overall greenhouse gas emissions (GHGs) in the US, presents a sizable opportunity for emission reductions. Given that buildings are long-term infrastructures, the choices made today concerning their energy systems can have profound implications for decades to come. The compelling trajectory of heat pump installations corroborates their increasing prominence in addressing this challenge. From a global standpoint, heat pump installations are witnessing a meteoric rise – escalating from 180 million units in 2020 to an anticipated 600 million units by 2030, projected to further soar to 1800 million by 2050. (This data is extracted from [9_1] and [0_0])

One of the notable hallmarks of GSHPs is their efficiency. These pumps stand out as being at least three times more efficient than traditional fossil fuel boilers and other polluting alternatives. Such heightened efficiency not only translates to reduced energy bills for consumers but also diminishes the carbon footprint of the building sector. By 2050, it is anticipated that two-thirds of residential buildings in advanced economies, and close to 40% in emerging market and developing economies, will be equipped with a heat pump. [0_0]

The potential of GSHPs in redefining the energy landscape of buildings is evident. Their unparalleled efficiency combined with their escalating adoption underscores their crucial role in steering the world towards a pathway of reduced emissions. Through this paper, we aim to analyze the techno-economic viability of GSHPs in numerous conditions of utilization, classify GSHP based on their operative and technical specifications, compare GSHPs and HPs in distinct use conditions and model their behavior in a residential building.

CHAPTER 2. STATE OF THE ART

Heat Pumps (HPs) are not a new kind of technology, the first examples of them date to 1748[oo]. HPs are devices designed to transfer thermal energy opposite to the natural flow of heat. By consuming a smaller amount of primary energy, HPs transport energy from a source, like the ground or air, to a destination, such as buildings, for heating or cooling purposes. This heat transfer, in opposition to heat creation is the reason why heat pumps are able to achieve efficiencies of 400% or 1000%; this is referred to as Coefficient of Performance (COP) instead of as an efficiency, as it measures the heat output at the desired end in relation to the energy used to transfer it, which can be greater than one.

$$COP = \frac{|Q|}{W}$$

Where:

Q is the useful heat supplied or removed by the system.

W is the energy put into the system; electricity consumed in most HP uses.

COP in modern day HPs and GSHPs with both input and output temperature for heating purposes can be seen in the following chart :

Table 1. HP Performance exemplification. Source: I. Sarbu and C. Sebarchievici, 'Using Ground-Source Heat Pump Systems for Heating/Cooling of Buildings', Advances in Geothermal Energy. InTech, Jan. 20, 2016. doi: 10.5772/61372. Notes: A Two-stage HP the compressor can run in two settings, a lower, smaller load one combined with a higher load, higher intensity setting. GSHP COPs are estimations for high-efficiency GSHPs

Pump type and source	**35 °C**	**45 °C**	**55 °C**	**65 °C**	**75 °C**	**85 °C**
HP, air at -20°C	2.2	2.0	-	-	-	-
Two-stage HP, air at −20 °C	2.4	2.2	1.9	-	-	-
High-efficiency HP, air at 0 °C	3.8	2.8	2.2	2.0	-	-
GSHP, water at 0 °C	5.0	3.7	2.9	2.4	-	-
GSHP, water at 10 °C	7.2	5.0	3.7	2.9	2.4	-
GSHP, water at 20 °C	8.1	7	5	3.9	3	2.5
GSHP, water at 30 °C	11.1	8.8	7.2	5	4.2	3.2
Theoretical Carnot cycle limit, source −20 °C	5.6	4.9	4.4	4.0	3.7	3.4
Theoretical Carnot cycle limit, source 0 °C	8.8	7.1	6.0	5.2	4.6	4.2
Theoretical Carnot cycle limit, source 10 °C	12.3	9.1	7.3	6.1	5.4	4.8
Theoretical Carnot cycle limit, source 20 °C	20.53	12.72	9.37	7.51	6.32	5.50
Theoretical Carnot cycle limit, source 30 °C	61.6	21.2	13.12	9.66	7.73	6.51

HPs can be primarily classified based on their heat sources and exchange mediums:

- Air-to-Air Heat Pumps: these are the most commonly used HPs that transfer heat between the indoor air and the outdoor air. They are versatile and can be used for both heating and cooling purposes. In winter the outside air, which we extract heat from, is cold, and in summer the outside air which we supply heat to is hot. This also applies to day/night cycles.
- Water Source Heat Pumps: these extract heat from a water source, such as rivers or lakes. Their efficiency is often tied to the water's temperature, which can vary seasonally, although usually in a much smaller range than air.
- Geothermal (or Ground Source) Heat Pumps: these utilize the constant temperature of the earth as the exchange medium. Geothermal HPs are particularly efficient since the earth's temperature is less subject to seasonal fluctuations as compared to air or water. Furthermore, the ground's shallow layer under determined conditions follows a thermal cycle with a retardation of 6 months respect to the surface temperature.

Depending on the installation and the heat exchange methods, GSHPs can be divided into:

- Horizontal GSHPs: these systems have their loops laid out horizontally a few meters beneath the ground. They are typically used in residential settings with adequate land. They require digging trenches and their efficiency is heavily affected by soil characteristics and depth in which the heat exchanger was installed.
- Vertical GSHPs: the loops in these systems are installed vertically, usually being closed by U-shaped pipe segments. They are preferred in commercial settings or places with limited land availability.
- Pond/Lake GSHPs: these are used when a water body is available close by. The loops are coiled and placed at the bottom of the pond or lake, leveraging the relatively stable temperature of the water source.
- Open loop GSHPs: these systems take water from a natural source (normally ground water), run it through the system and release it at a different temperature. Due to the inability to adapt the fluid’s composition to utilization requirements, challenges such as corrosion or limescale must be considered. Furthermore, the variation of ground water temperatures and their lack of replenishment could be environmentally damaging.

The cutting-edge performance of GSHPs cannot be understated. As seen in the previous chart, their COP can easily reach 5 in commercial buildings for both heating and cooling demand. [0_0] Furthermore, projections indicate a promising future for HPs in the broader heating industry, with expectations that "50% of heating demand will be met by heat pumps by 2045” [0_1].

The refrigerant choice also is a key part of the viability of HPs as well as GSHPs if they are wanted to represent the environment-friendly option to fossil fuel burners.

To put this into context, a regular HP contains approximately 3 kilograms of refrigerant. The amount of damage refrigerants could cause to the atmosphere if released is not measured by the Global Warming Potential (GWP) of each gas. Until 1987 the vast majority of refrigerants were CFCs, not having a great GWP but instead creating extremely destructive reactions with the Ozone Layer.

Propane cycles are in great use nowadays, they are cheap, have zero ozone depletion potential and GWP of around 0.072. However, they are flammable. 75% of refrigerators manufactured in 2020 used propane or iso-propane cycles. CO_2 cycles, on the other hand, are not widely available, their research and development are still continuing. They would have the advantage of having a GWP of 1, zero ozone depletion potential and would be the cheapest refrigerant in the market. Nonetheless, the upfront cost of these systems would be greater than other cycles. They would be ideal for big systems such as commercial installations.

In summary, the evolution and perspectives of heat pumps, especially GSHPs, have positioned them as vital components in the quest for energy efficiency and sustainability in both residential and commercial sectors. Their continually improving efficiencies, plummeting upfront costs and adaptations to different environments make them a promising technology, which has already proven itself, in the context of modern energy needs.

CHAPTER 3. SCOPE DEFINITION

4.4 MOTIVATION

In recent decades, as the world grapples with mounting environmental challenges, the quest for sustainable and efficient energy solutions has intensified. The importance of transitioning to greener energy alternatives cannot be overstated. As demonstrated earlier, heat pumps (HPs), and in particular, GSHPs emerge as one of the most promising technologies to counteract the adverse impacts of greenhouse gas emissions, primarily stemming from conventional heating methods.

Given that 55% of cumulative emissions reductions are attributed to consumer choices such as the adoption of GSHPs, it is evident that such technologies are central to the broader goal of climate mitigation. The building sector alone, while representing 7% of the overall greenhouse gas emissions in the US (direct emissions), holds immense potential for emissions reduction. Furthermore, the projections of heat pump installations, expected to reach 1800 million by 2050, showcases the technology's anticipated ubiquity and relevance in the near future.

GSHPs stand out among their counterparts, especially considering their inherent efficiency derived from the earth's relatively stable temperature. A crucial aspect to underline here is the COP. When a GSHP has a COP greater than 2.5, it transcends the efficiency of directly burning gas for heating, thereby offering not just an environmentally friendly alternative but also a more energy-efficient one.

The present circumstances offers near-perfect conditions for the proliferation of GSHPs. On one hand, we have a technology that has matured and proven its efficiency and reliability over the years. On the other hand, there's a palpable global demand to achieve energy independence and to distance economies from the volatilities and environmental ramifications associated with fossil fuels.

Thus, given the clear alignment of technological readiness, environmental imperatives, and the desire for energy autonomy, there arises a need for a complete study. This thesis, therefore, aims to provide an in-depth examination of GSHPs, charting their evolution, efficiency, and potential in shaping a sustainable future. By dissecting their mechanisms, types, and applications, we seek to bolster the discourse around GSHPs and champion their wider adoption in the years to come.

4.5 OBJETIVES

Main objective:

1- Techno-economic evaluation of GSHP under different operating conditions. This objective seeks to assess the feasibility and cost-effectiveness of GSHPs across diverse operational scenarios. By examining how varying conditions impact their efficiency and economic viability, we aim to determine the optimal settings for GSHP deployment.

Secondary objectives:

2- Analyze the technological challenges faced by GSHPs, especially refrigerant contamination. Dive into the potential technical issues surrounding GSHPs, this objective prioritizes understanding the risks and challenges of refrigerant contamination, its implications, and possible mitigation strategies.

3- Classification of GSHP based on operation and technical characteristics. By categorizing GSHPs based on their functional and technical features, this objective aims to create a guide of all the specific GSHP types.

4- Comparison of GSHP with standard HPs and other polluting technologies. This objective focuses on contrasting the environmental and operational attributes of GSHPs against conventional Heat Pumps and more pollutant-heavy technologies (burning fossil fuels). Such a comparative analysis is key to emphasize the advantages of GSHPs in the broader energy industry.

5- Formulation and modelling of GSHP system in residential building. Aiming to understand the real-world application of GSHPs, this objective revolves around creating a detailed model of a GSHP system within a residential context. Such modeling will shed light on its efficiency, challenges, and behavior.

4.6 METHODOLOGY

1- Literature review of GSHP technology-related articles.

A deep literature review will be conducted to gather pertinent information related to GSHPs). This will involve a thorough examination of academic journals, conference proceedings, technical reports, and industry publications. By analyzing previous studies, we aim to understand the historical context, technological advancements, and challenges associated with GSHPs, thereby building a solid foundation for our research.

2- Synthesis, identify main operative parameters and costs.

Upon extracting key insights from the literature, a synthesis process will be carried out. This will focus on pinpointing the main operative parameters of GSHPs, such as their efficiency, lifespan, and performance under various conditions. Concurrently, a cost analysis will be undertaken, examining data on installation, maintenance, and operational expenses. This synthesized information will be crucial in understanding the techno-economic aspects of GSHPs.

3- Formulation and modeling of GSHP system in a residential building.

Leveraging the data accumulated, a representative model of a GSHP system for a residential building will be formulated. This model will simulate the GSHP's operation, taking into consideration variables such as building insulation, ambient temperature, and ground properties and temperatures. By recreating a real-world scenario, we aim to gain a granular understanding of GSHP performance in residential settings.

4- Definition and execution of the cases that will be subject to study.

To further bolster the reliability of our research, a series of case studies will be delineated. These cases will encompass a spectrum of scenarios, varying in building sizes, climatic conditions, land types, and GSHP configurations. Once defined, each case will be executed, capturing data on GSHP performance, energy savings, and other pertinent metrics.

5- Analysis of results.

Post data collection from the model simulations and case studies, a rigorous analysis will be conducted. This will involve comparing the observed results against theoretical predictions, identifying discrepancies (if any), and understanding their origins. Moreover, by assessing the results, we aim to provide concrete recommendations on the optimal utilization of GSHPs in residential buildings and deduce their broader implications in the context of sustainable urban development.

By following this methodology, the research will present a holistic perspective on GSHPs and their readiness for decarbonizing the heating and cooling demands of individuals, bridging the gap between theoretical knowledge and practical applications.

CHAPTER 4. LITERATURE REVIEW

This chapter reviews articles published in previous years dedicated to GSHP technology. Due to the similar nature of GSHPs with ASHPs, this review also extracts pertinent insights from the ASHP literature, particularly in areas where studies specific to GSHPs are limited (compressor types, for example). The volume of literature, including numerous case studies, reflects the growing academic and industrial interest in the functionality and most importantly, economics, of GSHPs.

Given the advanced developmental stage and extensive analytical history of ASHPs, the methodologies and tools refined in their study provide a robust foundation for scrutinizing GSHPs. This rich background ensures that the approaches and perspectives applied in this review are grounded in a mature and developed analytical framework. This framework defines eight categories to better understand GSHP technology:

- **Types**. This category details the types/variations within GSHP technology and provides in-depth information for evaluating the performance parameters of different GSHP systems, and different classifications of both systems as a whole and their individual components. This detailed exploration of the types, components, and configurations establishes the required understanding basis of the factors that influence the efficiency and applicability of GSHP technology in diverse scenarios.
- **Uses**. Ranging from household/residential heating or cooling options to commercial and industrial uses, operating conditions often affect the ultimate use of the GSHP: a cold climate demands heating and a hot climate demands cooling.
- Challenges, viability, or lack thereof for GSHPs will be examined for each use application. With different uses come different configurations too, which is pivotal for housing uses and has been analyzed thoroughly. Utilization for industrial purposes has also been analyzed, finding an astonishing lack of studies in this field, in relation to commercial and residential uses of GSHPs.

- **Case studies**. The inclusion and thorough examination of various use scenarios of GSHPs in the literature review are key for a complete understanding of their versatility and applicability in diverse contexts. GSHP systems are not one-size-fits-all solutions; their efficiency and effectiveness can vary significantly based on a multitude of factors, such as geographic location, climate, soil conditions, and the specific energy needs of the building or application.
- By studying GSHPs across different scenarios, ranging from residential to commercial and industrial applications, the review aims to paint a holistic picture of their performance spectrum. This approach allows for the identification of best practices, potential challenges, and optimization strategies tailored to each unique scenario.
- **Technical characteristics**. This category focuses on the critical aspects of GSHP systems such as COP, capacity, and their performance variation with temperature. Of importance, it is examined the measurement of GSHP functionality, offering insights into their operational efficiency and adaptability under varying conditions.
- The variation of COP over time is highlighted as a significant challenge in the current state of GSHP technology. The review notes that while several studies have acknowledged this issue, compete long-term analysis remains relatively scarce. This gap in research is primarily due to the logistical and time constraints associated with multi-year studies, with most existing studies focusing on shorter, one-year timeframes. Understanding COP variation is crucial, as it directly impacts the long-term efficiency and cost-effectiveness of GSHP systems, especially when these systems are usually planned for 20–25-year utilization.
- Regarding the other technical aspects, it is provided an in-depth look at how GSHP capacity and efficiency respond to external temperature fluctuations. This analysis is key for predicting system performance under different climatic conditions and for designing systems that can maintain optimal efficiency despite environmental changes.
- **Costs of installation and operation**. This segment is crucial as it addresses one of the primary factors influencing the adoption of GSHP technology: its costs. The

initial assumption is that high installation costs are a significant barrier to the widespread adoption of GSHPs. It explores this premise by breaking down the expenses associated with each component of the GSHP system, offering a detailed view of where the bulk of the investment is required. This breakdown is essential for understanding the cost dynamics and for identifying potential areas where cost reductions could be achieved, making GSHPs more accessible.

- **Refrigerants**. This category examines the role of refrigerants in GSHPs, addressing a significant gap in existing literature: the impact of refrigerant choice on the COP of GSHP systems. The review acknowledges the presupposition that both thermal and physical properties of a refrigerant such as changes in performance during the heat cycle, variations in heat exchanger effectiveness, and different viscosities leading to energy losses play a crucial role in the overall efficiency of GSHPs.
- **Environmental damage**. This category analyzes the ecological implications of GSHP systems, exploring the balance between their environmental benefits and potential risks. This analysis is crucial in the context of increasing global focus on sustainable energy solutions and the alignment of this paper with SDGs.
- **Use in developing countries**. Under this category is examined the possible disparities in GSHP adoption between developed and developing regions.
- Studies on this topic are markedly scarce, as well as case studies in said geographies. This scarcity is largely attributed to the high capital costs associated with the installation and operation of GSHP systems, a significant barrier in regions where financial resources are more constrained.
- Contexts are examined in the literature to dive deep into the adoption of GSHPs in developing countries. It is relevant since the needs of heating and cooling in these countries are likely to be met with fossil fuels or traditional technologies if they are not met with GSHPs.

