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Design and operation of a vertical closed-loop geothermal plant

A case study in sustainable heating and cooling

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Abstract

This thesis explores the potential of low-enthalpy geothermal systems in the context of heating and cooling applications, addressing the growing demand for energy in these sectors. Geothermal systems offer a sustainable approach to energy production by harnessing a renewable energy source

An introduction to geothermal energy is followed by an analysis of the features and advantages of low-enthalpy systems, especially vertical closed-loop designs, while examining their components and regulatory aspects.

A comprehensive case study is presented, detailing the process of sizing the geothermal plant, including an analysis of ground characteristics and the building's energy efficiency. The system design ensures that all energy needs are met autonomously, without supplementary sources.

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1 Introduction to geothermal energy

Geothermal energy is a renewable energy source derived from the Earth's heat. It is extracted mainly by drilling into the ground and then transported to the surface using fluids. The planet Earth constantly emits energy in the form of heat: this is so-called heat flux, or geothermal flux, which propagate from the centre of the Earth towards the Earth surface. Despite the Sun irradiate the ground with a flux 6000 times higher than the one produced by the Earth, the geothermal flux represents an important source of heating because it is continuous. There are different ways to use geothermal energy [1]:

- ***electricity generation:*** this application consists in the heat conversion of fluids withdraw from the ground in electricity using turbine connected to a generator. To produce electricity economically, it is necessary to sufficiently concentrate geothermal heat, which requires the fluids to have high temperatures and flow rates. After use, the geothermal fluid is re-injected into the subsurface. The idea of this application was born in Italy, in Larderello, at the beginning of 1900.
- ***direct use:*** it uses wells to draw hot water from the subsurface to directly provide hot water in buildings, space heating, or industrial process.
- ***heating or cooling:*** geothermal resources such as naturally