In what follows, we describe each of the previous categories.

4.1 TYPES OF GSHPS

In every review of a system and its functioning parameters, a preliminary evaluation of its defining characteristics is conducted. In [1_1], a practical guide to interpret and comprehend GSHPs is provided. It dives into the following concepts that are inexorable for a thorough understanding of GSHP technology:

4.1.1 PARTS OF A GSHP

Commonly divided into three distinct functional sections (as described below). Different ways of clustering HPs components (heat sink instead of primary unit, heat source instead of secondary unit for cooling units) have been discarded in this review as well as in the eyes of [1_1] and other pieces of literature, since in a case of a reversible system, the heat sink and heat source nomenclatures would revert too.

1. Primary unit or heat exchanger. Elements designated to exchange energy with matter outside the GSHP system. In this analysis, they take the form of boreholes, piles, diaphragm walls, or refrigerant loops.
2. Secondary unit. Habitually, the network of pipes or fluid-carrying devices that deliver the heat or lack thereof exchanged with the ground or other matter through the primary unit.
3. Heat pump unit. Able to operate in the same course of action as a refrigerator or in a reverse manner. Technologically traditional loops have four subcomponents: evaporator, condenser, compressor, and expansion valve.

Starting from the mentioned parts of a GSHP, the types can also be extracted from the primary and secondary units, since they affect the installation configuration, which is the most visual aspect of the system.

4.1.2 TYPES OF GSHPS

A system can be communicated to the Ground Heat Exchanger (GHE) in two fashions: open-loop and closed-loop.

4.1.2.1 Open-loop GHE

Water is pumped from a water source through the heat pump to extract heat. After the heat is transferred, the exit water is discharged into drains, surface, or subsurface water. Depending on the primordial source of the fluid, GSHPs can be classified into pond/lake/surface GSHPs and subsurface/aquifer water GSHPs.

Open-loop systems come with a series of advantages, the main of which are a lower cost compared to a ground-coupled GSHP, as is analyzed by [4_6] and other papers in the literature, such as [4_4][5_4]. This is because ground excavation represents a significative percentage of the cost of these systems, as demonstrated by [4_6]. The second advantage of open-loop systems could be the possibility of pump-and-treat facilities which could reverse environmental damage by pumping polluted water into the system and releasing purified water back into the environment. This is explored by [7_1], however, there is a lack of exploration of this topic in other branches of literature.

Disadvantages of open-loop systems include the possible limestone buildup inside the water circuit under certain conditions, as is investigated by [7_1]. Furthermore, a variance of water temperature could lead to disastrous consequences for wildlife that interacts with the water sink. These variances can exceed 3 ºC [1_1], and it is particularly relevant for pond systems, not even considering the lack of natural groundwater resources or regulatory challenges. [4_2] is a thorough case study of a commercial sized system that uses an abandoned mine well, as a heat exchange medium.

4.1.2.2 Closed-loop GHE

These components utilize and circulate a constant volume of Heat Carrier Fluid in a close network installed underground. They are also referred to as ground-coupled GSHPs, although this nomenclature can also refer to certain kind of aquifer coupled GSHPs.

Their principal advantages consist of a reduced environmental impact compared to open-loop systems and a constant temperature of ground, resulting in lower operation costs.

Disadvantages include the higher upfront cost [4_6], lack of underground volume under certain circumstances, maintenance and replacement costs, and the possibility of refrigerant leak. The costs of running the pumps to move the fluid is exacerbated by the inclusion of antifreeze and other substances in the water, decreasing its freezing point and viscosity, resulting in a higher energy input required to circulate the Heat Carrying Fluid in the loops.

A threat to this technology is the heat buildup due to thermal imbalance in the ground if heat is not evacuated at the same rate as it is imputed into the soil or is extracted at a higher rate than is replenished. [4_4] gives an illustration of how this is presented in a real system that is evaluated though the years. In [3_1], an innovative solution using solar energy is utilized to tackle this issue, although a viable and reliable alternative could be the reduction of maximum heat capacity of the system. This could also benefit with lower installation costs, since it is estimated that a 40% reduction of nominal power can result in a 69% reduction of BHE length.

Loops can be connected in different configurations based on factors such as installation cost, land area availability, thermal demand, building's foundation type, depth of heterothermal influence zone, and the timing of the installation relative to the building's construction.

- Array of horizontal loops: usually installed at a depth of 1.5-2m [1_1], changes in temperature throughout the day are less significant, while sunlight still has an impact in temperature of the soil. Due to the thermal inertia of the ground, there is a 12-hour lag (depending on a series of factors) between outside and underground temperature peaks, boosting system performance. A minimum distance of 0.5-0.8 m [1_1] is responsible for minimizing heat exchange between the exit and return legs of the pipe network. [1_1] estimates a 10-40W of usable thermal energy output, depending on soil conditions. The rule of thumb established is 1.5-5 m of loop per 1 m^2 of area serviced (depending on climatic conditions too). This technique is not suitable for heavily populated areas. It has a relatively low installation cost and is relatively simple to set up.

- Vertical borehole heat exchangers: usually installed in the 20-220 m range and separated one another by 4.5 m at least [1_1]. The rule of thumb estimates 1 m of depth per 1 m^2 served. This technique has the advantage of requiring very limited land area and great thermic stability, resulting in higher efficiency and lower running costs. However, high initial cost is a force to be reckoned. A group of BHs is referred to as a geothermal field. Interactions between BHs and the importance of their design have been considered in studies by [4_1], stating the importance of the heat plume in the presence of underground water currents. Thermomechanical interactions should also be considered, specially, with foundation elements, as stated by [1_1].
- There exist other variations such as vertical helixes or sloping angle boreholes that are not described here due to its reduced use or being in developing process.

Leaving the heat exchange parts of the system, inside the heat pump unit we can find a series of components, of which the compressor takes a capital importance, since it carries the burden of adapting the fluid to the required functioning point. Being energy intensive, the compressor choice as well as its functioning modes are relevant to the COP of the complete system.

The used compressor depends primarily on the capacity of the system [0_3]. Larger outputs tend to utilize different compressor technologies than small-sized systems, like the ones used in houses. Rotary screw compressors, also used in larger systems have the advantage of providing a steady flow of air, while reciprocating compressors provide it in bursts. A lack of studies discussing this aspect of GSHP systems has been noticed, and therefore this information has been retrieved from articles versing about ASHPs.

A compressor can function in different manners depending on its control. A simple compressor works following an on/off fashion, while a two-stage compressor can have two separate settings under one state. These settings can be used depending on the load requirements, allowing less consumption and a reduction of the parasitic loads of the system. Parasitic loads are subject to study in [4_3], being framed as a key contributor to system inefficiency since they consume energy and do not produce a bump in heat output. This increase in the denominator reduces the COP in a nonlinear fashion. A variable compressor solves this issue, being able to operate in a range of loads, enhancing performance and thus the COP of the system.

4.2 DIFFERENT USES OF GSHPS

GSHPs can be used in numerous circumstances involving flow of heat between two or more volumes. Literature vastly explains many of the different circumstances under which GSHPs hold a strong stance, exemplified and illustrated with a collection of case studies. We can outline the following use objectives:

- District heating (DH): the most extensive study in the usage of GSHPs for this objective is [2_1]. It details and exemplifies the various kinds of district heating technologies through case studies from the UK, Finland, and the Netherlands, offering valuable insights into the real-world implementation of GSHPs in different climatic and infrastructural contexts. These case studies serve as practical examples, demonstrating the adaptability and efficiency of GSHPs in enhancing the sustainability of district heating.
- There exist different types of DH networks:
- Central HP in high-temperature DH network with additional heating plant. This configuration is noted for its high reliability but may require additional heating sources to meet peak demands.
- Central HP in medium-temperature DH network serving space heating. Suitable for residential areas, this system balances efficiency and cost-effectiveness but may face challenges in extremely cold climates.
- Central HP in medium-temperature DH network with aquifer thermal energy storage (ATES). This innovative setup enhances system efficiency and resilience, utilizing natural aquifers for thermal energy storage.
- Central HP in low-temperature DH network. This configuration operates at lower temperatures, reducing heat losses and improving overall system efficiency. A little

bit over 50% of the energy dissipated into a building through a GSHP can come from the ground.

- Building-Integrated distributed HP. A decentralized approach, allowing individual control and optimization but requiring significant initial investment.
- Residential: this is by far the most thorough researched use in all literature, [2_4][2_5][4_4] to cite a few. This use for GSHP has the possibility of creating a consumer market. IEA report [0_0] states that HP adoption figures will grow ten-fold around 2050, with a relevant percentage of this being GSHP systems for residential use. [2_5] explores the possibility of combining GSHP technology with building integrated photovoltaics and a solar collector. The building sector shows the highest potential for CO2 emission reduction in Europe [2_9].
- Industrial: [2_6] investigates the complexity of the industrial use of GHSPs, giving Beijing Daxing International Airport as an example. This use is by far the least researched about. Articles in this subsection have been more difficult to retrieve and less numerous. However, a promising application of GSHPs in machinery could be industrial ovens and refrigerators [0_2], specifically for food production, since the temperature difference could ensure a COP that justifies the initial investment.
- Commercial: another promising use of GSHP technology, represents a solid exit of this technology due to the capacity of a significative initial investment by companies or government branches that households could not be able to afford. Hybrid systems incorporating Personal Comfort Systems (PCS) and Natural Ventilation (NV) can mitigate the thermal load imbalance in cooling-dominated buildings, improving GSHP performance [2_8]. [2_6] Tianjin Meijiang Ecological Community Office Building (2003): this project is Tianjin's first GSHP project, using soil as the heat source with various underground heat exchanger configurations. The system has been running continuously for over 17 years, demonstrating stable performance and good efficiency. [2_6] also sheds light on Beijing Tianchuang Shiyuan Building, with annual operating cost savings reported to be 1.58 million yuan.

[3_2] explore the uses of GSHP technology so far, extracting the following proportions of the use that has been given to GSHPs (see Figure 1).

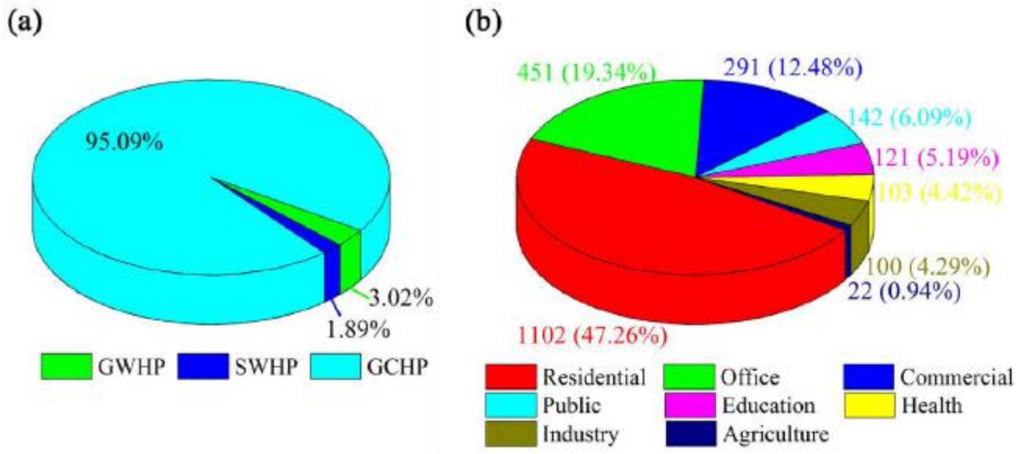


Figure 1. Proportion of GSHP systems installed in China as of year 2021 (left). Use per building type of installed GSHPs in China as of year 2021 (right). Source: [3_2]

4.3 CASE STUDIES

First case studies date back to 2004 [1_2]. In the United States, GSHP installations had steadily increased with an annual growth rate of about 12% in the previous year. In that time in Europe, GSHPs offered flexibility to meet various demands, with rapid market penetration and increasing commercial activity. The document discusses the climatic conditions, market penetration, technical optimization, and specific country experiences, particularly focusing on Germany and Switzerland. It is very common in Europe the retrofit purpose. In this same document and in spite of the year of publication, [1_2] provides relevant insights into the GSHP industry:

> "Geothermal heat pump (GHP) systems have spread rapidly in Switzerland, with annual increases up to 15%. In 2004 there were over 25,000 GHP systems in operation. The three types of heat supply systems used from the ground are: shallow horizontal coils (<5 % of all HPs), borehole heat exchangers (100 - 400m deep BHEs; 65%), and groundwater heat pumps 30%. Just in 2002 alone, a total of 600 kilometers of boreholes were drilled and

equipped with BHEs." In Switzerland there were plenty of technical incentives at the time…"

Other examples of exhaustively carried out case studies on GSHP technology range from residential buildings, single-family homes, airports, schools, and many other uses. As an illustration, [4_3] states that "commercial buildings often have considerably more complex GSHP systems than residential buildings". This complexity can often be afforded due to a higher initial investment availability, the importance of return on investment and incremental marginal returns of capital under certain ranges.

As a counterweight to the high initial investment, GSHPs offer higher performance indicators than their counterparts. Many authors have made descriptions and measurements of GSHP systems and their performances. Authors like [3_1] and [2_5] have studied hybrid GSHP systems combining solar collectors and conventional GSHPs to tackle the problem of heat depletion in the soil, causing a loss of COP over time.

[2_5], to dive deeper into the paper, studies three scenarios comprising different setups for residential purposes 74km East of Tehran. It also provides a deep economic analysis of the system and variances.

Following this deep analysis, analysis of systems and COP variances over time can also be found in the following studies. [3_3] reports a COP of 4.1 in a case study of a school building in South Korea. [4_4, Mos, Galicia] shows an average COP of space heating, domestic hot water and pool heating was 3.9, 3.2 and 4.1 during the first year and 3.4, 3.2 and 4.2 in the second year for a single-family house with a total heated area of 116 m2 and a 48 m3 heated swimming pool. The GSHP uses a variable speed compressor and has a heating capacity between 5 kW and 22 kW.

During the literature review, the identification of parameters has been a bottleneck for the analysis of GSHP systems and their performance. Thus, a table (2) with selected examples combining reviewed papers has been put together. An extensive list of installations can be found in [4_3]

Table 2. Selected GSHPs systems from literature review.

Location	Use	Capacity	Performance	Type	Reference	Year
Gloucester, UK	Police station --8500m2	860kW -C 765kW -H	-	150x98m BHE	[1_1]	2005
Aberdeen, UK	University campus	900kW -C 900kW -H	COP=6 -C COP=5 -H	66x200m BHE --granite	[1_1]	2013
Nottinghamshire UK	Hospital --140000m2	5.4MW -C 5MW -H	COP=7 -C COP=4 -H	140 surface water loops	[1_1]	2011
Anglesey, UK	16th century country house. 5000 m^2	300kW	COP: 4.08 SPF: 2.82 Cost of £600.000 and £40.000 in annual savings	Open loop, sea water	[1_1]	2011
Kingston upon Thames, UK	Residential	2.3MW heating.	COP: N/A	Open loop, Thames water.	[1_1]	N/A
London, UK	Commercial. 3500 m^2	614kW cooling, 614kW heating.	COP: N/A	199 x 150m BHEs, pile foundation.	[1_1]	2012
London, UK	Residential	650kW cooling, 760kW heating.	COP: N/A	132 x max 52m BHEs.	[1_1]	2011
London, UK	Commercial	150kW cooling, 150kW heating.	COP: N/A	N/A	[1_1]	2012
London, UK	Residential	370kW cooling, 200kW heating.	COP: N/A	10 x 100m BHEs	[1_1]	2009
London, UK	Commercial	2.3MW cooling, 2.4MW heating.	COP: N/A Savings of £27.000 in running costs annually	192 x 45m BHEs	[1_1]	2010
Kamphaengphet, Thailand	Research	N/A	COP: 3	57-m deep borehole with double U-tube	[3_8]	2006
Bangkok, Thailand	Research	N/A	COP: 3–4	200-m horizontal tube	[3_8]	2010
Bangkok, Thailand	Chulalongkorn University	N/A	COP: 3.45	2 x 50m BHEs.	[3_8]	2014

Saraburi, Thailand	University	N/A	COP: 5.53 – 5.66	300m coil style and 300m carpet style.	[3_8]	2016
Pathumthani, Thailand	Commercial	N/A	COP: 2.3-2.54	400m in total, BHEs	[3_8]	2015
Hanoi, Vietnam	Commercial	N/A	COP: 3.6 heating, 3.1 cooling.	400m in total, BHEs	[3_8]	2016
Indonesia	University	N/A	N/A	N/A	[3_8]	2018
Beijing, China	Commercial	GSHP 1: 52kW GSHP 2:104kW	GSHP 1: 3.9 GSHP 2: 5	20 x 100m double U-tube 50 x 60m single U-tube	[4_4]	Study beg 2014
Mos, Spain	Residential (with swimming pool heating)	22 kW	Pool and home: 3.2 and 4.1 during the first year and 3.4, 3.2 and 4.2 in the second year	Double U-tube 150m	[4_4]	Study beg 2014
Cleveland, OH, USA	Residential	11.7 kW	Heating COP between 3 and 4	6 x 49m	[4_4]	N/A
Nuremberg, Germany	Commercial	50 kW	Heating COP: 3.4 in winter. Decrease of 4% every year 4.1 to 3.4	18 x 80m	[4_4]	4 year study
Compilation of European cities	Residential	5.8 kW, some of them with 6m^2 solar	Solar+GSHP: 4.4-5.8 GSHP only: 4.3-5.1	2m deep trenches.	[4_4]	N/A
Wuhan, China	Commercial	170 kW	Heating: 2.79	N/A	[4_4]	2015 study

Thessaloniki, Greece	Commercial	150 kW	4.0 - 6.6	21 x 80m single U-tube	[4_4]	Study 2003-2010
Erzurum, Turkey	University	8 kW	2.1 – 2.5	2 x 53m	[4_4]	Study 5 months 2007
Erzurum, Turkey	N/A	8 kW	2.7	2 x 53	[4_4]	9 months 2009
Valencia, Spain	University	19.3 kW	N/A	6 x 50m	[4_4]	9 months 2006
Jinzhou, China	Residential	9 kW	2.9	4 x 20m	[4_4]	2013
Nanjing, China	University	7.5 kW	3.5 - 3.7	BHE	[4_4]	2015
Montana, USA	Research facility	175 kW	3.47	Heat sink is a flooded abandoned mine.	[4_2]	Study Jan to Jul 2019
Stockholm, Sweden	University	200kW heating, 120kW cooling	3.7	BHE	[4_3]	2013
Minnesota, USA.	Compilation of 37 homes.	N/A	Median COP of 5.2 for cooling and 3.19 for heating	BHE	[4_5]	N/A
Norway	Commercial	Heating 320 kW Cooling 380 kW	SPF 4.5.	50 x 200m double U-tube .	[5_5]	N/A
Pylaia, Greece	Commercial	Heating 321.7 kW	2.82 - 4	42 x 80m	[7_4]	Study of 2015

Cooling 288.9 kW

From the previous case studies, we can recognize that most are related to large commercial/public buildings, for which some analysis on their economics is provided. In general, these big customers are the perfect target due to their capability of facing high overnight costs and accessing to beneficial financial conditions.

Furthermore, and to conclude with the case study section of the literature review, we highlight a few cases that are remarkedly different from others:

First, the Robert Gordon University, Garthdee Campus, Aberdeen, UK [1_1], has the capacity to store heat in the ground due to the granitic nature of the soil. This use is the opposite of heat depletion due to thermal imbalance, the thermal imbalance in this case is used to the advantage of the system, improving its COP.

Second, [4_2] presents a detailed case study of an innovative GSHP system in Montana (USA) utilizing flooded mines as a heat source and sink, providing space conditioning to a 5,203 m^2 research facility. This heat sink is relatively uncommon in comparison to BHEs of regular depth.

Third, the development of GSHP technology in China is categorized into three distinct phases [8_1]: the initial phase, the rapid development phase, and the consistent growth phase. The study undertakes a statistical analysis of over 2,000 GSHP installations across China, focusing on various aspects such as the type of system, geographic location, floor area covered, building type, and the annual growth rate of these installations. Following this, the paper examines factors that influence the growth and development of GSHPs, including advancements in technology, policy incentives, and energy pricing. It also assesses the geographical distribution of GSHPs in China, utilizing density maps to pinpoint regions with the highest potential for their deployment. This assessment considers a range of factors, including air pollution, the thermal load of buildings, population density, and regional GDP. Concluding, the study highlights the substantial progress that GSHP technology has achieved in China, emphasizing its significant potential for further expansion. The research also identifies and discusses both the opportunities and challenges that are expected to influence the future trajectory of GSHP technology in the Chinese context. Some opportunities are the high heating costs, incentives for the adoption of GSHPs, technical innovation and the desire to reach carbon neutrality in China. While capital costs (as it has been presented previously) and the disparity in expected value and actual performance of GSHP systems could be cited within the challenges [8_1] discusses.

Finally, [8_3] is a study on the utilization of GSHPs in Turkey, which states that despite Turkey being in the top 7 of countries with the most geothermal resources, only 2% of its potential is used. Relevant conclusions are withdrawn, such as their main use condition being multiple-story houses, with floor areas ranging from 230 m2 to 1100 m2, primarily owned by high income residents. Izmit Archaeology Museum, with a floor area of 3500 m2, is also presented in the study. Pilot projects are proposed to demonstrate the viability of GSHPs as well as their advantages. Furthermore, [8_3] identifies the principal barriers to the adoption of GSHPs in Turkey, which resonates with points that will be discussed later in the paper.

4.4 TECHNICAL CHARACTERISTICS

Out of all technical characteristics of GSHPs, we can distinguish three principal ones that have the biggest impact on their functioning as well as in reasons for their adoption. The capital status of said characteristics is also reflected in the number of studies on them.

4.4.1 COP

To define COP, it must be understood that HPs are devices designed to transfer thermal energy opposite to the natural flow of heat. By consuming a smaller amount of primary energy, HPs transport energy from a source, like the ground or air, to a destination, such as buildings, for heating or cooling purposes. This heat transfer, in opposition to heat creation is the reason why heat pumps are able to achieve efficiencies of 400% or 1000%. This is referred to as Coefficient of Performance (COP) instead of as an efficiency, as it measures the heat output at the desired end in relation to the energy used to transfer it, which can be greater than one.

$$COP = \frac{|Q|}{W}$$

Q is the useful heat supplied or removed by the system.
W is the energy put into the system; electricity consumed in most HP uses.

Plenty of studies focus on the performance of GSHP systems. Once again, as [7_5] states, there is a consensus on the capital importance of this aspect over others. Studies such as [4_1] experiment with BHE shapes to better determine the most beneficial one. A COP of 3.47-3.64 is calculated for this building.

In the case study section of this literature review, plenty of examples were analyzed in depth. To illustrate some COP values, we have extracted some of them from the case studies table. For example, from [1_1], Robert Gordon University, 900kW both heating and cooling. COP 5 heating 6 cooling. Kingsmill Hospital, 5.4MW cooling 5MW heating. COP 4 heating, 7 cooling. Plas Newydd mansion, 300kW, COP 4.08 these 3 in UK. Or from [3_8], Chulalongkorn COP 5.53-5.66, 600m in total of GHE, in Thailand.

4.4.2 VARIATION OVER TIME

One of the foremost challenges faced by GSHPs is heat depletion, a phenomenon that significantly impacts their efficiency. This issue arises when there is a thermal imbalance in the soil the system relies on to make the heat exchange. Over time, if more heat is extracted from the ground than is naturally replenished, or if excess heat is deposited without adequate dissipation, it can lead to a substantial change in the soil temperature. Building energy simulations indicate that without hybridization, GSHP use could increase ground temperature by over 20°C over 50 years [2_8].

This alteration in ground temperature can be particularly problematic: a warmer ground can reduce the effectiveness of the GSHP in cooling modes, while a cooler ground may hinder its heating efficiency. For example, under certain circumstances, a 2º temperature variation can cause a 13% drop in COP [2_3]. Even if these certain circumstances implicate a very low temperature difference between volumes, a 20º difference is undoubtedly significant and could result in a more noticeable loss in COP. Another example is a 4 year long study of a 50kW GSHP system in Nuremberg, Germany [4_4]. This study sheds light at the loss of COP over time, resulting in a 4% loss in COP during each studied year due to thermal imbalance. The heating load was twice the cooling load during the year, decreasing COP from 4.1 to 3.4. The use is an office building with 1.150 m^2.

Studies have demonstrated that without intervention, such as hybridization or supplementary heat sources, the continuous operation of GSHPs could potentially increase ground temperatures by over 20C over several decades. The lifespan of these GSHP systems are consistently designed to operate during 25 years for housing purposes, for example. This rise in temperature not only diminishes the COP of the system but can also lead to environmental concerns.

Despite these challenges, GSHP systems continue to exhibit higher COPs and SPFs compared to ASHPs. This makes them an attractive choice for sustainable heating and cooling. However, enhancing their efficiency and mitigating the effects of heat depletion are crucial. [3_1] examines the possible use of solar energy to combat heat depletion. Other papers such as the previously mentioned one by [2_5] examine the combined use of solar panels and GSHPs to lessen the impact of said phenomenon.

4.4.3 CAPACITY

Apart from having a smaller cost/kW [5_6], due to the absorption of fixed costs and marginal costs of kW lowering in higher levels of capacity, bigger commercial systems (90kW or even in the MWs), tend to have greater COPs.

[5_6] as previously mentioned, lowering system's capacity can greatly reduce HE length and therefore initial cost. Furthermore, the technology of compressors is also affected by the capacity of the system, with the following indication being provided in Figure . Different technologies come with different associated costs. [0_4] studies the effect of using a variable compressor versus a simple compressor. Noticing an increase in COP from 2.95 to 3.7. The efficiency of this component directly affects system energy consumption and therefore its performance.

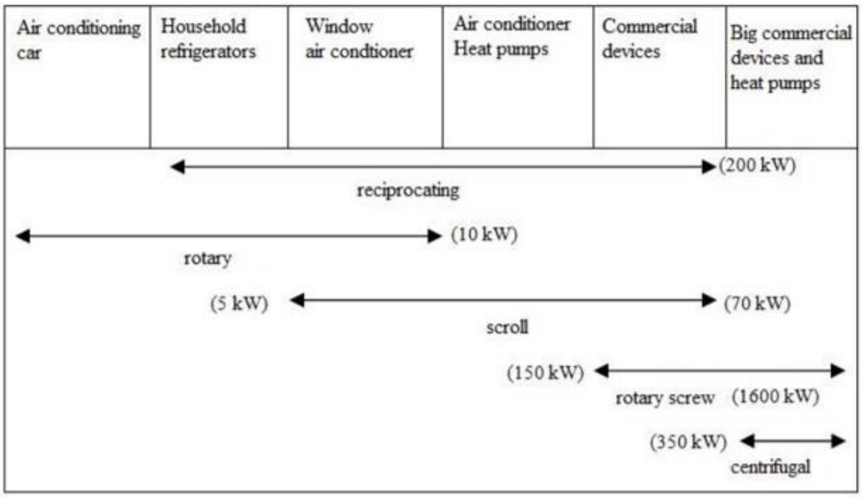


Figure 2. Scope of usage of various types of compressors. Source: Rubik (2006).

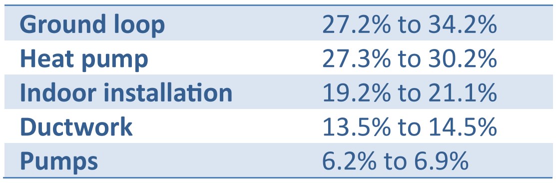
4.4.4 COSTS OF INSTALLATION AND OPERATION

Cost is one of the main barriers to GSHPs adoption. They present higher costs in comparison to ASHPs or fossil fuel boilers in its installation phase. Dependent on the size of the system and the technology used, installation costs can vary dramatically, impacted by aspects such as the complexity of the ground loop, heat pump, indoor installation, ductwork, and pumps per se. Installation is work intensive. However, lower running costs and higher COPs are the factors that in comparison to other heating/cooling alternatives, make GSHP a viable solution both economically and environmentally.

This phenomenon is studied by authors such as [4_6]. The report, compiled in 2016, projects an overall cost reduction of approximately 18% compared to the costs in 2014, with a 30% reduction in non-equipment costs and a 5-10% reduction in equipment costs. Furthermore, [0_6] estimates that under certain conditions, a 40% decrease in capacity / peak load of a GSHP can reduce borehole length in 69%. This is extremely significant since BHE installation and equipment represents a key portion of the initial investment. Furthermore, this segment of capacity is only used in a minority of days depending on the climate and system characteristics.

Another relevant study by [5_1] details the various components involved in GSHP systems, from the heat pump units, ground loop systems, to the auxiliary equipment, providing a clear breakdown of costs associated with each. By drawing comparisons between the costs of GSHP systems and their conventional counterparts, the research underscores the economic challenges and benefits associated with GSHP adoption. The paper highlights that while GSHPs generally entail higher upfront costs, their long-term operational costs and environmental benefits can present a compelling case for their implementation.

Table 3. Main drivers of installation costs and weights.



Ground loop	27.2% to 34.2%
Heat pump	27.3% to 30.2%
Indoor installation	19.2% to 21.1%
Ductwork	13.5% to 14.5%
Pumps	6.2% to 6.9%

The analysis examines the potential avenues for cost reduction across different GSHP components. It identifies specific areas where innovations, economies of scale, or process improvements can lead to significant cost savings, thereby making GSHPs more accessible and appealing to a broader audience.

In an effort to bridge the economic gap between GSHPs and conventional heating and cooling systems, the paper provides a set of tailored recommendations. These recommendations are categorized based on different types of heat pumps, ensuring relevancy and applicability across various GSHP systems. The dependance of these said costs on economies of scale and technological developments are considerable.

To bring in numbers from previous paper to current years, [5_6] also gives a surface understanding of the order of magnitude of the installation and running costs of a GSHP in the UK for 2016.

- Vertical GSHP installations, which require drilling to depths of approximately 50-100 meters, can cost between £17,000 and £45,000.
- Horizontal GSHP installations are less expensive due to shallower digging requirements of 1-2 meters, with costs ranging from £14,500 to £34,000.

A detailed cost breakdown for a 90 kW retrofit GSHP system indicates that non-equipment costs slightly exceed equipment costs, mainly due to drilling, boreholes, and groundwork, which constitute about 60% of these costs. The document states that 51% of the total installation cost is attributed to non-equipment expenses, while the heat pump and complementary equipment represent 49%. The document also notes that smaller GSHP installations (e.g., 12 kW systems) have a higher cost per kW than larger systems (e.g., 90 kW systems) due to the fixed costs of components and startup drilling expenses.

The UK Department of Energy and Climate Change [5_6] gives us these graphs to better comprehend the initial expenditures of installing a GSHP system.

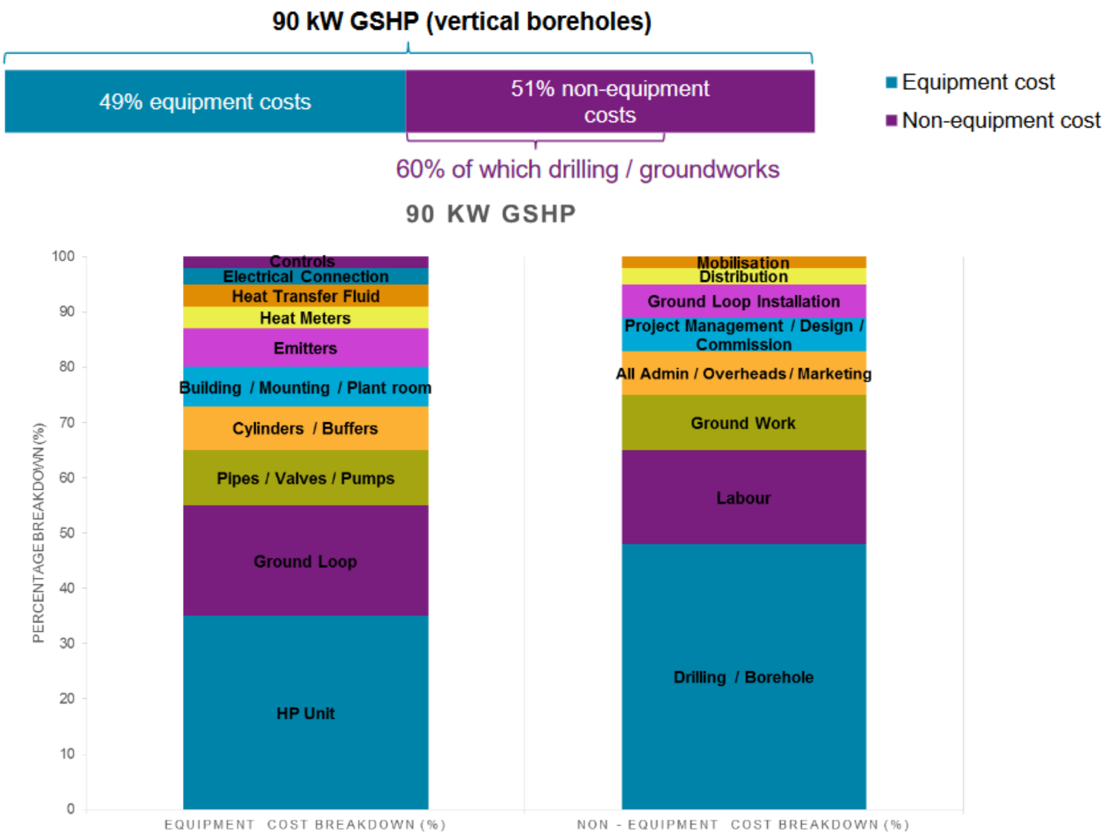
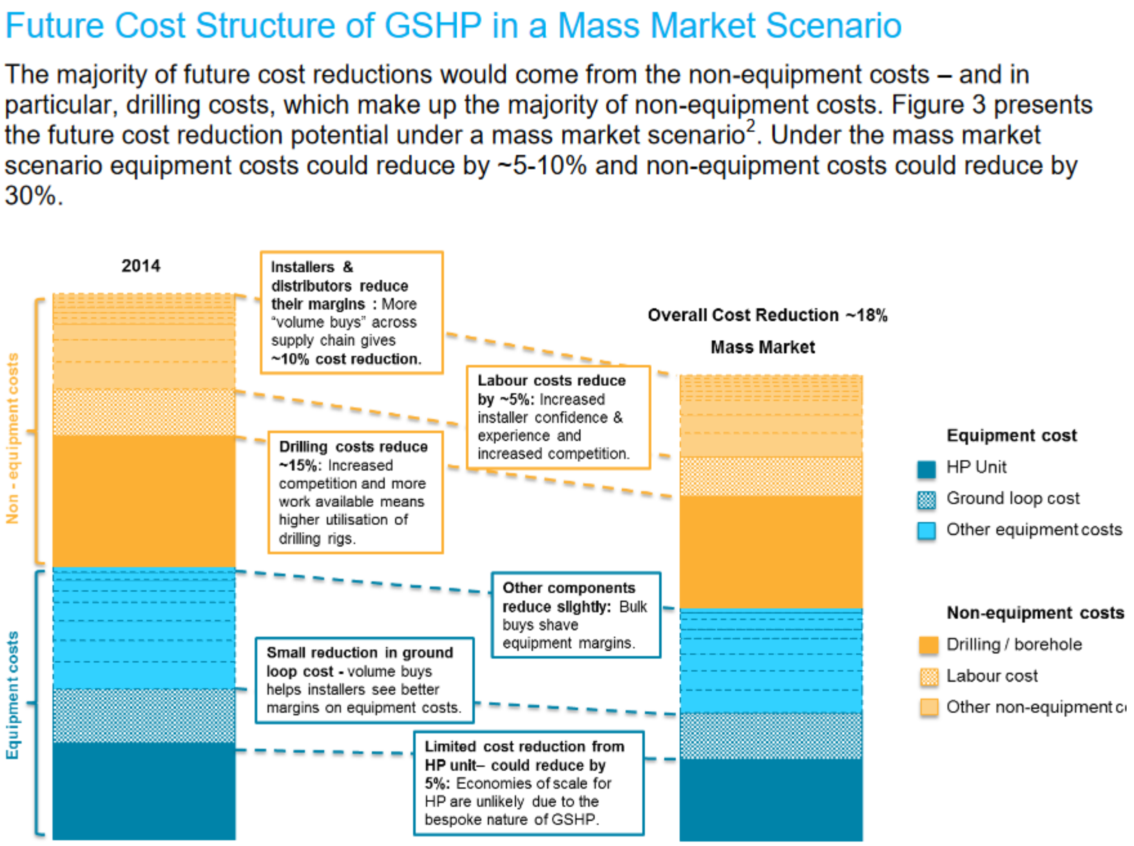


Figure 2. Percentage of costs of installations of GSHP systems. Source: UK Department of Energy and Climate Change.

The report underscores the importance of considering financial support for GSHPs, as grants can significantly decrease running costs. It also compares the annual running costs of different heating systems, with GSHPs at £1,020, ASHPs at £1,360, and gas boilers at £1,565. Over seven years, the benefit versus gas is £3,815 for GSHPs and £1,435 for ASHPs.



Future Cost Structure of GSHP in a Mass Market Scenario

The majority of future cost reductions would come from the non-equipment costs – and in particular, drilling costs, which make up the majority of non-equipment costs. Figure 3 presents the future cost reduction potential under a mass market scenario[2]. Under the mass market scenario equipment costs could reduce by ~5-10% and non-equipment costs could reduce by 30%.

Installers & distributors reduce their margins : More "volume buys" across supply chain gives ~10% cost reduction.

Labour costs reduce by ~5%: Increased installer confidence & experience and increased competition.

Drilling costs reduce ~15%: Increased competition and more work available means higher utilisation of drilling rigs.

Other components reduce slightly: Bulk buys shave equipment margins.

Small reduction in ground loop cost - volume buys helps installers see better margins on equipment costs.

Limited cost reduction from HP unit– could reduce by 5%: Economies of scale for HP are unlikely due to the bespoke nature of GSHP.

Figure 3. Future Cost Structure of GSHP in a Mass Market Scenario. Source: UK Department of Energy and Climate Change.

All of the GSHP installation figures can be considered relatively to the cost of alternative heating technologies; mainly being ASHP and gas boilers. Both electricity prices and fossil fuel prices affect the demand for GSHPs since they would change the expected returns [2_5]. An increase in electricity prices in comparison with gas would decrease the demand for GSHPs since the running costs of GSHPs would increase in comparison to those of the fossil fuel boilers, delaying the break-even and thus making it more difficult to justify the initial investment. [2_5] also exemplifies how the break-even is calculated.

[5_4] analyzed in 2017 costs for the Australian market, reaching similar conclusions than the previously commented paper. It also provides a graphed breakdown of the thermal loading of studied GSHP systems in Melbourne. These examples have not been added to the case studies chart due to lack of data on its performance aspects.

As to running costs, [5_5] as described in the case studies chart, deeply analyzes the running costs of a GSHP system for commercial use in a hotel in a cold climate. This hotel in Norway operates with a seasonal performance factor (SPF) of 4.5, which is considered high performance for such systems. The life-cycle cost analysis shows that the GSHP system is a profitable investment with internal rates of return of 4.9% and 5.9% over a 50-year life cycle when compared to systems using dry cooling and electric or district heating. The study also notes the impact of COVID-19 on the hotel's operation, with reduced heating loads in 2020 due to the hotel's closure.

4.4.5 REFRIGERANTS

Although it is supposed that both thermal and physical characteristics of a refrigerant would affect the efficiency of a GSHP (changes in the performance of the heat cycle or heat exchanger and different viscosities meaning different energy losses in BHEs…), a lack of literature discussing the choice of refrigerant and its relation to the COP of GSHPs has been noticed. There are aspects of refrigerants that need to be considered such as:

- Low toxicity.
- Non-flammability property.
- It has zero ozone depletion potential.
- Exceptionally low global warming potential.
- Excellent thermodynamic properties and low energy requirements.
- Easy to detect if it leaks.

Key research on the impact of refrigerants on the environment is conducted by [7_5], stating that “Crucial for the transmission of heat from the ground to the heating system is the heat pump refrigerant”. In this study the refrigerant was assumed to be the common R134a. This compound is also the main ingredient for other refrigerants such as R407c. An amount of 0.3 kg refrigerant per kW is needed to run the heat pump. This is an average value from test results of the Swiss heat pump test center [5_3]. There are average refrigerant losses of 3% during manufacturing and 6% per year during operation. At the end of the lifetime of the heat pump, steel and copper are recycled and R134a is reused. Another 20% of R134a is lost during the disposal of the heat pump.”

[7_5] also agrees with previously made assumptions, “So far, to our knowledge no comprehensive analysis is presented on shallow geothermal systems that contrasts the role of the individual technological elements, including well or BHE, heat pump, different types of refrigerants and power supply.” This paper also dilucidated the use of solutions of glycol and ethyl alcohol, with its own literature review pointing towards the importance of biodegradability and potential risk of groundwater pollution due to such liquids, finding no danger under both oxic and anoxic conditions. This possibility of environmental contamination will be further discussed in the next point.

Furthermore, [7_5] states that since GSPH heat exchangers are literally isolated from the environment, there is consensus that the refrigerant and heat exchanger fluid choice should be made in order to minimize the system's energy usage. To continue on this path, [6_2] expands upon the relationships of refrigerant pressure, system capacity and COP, finding a 25% difference between 100 bar and 150 bar pressures for a 20kW GSHP systems.

In a spin to the concept of the refrigerant choice, [6_1] discusses in a brilliant paper the possibility of the use of alternative thermodynamic cycles to enhance their efficiency and performance in opposition to a possible change in heat carrying fluids. However, it concludes that these innovative cycles are not yet ready for widespread implementation in GSHPs due to various technical and developmental challenges.

4.4.6 HARM TO THE ENVIRONMENT

To begin with this section, [7_5] discusses a consensus stating that the present main focus of GSHP development is maximizing its efficiency, since they are literally systems that operate and exist in almost total isolation from the environment, apart from thermal exchange. Nonetheless, this does not mean that GSHP have no associated emissions or risks to the environment. This is thoroughly discussed in retrieved literature.

[7_5] "The heat pump mainly consists of copper and steel. The tubing and electric cables are insulated with elastomer and PVC. During the manufacturing process medium voltage electricity and heat from natural gas in the order of 460 and 1400 MJ are needed." This statement itself gives us a framework in which to analyze the impact of GSHPs in the environment as a whole.

On a different page, [7_1] pays special attention to the critical conditions under which GSHP systems operate, with a focus on the output temperatures. The paper highlights that open-loop GSHP systems become inviable when the output temperature exceeds 40°C, underscoring the importance of careful system design and selection to ensure efficient and environmentally friendly operation.

Furthermore, [7_1] examines that GSHP systems can alter their surrounding environment through changes in temperature, the introduction of chemicals, and the proliferation of bacteria. The paper provides an analysis of how GSHP operations can lead to environmental alterations and what measures can be taken to prevent or mitigate these effects. Only 9 over 500,000€ damage events in Germany have taken place between 1990 and 2019, where there are 350,000HPs.

The paper discusses "pump and treat" water methods as effective strategies to decontaminate areas affected by human operations, a possibility that could mitigate possible or past leakages, and even revert the potential danger of GSHP in the aspect of soil/groundwater contamination.

[7_1] also comments that glycol-based antifreeze solutions are commonly used in GSHP systems. The paper notes that while they are not highly detrimental to the environment, they can pose significant risks to human health.

Another aspect that needs to be discussed is the CO2 impact of GSHPs. This is exactly why [7_3] concentrates on environmental damage not in the soil but rather in CO2 emissions. It introduces the concept of CO2 payback period: a crucial metric used to evaluate the environmental sustainability of heating and cooling systems. It represents the time it takes for the reduced greenhouse gas emissions of a more efficient system to outweigh the emissions produced during its manufacturing, installation, and operation. Essentially, it measures how long it takes for a system to "pay back" the carbon debt incurred by its introduction.

In the case of GSHPs, despite their higher initial carbon footprint due to more complex installation processes and the production of their components (not mentioning installation CO2 emissions), they tend to have a shorter CO2 payback period compared to conventional HPs, and even a more pronounced difference of CO2 payback period in contrast to fossil fuel boilers.

Finally, [7_5] shows the relative contributions of resources depletion (34%), human health (43%) and ecosystem quality (23%) of such GSHP systems to the overall environmental damage. Climate change, as one impact category among 18 others, contributes 55.4% to the total environmental impacts.

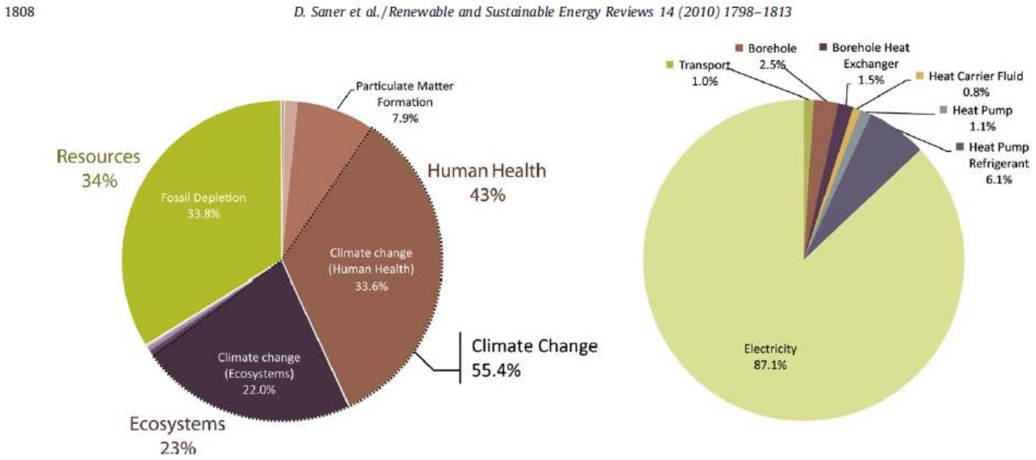


Figure 4. "Relative contributions of the impact categories and the technological elements to the ReCiPe 2008 single score under hierarchist's perspective (base case, assuming average continental European electricity mix). Saner et al. (2010)

4.5 USE IN DEVELOPING COUNTRIES

This aspect of GSHPs is by far the one with the least abundant literature found. This, of course, could be based on the lack of capital in developing economies, the principal limiting factor for the expansion of GSHPs even in rich geographies. In addition, the majority of case studies retrieved relied on GSHP technology to perform a heating function, while certain latitudes would require cooling instead, which is counterproductive for its implementation.

Not being a developing economy nowadays, [8_1] collects data of over 2000 GSHP systems installed in China and analyzes them statistically by considering location, system type, floorage, annual increment, and building type. It concludes that GSHP has achieved remarkable progress in China and has great potential for future development. The paper also suggests some challenges and opportunities for GSHP in China.

In the same continent, [8_2] evaluates the economic feasibility of GSHP systems in Bangladesh, with a series of simulations and case studies. It also analyzes importance of relative prices of conventional fuels and electricity in order to calculate break-evens for such costly equipment and installation.

For a warmer and more humid climate, [3_8] gives an example of a GSHP system in Chulalongkorn University in Thailand. With 600 m of GHE in total, achieving a COP of 5.53-5.56.

Another relevant study was conducted by [8_3], as previously mentioned, is a compilation of case studies of GSHP systems in Turkey, a country with over 150 natural sources of water over 40ºC and in the top 7 of nations with the most geothermal resources. It synthesizes deep conclusions that are subject to be transposed to other markets.

- The main residential use scenario (multiple-store houses, with floor areas ranging from 230 m^2 to 1100 m^2, primarily owned by high income residents) corresponds exactly to what it was expected: the main barrier to implementation is the high upfront cost. These installations are positive to the development of the technology overall, increasing local know-how and causing a drip in cases that will benefit both the market and consumer knowledge.
- There are market restrictions apart from lack of capital, such as customer reluctance to GSHP technology because of both single-family and multi-family houses being heated by using hydronic piping systems and terminal units, which add to the higher upfront cost of GSHP systems in comparison to alternative technologies. The transposing of this to other developing economies remains unclear.

Overall, well-prepared pilot projects that demonstrate the advantages of GSHP systems is of extreme utility. Both companies, private spaces and public entities are the perfect recipients of GSHP projects for their buildings, once again developing the GSHP market in the region and building economies of scale for the adoption by a larger demographic.

It is also worth noting that a substantially smaller quantity of literature has been found discussing the application of GSHP for residential use in the African continent and Latin America.

4.6 CONCLUSION OF THE LITERATURE REVIEW

In conclusion, this literature review has analyzed a vast array of bibliographic sources and case studies. Scientific literature versing about GSHPs is plentiful and of great quality. Despite the extensive research available, notable gaps persist in specific areas, such as the study of refrigerants/heat carrying fluids used in GSHPs in relationship to system efficiency or uses of GSHPs for industrial applications. To bridge some of these gaps, insights have been extrapolated from ASHP studies, given their considerable similarities with GSHPs.

A recurrent limitation in existing studies is their duration, typically spanning only one year. The need for multi-year or long-term interval assessments is evident, especially to understand the COP loss over time, a critical issue that this paper will revisit in subsequent sections. The relative novelty of GSHP technology in practical applications might account for the current prevalence of shorter-term studies.

The review underscores GSHPs' environmental superiority over traditional heating and cooling alternatives in their energy efficiency, performance, CO2 emissions, and long-term cost-effectiveness. However, this paper will also look over the main ongoing challenges that temper this positive outlook.

Interestingly, a consensus in the literature suggests that the environmental interaction of refrigerants in GSHPs is not a primary concern, owing to their contained use within the system. Meanwhile, the economic aspect of GSHP technology, extensively explored in various studies, remains a significant barrier to widespread adoption. Nevertheless, as economies of scale evolve, these costs are anticipated to diminish.

The technical characteristics of GSHPs, akin to those of ASHPs, exhibit variability, offering design flexibility that can accommodate budgetary and technical constraints. The readiness of GSHP technology for practical use and its role in decarbonizing heating and cooling needs are evidenced through case studies, such as those examining its expansion in China [8_2] over 2000 cases compiled.

To give some context of the expectations of performance for GSHPs, a table has been created based on the case studies presented in previous sections. It should be noted that the cost estimation/kW is highly variable, and this table is a qualitative product of literature review. Costs should be studied in a case-by-case basis (specially in bigger systems since commissioning costs and site expenses could result in a great variance of the final budget) and might also change with time and different geographies.

Table 4. COP of different GSHP depending on size—small, medium, large---and climate conditions: hot for cooling, cold for heating and temperate for both.

Capacity (performance)	**Hot**	**Temperate**	**Cold**	**Cost($)/kW**
10kW, (poor)	2.1-2.5 [4_4]	3.2-4.2 [4_4]	3-4 [4_4]	1200
10kW, (median)	2.7-3.1 [4_4]	3.5-3.7 [4_4]	3.5-4.3 [2a foto 4_3]	1400
10kW, (high)	5.2 [4_5]	4.3-5.1 [4_4]	4.7-5.6 [1a foto 4_3]	1600
70kW, (poor)	2.3-3 [3_8]	3.2-4.2 [1a foto 4_3]	3.4-4.1 [4_4]	1100
70kW, (median)	3.45-3.65 [4_2]	>3.5 [1a foto 4_3]	4-4.3 [1a foto 4_3]	1300
70kW, (high)	5-5.6 [3_8]	4.4-5 [1a foto 4_3]	4.5-4.9 [2a foto 4_3]	1500
>150kW, (poor)	3.3-3.7 [3a foto 4_3]	3.1-3.3 [1a foto 4_3]	2.8-4 [7_4]	1500
>150kW, (median)	4.5-4.9 [3a foto 4_3]	3.6-4.4 [4_4]	~4 [1_1]	1700
>150kW, (high)	>4-6.5 [4_4]	>3.9-5 [4_4]	>3.7-4.5 [4_3][5_5]	1900

In spite of this relative performance superiority to other heating/cooling alternatives that can be observed in the previous table, the paper will address some of the key issues that have emerged from this review, exploring the challenges and potential solutions that shape the future of GSHP technology in sustainable energy systems.

4.7 KEY ISSUES FOUND

An exploration of the challenges associated with this technology in its current state is essential. The following text expands upon the provided ideas, addressing economic, technical, environmental, and knowledge-based factors that impact the implementation and operation of GSHP systems:

- **Upfront cost and economic feasibility**. One of the most significant barriers to the widespread adoption of GSHPs is the high upfront cost, an issue even in richer economies. While this cost can be mitigated by integrating thermally-active building foundations in new constructions, the break-even point often takes 6 to 8 years, a duration that might deter investment. However, it is anticipated that these costs will decrease with economies of scale as the technology becomes more widespread.
- **Lack of financial incentives**. The adoption of GSHPs is further delayed by insufficient financial incentives from governments and other institutions. Tax breaks, subsidies, or other forms of financial support could significantly boost the adoption of this environmentally friendly technology.
- **Performance gap and maintenance**. Post-installation checks are crucial to ensure the long-term efficiency of GSHPs. A performance gap has been noted in cases where such maintenance is neglected [3_8]. Regular monitoring and maintenance are essential to sustain optimal performance, which comes with associated costs.
- **Public awareness and knowledge**. There is a general lack of public knowledge regarding the benefits and operation of GSHPs. This lack of awareness can be a

barrier to their adoption and acceptance, necessitating targeted educational and marketing efforts. This could be particularly harmful for the adoption of GSHPs for residential purposes.

- **Feasibility in high-rise buildings**. The application of GSHPs in skyscrapers presents unique challenges. The numbers, in terms of energy efficiency and cost-effectiveness, do not always align favorably when compared to traditional heating and cooling methods in such high-density constructions.
- **Parasitic loads**. The energy required to operate auxiliary components of GSHP systems, known as parasitic loads, can detract from their overall efficiency since they do not provide extra thermal output and add to the denominator of the COP equation.
- **Thermal imbalance and longevity of COP**. Over time, if there is a heat imbalance in the ground, the COP of the system can decrease. This can be mitigated with supplemental heating or cooling sources like solar panels or mirrors, as demonstrated by [3_1]. However, concerns arise when the ground becomes excessively hot, leading to inefficiencies, this can result in a much lower economic performance. This affects to a large extent of its lifetime, modifying the break-even times and the performance afterwards.
- **Refrigerant leakage and alternatives**. The risk of refrigerant leakage, with its environmental and health hazards, is a significant concern. While CO2 loops present a potential solution, they are costly and in developmental stages. Alternatives like glycol must be handled cautiously due to their toxicity.
- **Ground and borehole impact**. The installation of GSHPs can lead to borehole ground damage and temperature changes in the soil. Exceeding certain temperature thresholds (e.g., 40°C) can lead to bacterial proliferation and chemical alterations in the soil. Ensuring soil viability before installation is critical but adds another layer of complexity and cost.
- **Horizontal heat exchangers and soil impact**. Horizontal heat exchangers can have adverse effects on soil quality and composition. This concern needs further

investigation to understand the long-term implications. Wildlife in the shallow layers of the soil could also be affected.

- **Decommissioning and removal costs**. The costs associated with the removal or decommissioning of GSHP systems, especially when compared to other heating and cooling technologies, can be substantial and should be factored into the total cost of ownership.
- **Challenges with open loop systems**. Open loop systems, particularly those using surface water, can lead to environmental challenges like clogging and increased water temperatures, potentially causing ecological damage.
- **Lifecycle and replacement costs**. GSHP systems are typically calculated with a 20-25 year lifespan, with replacement costs being significant, especially for the ground loop as it was analyzed in the costs section of the literature review. However, the extended operational period post break-even point (up to 13 years, on average) can offset these costs.
- **Industrial applications**. The potential for GSHP use in industrial settings remains largely unexplored. Research into broader applications could reveal significant opportunities for energy efficiency improvements in the industrial sector.

As previously stated, despite the numerous current challenges that GSHPs present as a whole, the number of this technology’s advantages and its relevance (specifically economical advantages) still remain a force to be reckon. Its expansion is expected to grow in the coming years and decades [0_0].

Within this project, we will analyze the technoeconomic viability of GSHP systems under different weather conditions and for different types of buildings in the US. We will also compare the costs of such installations against current solutions, like ASHP or boilers and cooling devices.

CHAPTER 5. METHODOLOGY

In progressing from the literature review to the practical aspects of modeling GSHP systems, our research was faced with the task of identifying the necessary equations to accurately represent the dynamics of these systems. The selection of equations is critical, as it underpins the robustness and applicability of the model, directly influencing its utility in predicting GSHP performance under various operational conditions. And what is more, their economic performance.

Modeling GSHP systems involves a multitude of parameters, each contributing to the overall accuracy of the simulation. Given the extensive range of variables that could potentially be included—ranging from thermal properties of the ground and heat exchanger characteristics to the specific heat capacity and flow rate of the working fluid—a manageable subset of parameters has been selected. The challenge lies in achieving an optimal balance: the model must be sufficiently detailed to provide an accurate representation of the system, yet not so complex that it becomes impractically specific, applicable only to a narrowly defined set of conditions.

This balance is especially pertinent in the context of GSHPs. Although the operational principles of these systems are less complex compared to some other technologies, the level of detail required in a model can vary significantly based on the intended application. For a basic operational model, fewer parameters may be necessary, focusing perhaps only on the primary heat transfer characteristics and the average ground temperature. However, for a more detailed analysis—such as evaluating the system's performance over different seasons or under varying load conditions—additional factors like building heat loss, thermal conductivity of the ground, and the thermal resistance of the heat exchanger system might also need to be considered. These parameters are often site-specific and therefore are out of the scope of this paper.

4.8 EQUATIONS USED

To address these modeling challenges, we extracted several key equations to form the backbone of our GSHP model. These equations are designed to capture the essential thermal dynamics and interactions within the system. These are the main equations and parameters used:

Home surface: refers to the available living space in square meters. It is important due to the approximation to the needed borehole length with this parameter as explained previously.

***Borehole length*:** total length of the ground heat exchanger in meters.

$$\text{Approximately } 1 \text{ square meter } = 1 \text{ meter of borehole length}$$

***Borehole depth*:** maximum depth of the boreholes installed in meters.

***Number of boreholes*:** total perforations and tubes into the ground.

$$Number\ of\ boreholes = \frac{Borehole\ length}{Borehole\ depth}$$

Cooling capacity: maximum cooling output of the system in kW.

***Heating capacity*:** maximum heating output of the system in kW.

***Initial ground temperature*:** average ground temperature under the layers affected by climate conditions and surface temperature cycles in Celsius.

***Thermal inertia coefficient*:** parameter modeling the change in ground temperature with the input of the heat exchange with the GSHP system in Celsius/kWh.

***Maximum/peak cooling output*:** maximum hourly demand of heat extraction by the system in kWh.

Maximum/peak heating output**:** maximum hourly demand of heat input by the system in kWh.

Yearly thermal imbalance**:** difference between the heat extracted from and pumped into the ground by the GSHP system in kWh.

Total energy used**:** energy obtained from the grid in ASHP/GSHP cases and the sum of it and the one contained in gas burned for the AC + gas burner cases.

AC + gas burner case:

$$Total\ energy\ used = \ energy\ in\ gas\ burned + energy\ obtained\ from\ grid$$

COP: Coefficient of Performance of the ASHP/GSHP as stated earlier:

$$COP = \frac{|Q|}{W}$$

Where:

Q is the useful heat supplied or removed by the system.

W is the energy put into the system; electricity consumed in most HP uses

Burner efficiency: percentage of the energy contained in the natural gas burned that is pumped into the home.

Coefficient of degradation: parameter that indicates the decrease in the efficiency of the ASHP system per Celsius degree change in temperature in COP units/ºC.

Outside temperature**:** measure of the atmospheric temperature in the system location obtained from historic weather databases in Celsius.

Energy costs**:** total price of the electricity used to run the ASHP/GSHP system or cost to run the AC + gas burner system (includes both the cost of the electricity and gas used), in USD due to the location of the studied demands, corresponding atmospheric temperature and utility price data.

AC + gas burner case:

$$Energy\ cost = \ cost\ of\ gas\ burned + cost\ of\ electricity\ used$$

4.9 COST

Building upon the foundational equations previously identified, our research proceeded to incorporate an understanding of the relationships among key factors such as the heat source or sink, the COP, system capacity, and associated costs. Previously in our literature review, we aimed to extract the most relevant and impactful strategies that could be applied to our modeling efforts, particularly those that address system efficiency and cost-effectiveness.

To ensure our model's practical relevance, we simulated a preliminary design tailored to meet a specified real-world demand. This initial model served as a conceptual prototype, providing insights into the system's potential performance and allowing us to identify areas for further refinement. The model effectively represented the interactions and dependencies among the heat exchange process, the efficiency of the system as indicated by the COP, and the overall capacity required to meet the demand.

As the model development progressed, we encountered the critical task of estimating the financial aspects of the GSHP system, including both initial investment and ongoing operational costs. The operational costs were relatively straightforward to approximate, as they primarily depend on the system's electricity utilization, which can be calculated based on known energy prices and the efficiency of the system.

However, accurately estimating the initial investment required for the system proved to be more challenging. We initially attempted to gather data from product catalogues and industry suppliers to gain a broad view of the component costs involved in GSHP installation. Despite these efforts, we found that the available information was often incomplete or lacked the specificity required for precise cost modeling. Catalogues and standard industry listings frequently did not provide detailed pricing or failed to cover the full range of components needed for a complete GSHP installation.

This gap in readily accessible data necessitated a more creative approach to estimating initial costs. Since direct data from catalogues was insufficient, we turned to secondary sources such as case studies and industry reports to construct a more accurate picture of the potential investment needed. These sources provided broader context and insight into the range of costs associated with similar projects, allowing us to formulate a more informed estimate that accounted for variations in system size, complexity, and geographic factors.

Incorporating these cost estimates into our model was crucial for providing a realistic view of the financial viability of implementing a GSHP system. By aligning our theoretical model with practical cost considerations and technology readiness, we aimed to create a tool that could not only predict system performance but also assist in the making of informed decisions about GSHP investments based on a complete understanding of both performance metrics and cost implications. improvements in real-world settings.

The following options were deemed viable for the estimation of the initial cost of the soon to be studied GSHP system:

4.9.1 OPTION 1: UTILIZING A PREVIOUSLY EXISTING RELATIONSHIP

The first option involved employing an equation from a study outlined in paper [8_4], which proposes a cost estimation formula:

$$(500 * \#boreholes + 20 * m + 2000) * 1.4$$

Where:

#boreholes is the number of boreholes that compose the BHE.

m is the total length of the BHE

This equation provides a straightforward method for calculating initial costs based on the number of boreholes and the depth of those boreholes, which are key factors in BHE systems. However, its applicability is limited to GSHP configurations that utilize BHEs. The formula does not account for systems like open-loop or horizontal heat exchangers, where cost drivers differ significantly from those of BHE setups. Given the specificity of this equation to a particular type of GSHP system, its utility for our research was restricted to scenarios involving vertical BHEs.

4.9.2 OPTION 2: USING PRICE INTERVALS FOR SIMILAR SYSTEMS

The second option considered was to bypass specific cost modeling in favor of using a price range based on observed costs for similar-sized GSHP installations. This approach leverages market data to set a plausible cost interval, reflecting the typical investment range encountered in the industry for GSHPs of a comparable scale and design. While this method does not provide the precision of a bespoke cost model, it offers a pragmatic estimate that could be sufficient for preliminary financial assessments or feasibility studies. The advantage of this approach lies in its simplicity and its grounding in actual market conditions, which can provide stakeholders with a realistic expectation of investment requirements based on empirical data.

4.9.3 OPTION 3: DEVELOPING A NEW COST MODEL

The third option was to develop a new model specifically tailored to the nuances of the initial investment for GSHP systems. This approach would involve an analysis of various cost components, including equipment, installation labor, site preparation, and any additional expenses unique to different GSHP configurations. Developing a new model would allow for a high degree of customization and accuracy, particularly valuable for detailed economic analysis or when assessing the viability of GSHP systems under diverse operational conditions. However, this option requires significant resources, including detailed market research and other kinds of data which are not widely available in literature and therefore would result in a flawed parametrization.

4.9.4 DISCUSSION:

Continuing the discussion on the selection of an appropriate model for estimating GSHP installation costs, a key consideration that emerged was the influence of site-specific factors, such as soil type. The kind of soil at the installation site is critical for accurately approximating costs due to its impact on drilling and construction requirements. Unfortunately, this factor is often overlooked in academic studies, which predominantly focus on operational efficiencies and generalized cost metrics. This oversight left us with limited data to develop a model that could adequately incorporate such a pivotal variable or even others that are easier to quantify.

The complexity of accurately modeling GSHP installation costs is further illustrated by the European Heat Pump Association's online resources. Their website features an interactive tool that outlines the running costs and performance of GSHPs relative to climate conditions, emphasizing the potential financial benefits of GSHP technology. This tool highlights the relationship between environmental factors and operational efficiency but does not extend this detailed analysis to the upfront installation costs. This gap underscores the broader challenge within the field: installation costs are the least studied aspect of GSHP deployment, yet they are crucial for a complete economic assessment.

The variability of installation costs is influenced by numerous factors, including local wages, material costs, and logistical complexities, which can significantly alter the financial outlay required. These considerations make precise cost modeling challenging without specific input from potential GSHP users who can provide detailed personal or localized data. While there is ample information available online, especially from companies offering GSHP installation services, these resources tend to focus on end-user implementation rather than providing a breakdown suitable for academic modeling.

For systems with larger capacities, studies tend to report only the final installation cost, rather than a detailed component cost breakdown. This approach reflects the inherent variability and discrepancy found in commissioning costs among other expenses, which can vary widely. Access to detailed catalogues that list these systems with their associated costs is also complex, and such granularity is often unnecessary for the scope of projects focused on residential applications. Given these constraints and our project's focus on residential systems, we opted for a pricing model that utilizes observed price ranges rather than detailed component-based pricing.

This decision aligns with the practical limitations and the data availability specific to our study's scope. The chosen model, therefore, provides a reasonable approximation of costs, suitable for the residential context we are analyzing. It simplifies the cost estimation process while acknowledging the inherent variability and lack of detailed cost data in the academic literature. This approach allows us to proceed with an analysis that is both feasible and relevant, given the available resources and the specific objectives of our research.

4.9.5 OTHER CONSIDERATIONS ABOUT COST:

Recent literature provides further insights into how these costs can be structured and analyzed effectively. An interesting revelation from the literature is the negligible impact of the nominal COP on the purchase costs of heat pumps. According to a study highlighted by [8_5], there is no significant effect of the nominal COP on the purchase costs, but rather a developed correlation estimating purchase cost as a function of the nominal cooling load of the heat pump. This finding underscores that factors such as inlet and outlet temperatures, among others, play a crucial role in determining costs, suggesting that GSHPs priced at €18,000 could perform similarly to those priced at €25,000, with differences likely attributed more to installation costs than to the equipment costs themselves.

This understanding reinforces the rationale for adopting the model we developed, particularly since the cost and therefore number of boreholes significantly influences the overall financial outlay. Additionally, the suggestion noted in [5_6] proposes segmenting costs by capacity—using a base of 90kW with adjustments for smaller or larger installations—which introduces a progressive scaling method that could be beneficial for medium-sized installations. This approach, however, does emphasize the variability inherent in project-specific factors, making it less predictable for large-scale applications where installation costs become more pronounced, as confirmed by [4_6]. According to this source, large capacity installations (250kW and above) incur significant management and commissioning costs, further complicated by the terrain's workability affecting drilling costs.

The equation from [5_2] ($(2000kW + 80m) * 0.61$), (the 0.61 is to convert Australian Dolars to Euros), illustrates the difficulties in applying a uniform model across different system sizes due to the high correlation between GHE length and system capacity. This correlation nearly approaches unity, suggesting that while the equation provides a basic framework, it falls short in accommodating the nuanced cost factors for larger installations.

Given the multitude of variables impacting installation costs—ranging from the type of terrain, which might only account for up to 10% of BHE costs (2-6% of total installation costs), to access issues, seasonal timing, project scale, installer experience, and even the economic standards of the installation country—the complexity of creating a universally accurate model becomes apparent. Factors like economies of scale also introduce discrepancies in costs between countries; installation in Spain might be costlier than in Germany, cheaper in Switzerland, and even less in Australia.

Therefore, after considering all these aspects and the limitations of available data, we opted for the first model option as our method for estimating the initial cost of the GSHP system under study. This decision was driven by a process of elimination and the practical need for a model that, while not perfect, provides a useful approximation within the constraints of our research scope. This choice allows us to move forward with a feasible and functional approach to cost estimation, tailored to the specific conditions and requirements of the GSHP systems we aim to analyze.

4.10 MODEL

To begin with, a brief description of the main parameters of the system:

HPs are devices designed to transfer thermal energy opposite to the natural flow of heat. By consuming a smaller amount of primary energy, HPs transport energy from a source, like the ground or air, to a destination, such as buildings, for heating or cooling purposes. This heat transfer, in opposition to heat creation is the reason why heat pumps are able to achieve efficiencies of 400% or 1000%; this is referred to as Coefficient of Performance (COP) instead of as an efficiency, as it measures the heat output at the desired end in relation to the energy used to transfer it, which can be greater than one. If the operating COP is under the unit, it would be more efficient to use a electric resistance for heating than the GSHP system.

$$COP = \frac{|Q|}{W}$$

Where:

Q is the useful heat supplied or removed by the system.

W is the energy put into the system; electricity consumed in most HP uses.

Cooling capacity: this parameter represents the maximum amount of heat that can be removed from the indoor environment by the GSHP system during the cooling mode. It is a critical measure of the system’s ability to maintain comfortable indoor temperatures during warmer periods.

Heating capacity: this parameter represents the maximum amount of heat that can be moved to the indoor environment by the GSHP system. For the purposes of our model, which focuses on a small reversible GSHP system, the heating capacity is assumed to be equal to the cooling capacity. This assumption is based on the system's design, where the same components are used for both heating and cooling, allowing for a symmetrical performance in both modes.

Initial ground temperature: the initial ground temperature is a fundamental factor that influences the efficiency of the heat pump. It varies based on the depth at which the system is installed and the climatic conditions of the location. To standardize this variable and focus on the operational aspects of the GSHP, we consider the temperature of the water exiting the heat exchanger, which acts as the primary heat source or sink. This approach simplifies the model by eliminating depth as a variable and focusing on the temperature that directly affects the heat pump's performance.

Heat exchanger length: the length of the heat exchanger, measured in meters, directly impacts the system's ability to transfer heat between the ground and the heat pump. This parameter is crucial for determining the efficiency of the heat exchange process and is adjusted based on the specific heating and cooling requirements as well as the geological characteristics of the installation site.

Initial cost: this encompasses all the expenses associated with the installation of the GSHP system, including equipment, labor, and any site preparation costs. Accurately estimating this cost is vital for economic analysis and helping potential users assess the financial feasibility of installing a GSHP system.

Maximum heat output: this parameter represents the peak heating demand that the GSHP system is expected to meet. It is a critical measure for ensuring that the system is capable of delivering adequate heat during the coldest periods of the year.

Maximum cooling output: similarly, the maximum cooling output defines the peak cooling demand. This figure is essential for ensuring the system can adequately cool the indoor environment during the hottest times of the year.

Thermal imbalance: measured in kWh, thermal imbalance quantifies the net amount of heat either extracted from or delivered to the ground over a given period. This parameter is critical for assessing the long-term sustainability of the ground as a heat source or sink. Significant thermal imbalances can lead to reduced system efficiency over time if the ground temperatures deviate too far from their initial values.

Together, these parameters form the backbone of our GSHP model, enabling us to simulate the system's performance under various conditions and assess its viability both technically and financially. All parameters in this model have been carefully selected based on a thorough literature review, ensuring they are reflective of typical scenarios encountered in GSHP installations. However, for modeling a specific installation, these parameters can and should be adjusted to align with the actual climate conditions, ground temperatures, and other relevant factors specific to the site. By carefully adjusting these parameters based on specific project requirements and local conditions, the model can provide valuable insights into the optimal design and operation of GSHP systems.

Excel model:

To construct the model, we incorporated the heat and cold demand curves, which represent the energy requirements throughout various times of the year. These curves are essential for determining when and how much heating or cooling is required. To this end, the model applies specific parameters such as the COP, capacity limits, and the selected initial investment formula to calculate the number of boreholes needed, each assumed to be approximately 100 meters deep in the first trial. This borehole depth serves as a default input but is adjustable based on the contractor’s available materials, the kind of soil, and spatial constraints for installation.

The input for the model is in kilowatt-hours (kWh) since it models the energy requirements for heating and cooling of the residence, allowing us to assess the system's performance in energy terms. Through this model, we are able to simulate scenarios to calculate the maximum and total energy requirements, and effectively manage the operation of the heating or cooling system to maintain energy efficiency and address potential thermal imbalances.

Case study: 200m² Standalone House

To illustrate the practical application of our model, we considered a case study involving a 200m² standalone house equipped with a garden suitable for installing the boreholes. This setup provides a concrete example of how the model can be applied to typical residential settings. The garden space allows for sufficient installation of the necessary boreholes, making it an ideal scenario to test the model’s capabilities.

Using the model, we analyzed the energy dynamics for this house over different seasons, applying the heat and cold curves to determine the varying energy needs. The model’s flexibility in adjusting the borehole depth and other parameters allowed us to explore various configurations and optimize the system based on the specific environmental and spatial conditions of the house.

Energy calculations and thermal imbalance control:

The model's capability extends beyond energy consumption calculations. It also includes features to control the operation of the heating or cooling system, which is crucial for preventing thermal imbalance—a common issue in GSHP systems where the ground temperature could either increase or decrease excessively, affecting long-term performance. By monitoring and adjusting the system operation according to real-time data fed into the model, we can ensure optimal performance while minimizing wear and inefficiencies.

Control mode:

To establish a realistic control model for the GSHP system, it was crucial to address common operational limitations that GSHPs encounter in real-world settings. The key aspect of this model is the functionality of the compressor, a core component whose operation significantly affects the system's overall performance and efficiency.

The compressor's operational dynamics are central due to the potential absence of a hot water reservoir. In systems without such a reservoir, the GSHP must frequently cycle on and off to align with the intermittent demands of heating or cooling. This cycling is necessary to maintain the desired indoor temperature and it is periodic since turning the compressor on and off too frequently would reduce its lifespan, but it can lead to increased wear on the system and reduced efficiency over time.

In light of these considerations, the control strategy for the compressor is designed to mirror the operational characteristics described in current technological standards. Compressors can generally be regulated in one of three ways:

Binary regulation: the compressor operates in an on/off mode, which is straightforward but can lead to greater temperature fluctuations and potential inefficiency in energy use.

Variable regulation: this allows for continuous adjustment of the compressor’s output to match the exact demand, optimizing energy use and reducing wear. This requires a variable compressor in the absence of a water reservoir, these compressors are more expensive and are often encountered in bigger installations.

Stepped Regulation: in our model, we also incorporate control in steps, specifically choosing to regulate at quarter-capacity increments. This method strikes a balance between the binary and fully variable modes for semi-variable compressors, allowing for moderate adaptability to changing thermal demands while maintaining system simplicity and reliability.

Additionally, the control model must account for any lag between the actual thermal demand and the system's response. This discrepancy can result in either oversupply or undersupply of heating or cooling, which not only affects immediate comfort levels but can also lead to long-term inefficiencies. Typically, the installation of a water reservoir acts as a thermal buffer, mitigating these issues by storing excess heat or coolness until it is needed. However, in our simulations, we operate under the assumption that such a reservoir is not present, highlighting the importance of precise control and efficient operation of the compressor.

Given that we are working with demand data spanning an entire year, the control model needs to be robust enough to handle seasonal and daily variations effectively. The absence of a water reservoir for buffering demands that the compressor's control logic be particularly adept at managing these fluctuations to maintain system efficiency and longevity.

This approach to modeling the control aspects of a GSHP system allows us to simulate a realistic operational scenario, where the limitations and capabilities of current compressor technology are taken into account, ensuring that our model can provide insightful and applicable results for real-world GSHP applications.

4.10.1 SYSTEM COMPARISONS

In our model, we explored various heating and cooling solutions by comparing traditional systems, such as gas burners paired with AC units, against more sustainable options like ASHPs and GSHPs, our subject of study. To ensure an accurate simulation, we included critical environmental variables such as exterior air temperature, which was particularly essential for modeling the ASHP unit. Temperature data, crucial for our analysis, was sourced from a reliable, ensuring that our model reflected realistic environmental conditions.

We focused our study on three single-family homes located in distinctly different climatic regions across the United States: Texas, North Carolina, and Massachusetts. Each location presents unique weather patterns that significantly influence the performance of heating and cooling systems:

Texas: hot summers, Texas often experiences extreme heat, particularly in the southern parts of the state. Winters are generally mild but can vary significantly from north to south. Such conditions challenge cooling systems, which must operate efficiently under high thermal loads.

North Carolina: this region experiences a moderate climate with hot, humid summers and mild to cool winters. The state's weather can vary somewhat from the coastal areas to the Appalachian Mountains, affecting how heating and cooling systems perform throughout the year.

Massachusetts: characterized by cold winters and moderately warm summers, Massachusetts' climate demands effective heating solutions for the cold months, while the cooling needs in summer are significantly less intense compared to the southern states.

All of the detailed information in the data used sheds light into the exact settings used. In each of these environments, the external weather conditions play a crucial role in determining the efficiency of the heating and cooling systems. ASHPs, for instance, tend to perform less efficiently in extremely cold or hot temperatures due to their reliance on the ambient air temperature. Similarly, the performance of AC systems and GSHPs is influenced by regional climate variations. GSHPs, which utilize the stable underground temperatures, generally maintain better COPs across diverse climates but can still be impacted by severe above-ground weather conditions. Continuing with this last point, thermal imbalance will be studied and will also affect both the modelling and the real-world performance of GSHP systems.

The efficiency of gas burners, which are commonly used for heating, also varies depending on the ambient temperatures and the specific installation characteristics of each building. For instance, in colder climates like Massachusetts, gas burners might be preferred due to their capacity to provide consistent heating without the efficiency losses associated with electric heat pumps in freezing conditions.

Moreover, the energy demands of these houses—both for cooling in summer and heating in winter—differ notably due to their geographic and climatic disparities. A home in Texas, for instance, might require a robust cooling system capable of handling prolonged periods of high temperatures, whereas a home in Massachusetts would prioritize efficient heating solutions to combat the harsh winters.

Following this same model, commercial buildings introduce more layers of complexity, typically presenting higher energy needs and are subject to different operational dynamics and economic considerations. The cost of electricity and gas, which can vary significantly by region and over time, plays a crucial role in determining the operational costs of these systems. For commercial settings, fluctuations in utility prices can impact the choice of heating and cooling systems—decisions that are often made based on long-term economic analyses rather than immediate climatic needs.

In regions or countries where electricity is expensive or peak demand charges are significant, gas-powered systems or hybrid solutions might be economically favorable despite potential environmental drawbacks. Conversely, in areas with lower electricity costs or where incentives are offered for renewable energy solutions, electric heat pumps, including GSHPs, might be more viable.

This approach highlights the variable performance of different systems across various climates and building types but also underscores the economic factors influenced by regional energy pricing dynamics. By considering both the micro (individual building level) and macro (regional economic conditions) factors, our model provides a nuanced perspective on the optimal solutions for heating and cooling needs tailored to specific environmental and economic contexts.

4.10.2 DEMAND COMPARISONS

In our comparative analysis of GSHP system performance across three distinct climatic zones in the United States, the findings corroborate expected trends regarding heating and cooling demands due to regional temperature variations. Massachusetts (MA), being the coldest of the three states evaluated, exhibited a higher dependency on heating systems compared to North Carolina (NC) and Texas. This geographical variation significantly influences the operational dynamics and efficiency of GSHP systems, particularly in terms of thermal energy management within the ground.

A notable observation across all regions was the occurrence of thermal imbalance in the ground where the GSHP systems were installed. This imbalance reflects a disparity between the amount of heat energy absorbed into the ground versus the amount extracted, impacting long-term ground temperature stability and system efficiency.

Texas: the state's warmer climate naturally led to a greater cooling requirement, with a peak cooling demand of 4.42 kWh and a much lower heating demand of 15.7 kWh. The total thermal imbalance calculated was 1891.92 kWh, indicating that significantly more heat was transferred to the ground than was extracted. This excess heat accumulation around the BHE is predicted to raise ground temperatures over time, potentially reducing the system's efficiency and increasing operational costs as the ground becomes a less effective heat sink.

North Carolina: in contrast to Texas, North Carolina required more heating than cooling, with peak demands of 2.03 kWh for cooling and 17.54 kWh for heating. The total thermal imbalance here was -9997.14 kWh, suggesting that a substantial amount of heat was extracted from the ground compared to what was inputted. This net extraction leads to a cooling of the ground surrounding the BHE, which can enhance cooling efficiency but may require more energy for heating as the ground temperature drops.

Massachusetts: reflecting its colder climate, Massachusetts had the highest heating demand among the three states, with peak heating and cooling demands of 20.83 kWh and 2.185 kWh, respectively. The total thermal imbalance reached -14482.09 kWh, the highest among the states studied, indicating that a significant amount of heat was drawn from the ground, exceeding the energy input. This extensive heat extraction can lead to a marked decrease in ground temperature, potentially affecting the GSHP system's heating efficiency during colder months.

These disparities in thermal energy exchange within the ground highlight critical considerations for GSHP system design and operation. Systems in warmer regions like Texas may need measures to mitigate heat accumulation in the ground, such as integrating thermal regeneration techniques or enhancing system design to better manage excess heat. Conversely, in colder regions like Massachusetts and North Carolina, strategies to minimize excessive cooling of the ground might include the use of hybrid systems or seasonal thermal energy storage solutions to balance the thermal inputs and outputs throughout the year.

The average annual temperatures—20.71ºC in Texas, 15.05ºC in North Carolina, and 10.54ºC in Massachusetts—further elucidate the thermal dynamics each GSHP system must accommodate. These temperature metrics are essential for predicting system performance, informing system design, and planning for long-term sustainability in varying climatic conditions. Understanding these dynamics allows for a more tailored approach to GSHP deployment, ensuring optimal performance and cost-effectiveness across diverse environmental settings.

4.10.3 SYSTEM SETTINGS

Gas burner + AC unit:

The efficiency rates of the gas burner in the heating system vary significantly between the regions due to different installation standards and possibly different models of equipment being used. In TX, the heating efficiency is set at 80%, while in NC and MA, the efficiency is higher at 92.5%. This discrepancy might be due to better insulation standards, more modern equipment, or stricter regulations in NC and MA compared to TX. A higher efficiency percentage reflects a more effective conversion of fuel into usable heat, which not only enhances the heating performance but also reduces the amount of fuel consumed and minimizes waste.

The COP for the AC unit also differs based on the regional settings. In Texas and North Carolina, the AC units operate with a COP of 3.28, indicating that for every unit of electrical energy consumed, the unit provides 3.28 units of cooling energy. In Massachusetts, the COP is slightly higher at 3.61, which could be due to cooler ambient conditions that make the heat expulsion process more efficient or possibly the use of more advanced or better-maintained AC systems in this state.

These regional differences in efficiency settings for both heating and cooling components of the system underscore the need to tailor energy solutions to specific environmental and infrastructural contexts. Higher efficiency in heating and cooling not only impacts the operational cost but also affects the overall energy consumption and carbon footprint of residential heating and cooling systems.

In regions with higher heating efficiencies (NC and MA), residents can expect lower operational costs during colder months due to less fuel consumption for the same amount of heat output compared to regions with lower efficiencies (TX). Similarly, the higher COP values in cooler regions like MA indicate better performance of air conditioning systems under less harsh conditions, leading to energy savings during warmer periods. This will be studied in further detail later in this paper.

ASHP:

In the simulation of the ASHP system, specific parameters were set to model its performance under varying external temperatures. These settings are crucial for accurately predicting the efficiency of the ASHP in both heating and cooling modes.

Heating: the COP for the ASHP is initially set at 3.22 when the external air temperature is 8 degrees Celsius. This COP value indicates the efficiency of the heat pump at converting electrical energy into heat energy under specified conditions.

A degradation factor of 0.05 per degree Celsius is applied to model the decrease in COP as the external temperature deviates from the 8-degree baseline. This factor reflects the sensitivity of the ASHP's heating efficiency to changes in external temperature. As the temperature decreases, the COP also decreases, reflecting the increased difficulty of extracting heat from cooler air.

Cooling: in cooling operations, the ASHP starts with a COP of 6.45 at the same baseline external temperature of 8 degrees Celsius. This higher COP reflects the general efficiency of heat pumps in cooling mode under mild conditions, where the heat extraction process is less energy-intensive compared to heating.

Similarly, the degradation factor of 0.05 per degree Celsius applies for cooling efficiency. As external temperatures rise above the 8-degree mark, the COP decreases, illustrating the increased energy required to expel heat into the warmer outside air.

It is important to note that the COP cannot drop below 1.0. A COP of 1.0 represents the efficiency threshold where the ASHP operates equivalently to an electric resistor, meaning that the energy output (in the form of heat or cooling) equals the electrical energy input. This limitation ensures that the heat pump remains a more efficient choice than conventional electric heating or cooling devices, which operate at a COP of 1.0 or less.

These parameter settings are critical for ensuring that the ASHP operates within realistic and technically feasible limits. They allow us to model how the ASHP would perform in a range of climatic conditions, providing valuable insights into its practicality and effectiveness as a heating and cooling solution. By understanding and applying these parameters, we can better design, optimize, and implement ASHP systems that are both energy-efficient and capable of meeting diverse environmental and operational demands.

GSHPs:

Texas: the GSHP system in Texas is characterized by an original COP of 5.0, indicative of high efficiency in both cooling and heating modes. This is optimal given Texas' relatively stable ground temperatures which favor the operation of such systems. Both the cooling and heating capacities are set at 18 kW, balanced to meet the typical demands of family homes within the state. The initial ground temperature is recorded at a relatively warm 18°C, influencing the system's efficiency and the energy requirements for achieving desired indoor temperatures. The system's BHE stretches to 350 meters, reaching depths where ground temperatures are more constant, with each borehole dug to a depth of 50 meters. This configuration leverages the earth’s stable underground temperatures for effective heating and cooling.

North Carolina: in North Carolina, the GSHP system operates with a COP of 4.6. This slightly lower efficiency compared to Texas reflects the influence of North Carolina's cooler ground temperatures. The cooling and heating capacities are slightly increased to 20 kW each to accommodate the state’s broader climate variability and ensure adequate control of indoor temperatures throughout changing seasons. The ground temperature starts at a cooler 14°C, presenting a different set of efficiency dynamics. Despite these variations, the BHE length is maintained at 350 meters, and the system includes seven boreholes, each 50 meters deep, to ensure sufficient ground contact and efficient energy exchange.

Massachusetts: the GSHP in Massachusetts is designed with a lower COP of 4.1, which is primarily due to the significantly cooler average ground temperatures affecting heat pump efficiency, particularly during the long cold winters. Both the cooling and heating capacities are set at the highest among the three states at 22 kW, to address the heightened heating requirements during Massachusetts's extensive colder periods. The initial ground temperature is quite cold at 8°C, necessitating more energy to modulate indoor temperatures to comfortable levels. The BHE extends to 350 meters with a total of seven boreholes, each also reaching 50 meters deep, similar to North Carolina. This setup is intended to maximize the thermal exchange capacity required for the higher energy demands in this colder climate.

In each state, the GSHP system design is strategically optimized to local environmental and geothermal conditions. This ensures efficient operation, leveraging local ground properties to maximize heating and cooling outputs while maintaining energy efficiency and cost-effectiveness. These configurations illustrate a careful consideration of regional climatic conditions, ground temperatures, and the specific energy needs of each area, ensuring each installation provides optimal and sustainable performance.

4.10.4 LIFESPAN TEST

For the Massachusetts example, because it was considered more interesting (colder climate, costs of heating and cooling are more considerable, as we will also analyze in the conclusions) a study taking 2018 as a repeated weather pattern repeated in the future, we examined how the GSHP system would compare to other said alternatives.

We have to keep in mind the limitations in the prediction of future weather, gas and electricity prices, and the conclusions extracted from this model will be affected by changes in these parameters too.

Also, change in ground temperature was modelled as an exponential curve to depict the change in ground temperature at the beginning of the life of the GSHP with two counteracting phenomena:

-Thermal imbalance: as the ground keeps getting cooler due to the heat extracted from it, there needs to be more water flow to extract the same quantity of heat from the ground. This creates a positive feedback loop that cools down the soil as time passes.

-Thermal differential: as the ground around the BHE cools down (or warms up), due to thermal conductivity, the soil around it would transfer heat to it. The bigger the temperature difference is, the bigger the results of this effect become. At one point this thermal difference would become so big that the efficiency of the system could be compromised, making it more efficient to just use a GSHP in an extreme case.

For this lifespan test, we assumed that the ground temperature would decrease gradually (due to the predominance of heat extraction over energy input to the ground, at the same time due to the cold climate) from an average of 7ºC to 5.5ºC. This is a simplification of reality was designed to give a stabilization of the ground temperature around other observed parameters. This was also because to model the weight and formulation of the second phenomenon, there would need to be knowledge of the type of terrain, soil conductivity, humidity, borehole field disposition and a plethora of factors that would influence this phenomenon's behavior. Also, there was almost no literature available that would allow us to make a model that is representative of reality. To simplify all of this, we assumed the exponential influence of thermal imbalance that was explained previously.

4.10.5 COST ANALYSIS

For the cost analysis and comparison of the various heating and cooling systems under study, including gas burners, ASHPs, GSHPs, a detailed examination of energy consumption was essential. After quantifying the energy needs of each system in kWh, we proceeded to calculate the associated costs based on current fuel prices.

To accurately assess these costs, we sourced the latest data on electricity and gas prices from the U.S. Energy Information Administration (EIA). The electricity prices were accessed via their dedicated electricity data browser (EIA electricity data), while gas prices were obtained from their summary of natural gas prices (EIA gas price source). These sources provided, up-to-date, accurate and historic information for the financial evaluation.

By multiplying the total energy consumed by each system by the respective costs of electricity or gas during the year in question—as well as considering the prevailing weather conditions—we derived a precise estimation of the operational costs. This approach not only reflected the actual energy usage but also aligned with the financial implications experienced by the end-users.

An essential step in this process was converting gas measurements from thousands of cubic feet to kWh, a conversion clearly delineated by the EIA as well. This standardized the energy units across different fuel types, enabling a direct comparison of costs irrespective of the energy source.

For a more consumer-centric analysis, we utilized residential cost figures for single-family homes. This differentiation was vital as it aligns calculations with the likely billing scenarios encountered by different types of properties.

To add another layer of realism to our cost analysis, we opted to use the monthly average prices of electricity and gas, reflecting the typical billing cycle of these utilities. This choice was particularly pertinent as it accounted for seasonal fluctuations in energy costs—especially notable during winter months, when the demand for heating typically results in higher consumption of electricity and gas, coinciding with peak pricing periods for these utilities.

This approach to cost analysis not only provided a clear picture of the financial burdens associated with each heating and cooling system but also offered valuable insights into the economic impacts of climatic variations on energy consumption and costs. By integrating these considerations, our study presents a robust model of the financial realities faced by consumers using different types of heating and cooling systems under varying environmental conditions.

CHAPTER 6. RESULTS

As previously stated, the three medium-sized individual homes were modelled as having reversible GSHPs capable of outputting 18kW in Texas, 20kW in North Carolina and 22kW in Massachusetts. The details of the houses were not incorporated in the calculations as having a heat sink after the input but rather they were incorporated in the demands per se, this means that in a colder climate there would be more heat losses and therefore the demand would be greater (as it can be seen in the model). They have been modelled as all of them having the same 350m long BHE, consisting of 7 50m deep tubes.

The maximum heating/cooling output for the Texas system was 15,7kW and 4,42kW respectively. The maximum heating/cooling output for the North Carolina system was 17,54kW and 2,03kW respectively. The maximum heating/cooling output for the Massachusetts system was 20,83kW and 2,19kW respectively. These noticeable differences in the maximum values of the demanded heating and cooling already throw some information about the nature of the demands although it is not recommended to assume that heating will be predominant in all the three cases studied. For example, a winter storm could make the maximum heating demand skyrocket only for one day while the rest of the year cooling is predominant.

Overall, the total demand for heating and cooling for Texas is 7129kWh and 9021kWh respectively. These figures for North Carolina amount to 12502kWh and 2505kWh respectively, while for Massachusetts they sum 17221kWh and 2739kWh. As it was expected, in Texas cooling is predominant while heating is in the other regions studied despite the higher peak demand for heating in Texas. In the three regions studied there is an imbalance between heating and cooling.

Due to said differences in the demand (and therefore system output), there will be a thermal imbalance (more about it in the following paragraphs). A correlation between thermal imbalance and COP is present in the model, in which thermal imbalance alters the average ground temperature over time (if heating is predominant the ground will cool down and if cooling is predominant it will increase the average ground temperature), resulting in a loss of COP which is the object of study.

The model also approximates the change in ground temperature with a lineal correlation. It is an approximation based on the literature review due to the absence of information on the plethora of factors that influence thermal conductivity on the specific site. The approximation is useful not to get the exact figures on average ground temperature around the BHE but to test if thermal imbalance would result in an excessive loss of COP over time.

The gas and electricity prices used for our calculations were the following: (gas prices in $ / Thousand Cubic Feet, electricity prices in $/kWh)

Gas prices:	Texas	North Carolina	Massachussets
Month	Residential	Residential	Residential
1	8,8	9,77	14,27
2	9,57	13,53	16,26
3	11,12	10,46	15,71
4	12,86	13,25	17,75
5	16,15	20,82	16,75
6	20,1	21,56	14,62
7	21,54	24,76	15,87
8	23,73	21,73	16,62
9	21,97	25,37	16,07
10	16,88	17,31	13,32
11	10,71	10,86	13,44
12	8,65	11,08	15,21

Table 5. Gas prices in $/Thousand Cubic feet for the period of time studied (2018). Source: Energy Information Agency. Available: https://www.eia.gov/dnav/ng/ng_pri_sum_dcu_SMA_m.htm

Month	Residential
1	0,1222
2	0,1263
3	0,1297
4	0,1288
5	0,1312
6	0,1303
7	0,1313
8	0,1326
9	0,1301
10	0,1285
11	0,129
12	0,1243

Table 6. Electricity prices in $/kWh for the period of time studied (2018). Source: Energy Information Agency. Available: https://www,eia,gov

As said, observed thermal imbalance that causes a loss of COP over time. In the cases studied the first year we observed a loss of COP of less than 0.5%, 1% and 2% for TX, NC and MA respectively. Once again, this would be highly variable in a real-world scenario due to the big number of factors that affect ground thermal conductivity to BHE geometry and disposition.

This thermal imbalance resulted in a 0.44ºC, 1ºC and 1,45ºC difference in ground temperature for TX, NC and MA respectively. With initial ground temperatures of 18ºC, 14ºC and 8ºC respectively. This is the main cause of the loss of COP previously discussed in systems in the long run.

The total energy consumption in kWh was of 11662 for the Gas burner + AC unit in TX, of 4138 for the ASHP and 3230kWh for the GSHP system, 65% reduction in comparison to the initial case for the ASHP and a further 22% reduction for the GSHP for Texas as well. In NC the figures jump to 14210kWh, 4870kWh and 3274kWh respectively, reductions are in the same order with a 66% reduction of total energy consumption for the ASHP system and a further 33% one for the GSHP. To finish, in MA the consumptions skyrocketed to 19337kWh, 6424kWh and 4897kWh, amounting to a similar 67% reduction of energy consumption for the ASHP and a lesser reduction of 24% of the GSHP. This lesser reduction of energy consumption in the GSHP in relation to the other cases is the extreme nature of the thermal imbalance. The soil stops becoming a perfect energy source and becomes affected greatly by the energy extracted from it. This can also be seen in the previous temperature change of 1.45ºC. It should be noted that this is in total energy consumed taking in mind losses in inefficiencies in aspects such as gas burner losses.

In each case, as said previously, we included the same demand to compare the three systems. With this in mind, it can be observed that:

For scenario 1: yearly costs ascended to \$638, \$526, \$413 for the AC and gas burner, ASHP and GSHP systems respectively. Most part of the savings can be attributed to the reduction in costs for cooling. As in this setting for simulation there is more need for cooling than heating and the AC unit is less efficient than ASHP system for cooling purposes, and the ASHP at the same time presents a lower COP in comparison to the GSHP unit. It is noted that for heating, despite the GSHP being a more efficient and overall less expensive system to run, the ASHP outperforms it in running costs for this period of time.

For scenario 2: in NC yearly costs ascended to \$580, \$613, \$413 for the AC and gas burner, ASHP and GSHP systems respectively. Most part of the savings can be attributed to the reduction in costs for heating in this case for the GSHP. As in this setting for simulation there is more need for heating than cooling and the AC unit is less efficient than a ASHP system for cooling purposes, but it is compensated by a cheaper cost of gas than running the ASHP in winter. This is, however, gained back by the greater efficiency of the GSHP and is able to reduce running costs for \$167 against the gas burner + AC system and for \$200 against the ASHP.

For scenario 3: in MA yearly costs ascended to \$1,027, \$812, \$620 for the AC and gas burner, ASHP and GSHP systems respectively. Most part of the savings can be attributed to the reduction in costs for heating in this case for the GSHP. If only heating was needed, the GSHP would represent a 42% decrease in annual running costs.

As in this setting for simulation there is more need for heating than cooling, this advantage is still kept and running costs are still the lowest for the GSHP by 39% against the gas burner + AC system and 23% against the ASHP. In this scenario, there is a $407 annual savings, which could easily be improved with higher efficiency systems (the GSHP has been modelled with a moderate performance for what the technology is capable of).

These running costs estimations modelled, even though the case-to-case variations are hugely influential, these estimation of running costs provide good understanding of real ones.

TX33 – Climate Zone 2		**Total**	**Cooling**	**Heating**
Anual costs	AC + gas burner	$ 638,02	$ 359,56	$ 278,46
	ASHP	$ 526,09	$ 215,06	$ 311,03
	GSHP	$ 413,73	$ 235,86	$ 177,88
Average monthly costs	AC + gas burner	$ 53,17	$ 29,96	$ 23,21
	ASHP	$ 43,84	$ 17,92	$ 25,92
	GSHP	$ 34,48	$ 19,65	$ 14,82
Average monthly savings	AC + gas burner	N/A	N/A	N/A
	ASHP	$ 9,33	$ 12,04	$ - 2,71
	GSHP	$ 18,69	$ 10,31	$ 8,38

Table 7. Estimations of annual running costs for 2017 weather and energy demand of a 350 square meter house in Texas comparison of AC + gas burner system against ASHP and GSHP installations.

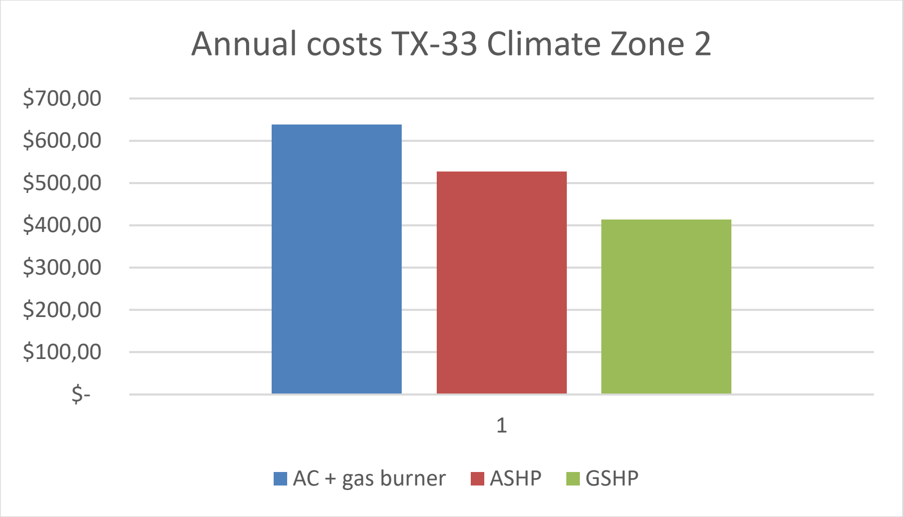


Figure 6. Estimations of annual running costs for 2017 weather and energy demand of a 350 square meter house in Texas comparison of AC + gas burner system against ASHP and GSHP installations.

Monthly costs		TX-33 Climate Zone 2	
Month	AC + gas burner	ASHP	GSHP
1	$ 107,30	$ 126,10	$ 72,52
2	$ 53,60	$ 58,40	$ 34,53
3	$ 14,93	$ 9,37	$ 9,57
4	$ 21,68	$ 14,08	$ 13,26
5	$ 49,59	$ 29,65	$ 32,59
6	$ 68,68	$ 41,72	$ 45,09
7	$ 67,82	$ 41,37	$ 44,49
8	$ 70,45	$ 42,94	$ 46,16
9	$ 42,33	$ 24,83	$ 27,71
10	$ 36,03	$ 21,19	$ 19,79
11	$ 52,18	$ 50,33	$ 30,80
12	$ 53,42	$ 66,11	$ 37,22
Total	$ 638,02	$ 526,09	$ 413,73

Table 8. Estimations of monthly running costs for 2017 weather and energy demand of a 350 square meter house in Texas comparison of AC + gas burner system against ASHP and GSHP installations.

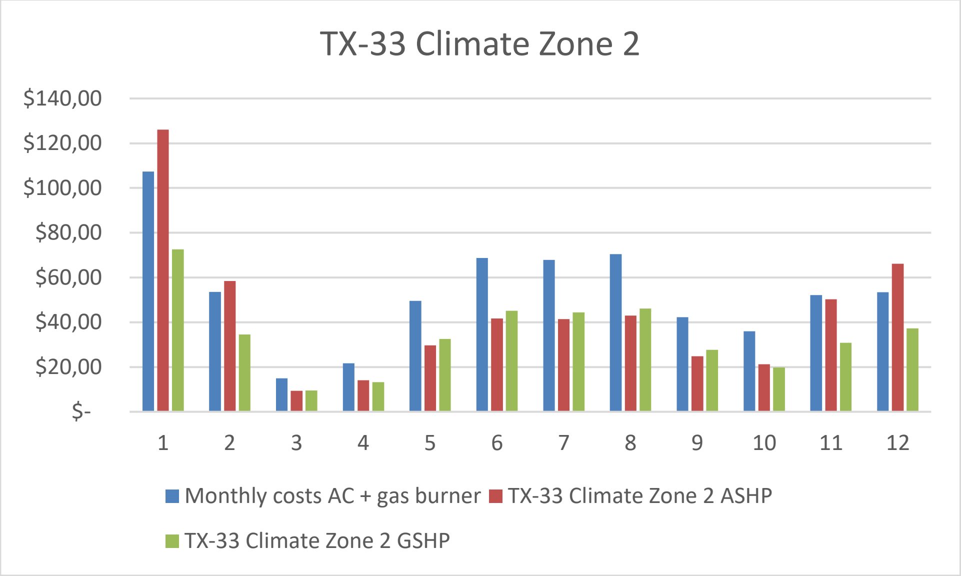


Figure 7. Estimations of monthly running costs for 2017 weather and energy demand of a 350 square meter house in Texas comparison of AC + gas burner system against ASHP and GSHP installations.

NC-192 Climate Zone 4		**Total**	**Cooling**	**Heating**
Anual costs	AC + gas burner	$ 580,16	$ 90,72	$ 489,44
	ASHP	$ 613,84	$ 57,71	$ 556,14
	GSHP	$ 413,65	$ 71,50	$ 342,15
Average monthly costs	AC + gas burner	$ 48,35	$ 7,56	$ 40,79
	ASHP	$ 51,15	$ 4,81	$ 46,34
	GSHP	$ 34,47	$ 5,96	$ 28,51
Average monthly savings	AC + gas burner	N/A	N/A	N/A
	ASHP	$ -2,81	$ 2,75	$ -5,56
	GSHP	$ 13,88	$ 1,60	$ 12,27

Table 9. Estimations of annual running costs for 2017 weather and energy demand of a 350 square meter house in North Carolina comparison of AC + gas burner system against ASHP and GSHP installations.

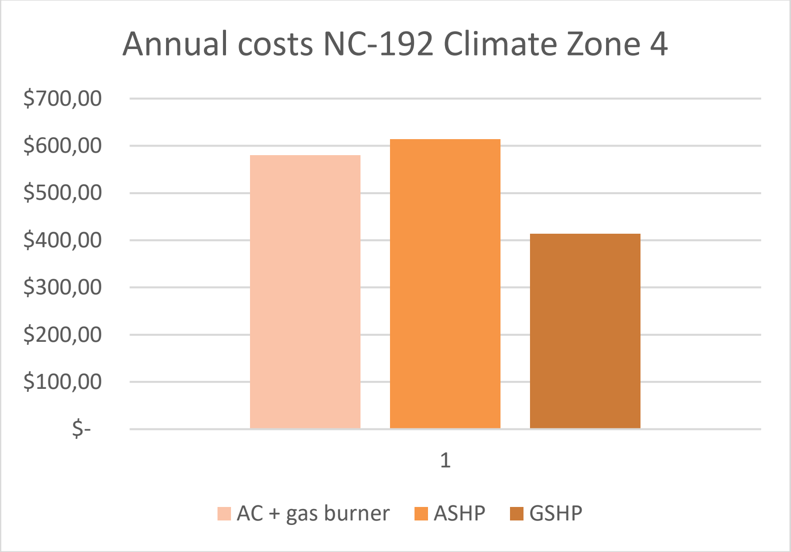


Figure 8. Estimations of annual running costs for 2017 weather and energy demand of a 350 square meter house in Texas comparison of AC + gas burner system against ASHP and GSHP installations.

Monthly costs		NC-192 Climate Zone 4	
Month	AC + gas burner	ASHP	GSHP
1	$ 144,72	$ 168,96	$ 110,81
2	$ 77,14	$ 71,72	$ 44,33
3	$ 63,05	$ 81,04	$ 48,02
4	$ 16,59	$ 15,89	$ 10,24
5	$ 10,94	$ 6,90	$ 8,62
6	$ 18,34	$ 11,84	$ 14,46
7	$ 18,46	$ 11,89	$ 14,55
8	$ 17,76	$ 11,39	$ 14,00
9	$ 15,00	$ 9,58	$ 11,81
10	$ 18,73	$ 14,03	$ 10,16
11	$ 70,63	$ 85,27	$ 51,54
12	$ 108,81	$ 125,33	$ 75,11
Total	$ 580,16	$ 613,84	$ 413,65

Table 9. Estimations of monthly running costs for 2017 weather and energy demand of a 350 square meter house in Texas comparison of AC + gas burner system against ASHP and GSHP installations.

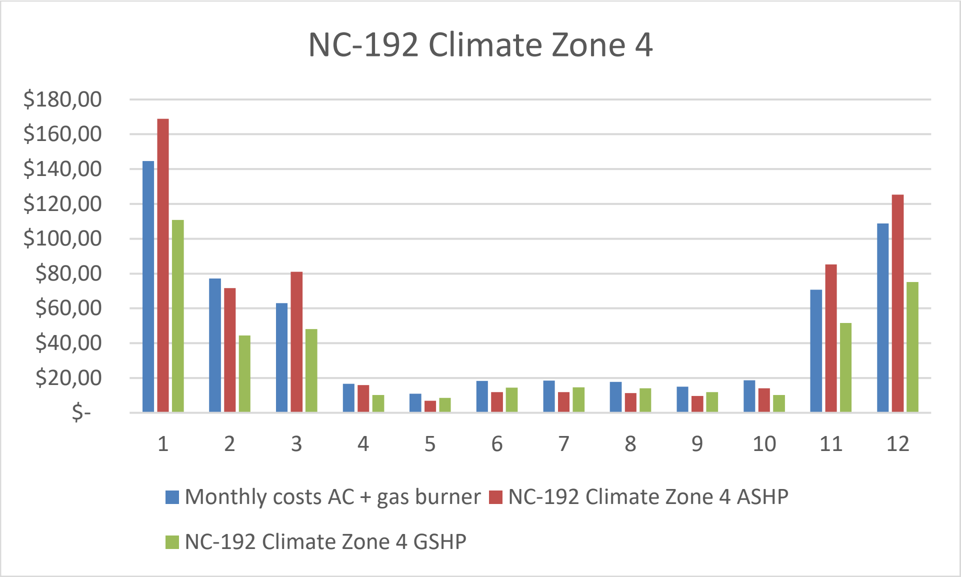


Figure 9. Estimations of monthly running costs for 2017 weather and energy demand of a 350 square meter house in Texas comparison of AC + gas burner system against ASHP and GSHP installations.

MA-281 Climate Zone 6		**Total**	**Cooling**	**Heating**
Anual costs	AC + gas burner	$ 1.027,29	$ 99,35	$ 927,93
	ASHP	$ 812,27	$ 61,96	$ 750,31
	GSHP	$ 620,20	$ 88,14	$ 532,06
Average monthly costs	AC + gas burner	$ 85,61	$ 8,28	$ 77,33
	ASHP	$ 67,69	$ 5,16	$ 62,53
	GSHP	$ 51,68	$ 7,34	$ 44,34
Average monthly savings	AC + gas burner	N/A	N/A	N/A
	ASHP	$ 17,92	$ 3,12	$ 14,80
	GSHP	$ 33,92	$ 0,93	$ 32,99

Table 10. Estimations of annual running costs for 2017 weather and energy demand of a 350 square meter house in Massachusetts comparison of AC + gas burner system against ASHP and GSHP installations.

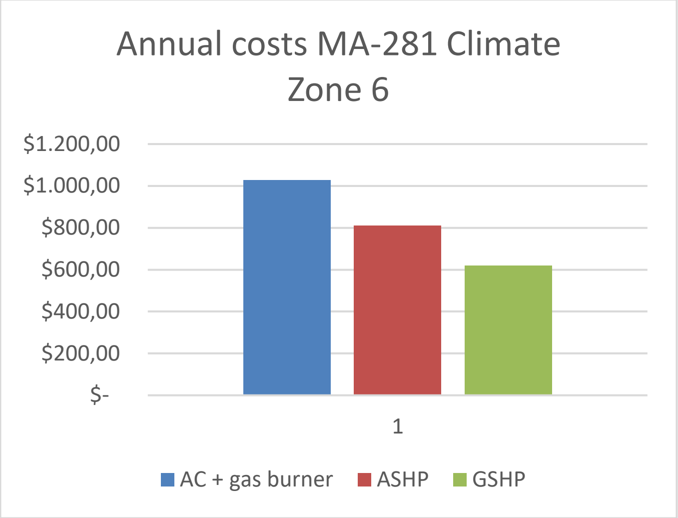


Figure 10. Estimations of annual running costs for 2017 weather and energy demand of a 350 square meter house in Texas comparison of AC + gas burner system against ASHP and GSHP installations.

Monthly costs		MA-281 Climate Zone 6	
Month	AC + gas burner	ASHP	GSHP
1	$ 240,77	$ 186,32	$ 141,98
2	$ 167,60	$ 127,67	$ 90,09
3	$ 156,72	$ 130,02	$ 89,71
4	$ 85,89	$ 63,83	$ 43,62
5	$ 9,11	$ 5,69	$ 7,83
6	$ 14,54	$ 9,11	$ 12,88
7	$ 25,86	$ 16,44	$ 22,95
8	$ 26,93	$ 17,21	$ 23,89
9	$ 13,88	$ 8,64	$ 12,31
10	$ 21,79	$ 20,54	$ 15,13
11	$ 99,47	$ 95,30	$ 66,23
12	$ 164,72	$ 131,51	$ 93,57
Total	$ 1.027,29	$ 812,27	$ 620,20

Table 11. Estimations of monthly running costs for 2017 weather and energy demand of a 350 square meter house in Texas comparison of AC + gas burner system against ASHP and GSHP installations.

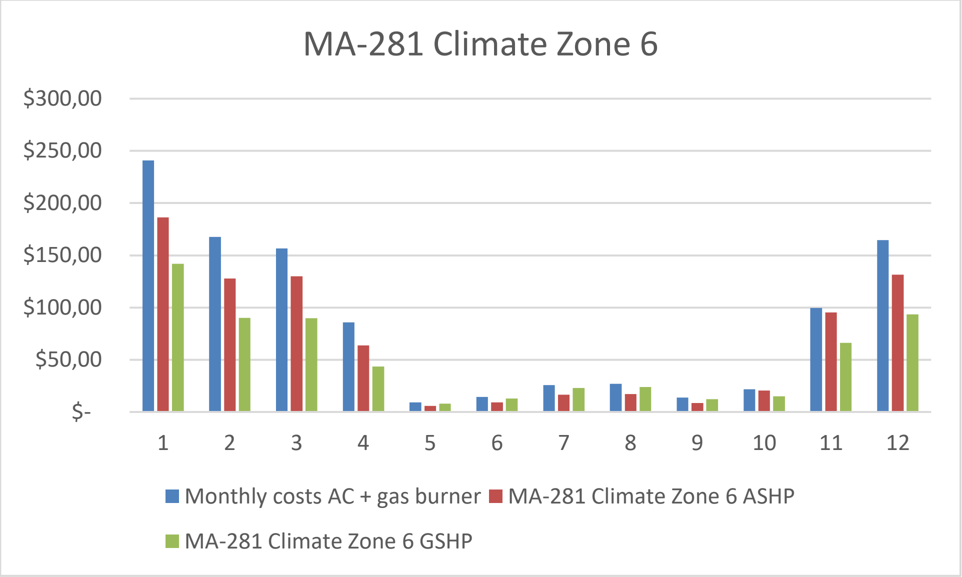


Figure 11. Estimations of monthly running costs for 2017 weather and energy demand of a 350 square meter house in Texas comparison of AC + gas burner system against ASHP and GSHP installations.

CHAPTER 7. CONCLUSIONS

As a conclusion from the analysis of GSHPs, it becomes evident that the viability of these systems is significantly influenced by the economic interplay between electricity and gas prices. The cost-effectiveness of GSHPs hinges on these variables, with shifts in energy pricing greatly impacting operational expenses. Particularly in commercial settings, GSHPs demonstrate promising utility; they not only achieve higher COPs but also mitigate the impact of high installation costs through significant energy savings over time. This aspect is crucial for larger applications where the economies of scale can be leveraged more effectively than in residential settings.

The industry's rapid adaptation and scaling capabilities suggest a bright future for GSHP technology. As manufacturers scale up and the market expands, we anticipate a reduction in unit costs, further enhancing the accessibility and affordability of GSHPs. The industry response underlines the growing recognition of GSHPs as a viable solution for decarbonizing heating and cooling systems across both residential and commercial sectors.

Addressing the initial question of whether GSHPs are prepared to facilitate widespread decarbonization, our findings affirmatively suggest that they are indeed poised for such a role. Despite existing challenges, mitigation approaches can enhance system safety and efficiency. In this study it has also been carried out a classification of GSHPs under different types for easier understanding of the technology and the options it brings.

Our comparative analysis further positions GSHPs favorably against traditional heat pumps and other technologies reliant on fossil fuels. Not only do GSHPs exhibit superior long-term cost-effectiveness and energy efficiency, but they also present a significant reduction in environmental impact. This comparison is crucial for understanding the broader benefits of GSHP technology in the context of global sustainability goals.

Furthermore, the practical modeling of a GSHP system within a residential building has illuminated its real-world efficacy. Through simple to understand yet robust equations, the model demonstrated the operational dynamics of GSHPs, despite the complexity of their installation. This modeling serves as a key tool for predicting system behavior under various operational conditions.

In conclusion, GSHP technology stands at a promising time. The increasing installation rates, driven by their economic and environmental benefits, signal a 'spring' for GSHP technology—a period of growth and widespread acceptance. This optimistic outlook is supported by both our detailed cost analysis and the operational modeling carried out in this study. As the technology continues to mature and overcome its initial barriers, GSHPs are expected to play a crucial role in the transition towards a more sustainable energy utilization.

CHAPTER 8. REFERENCES

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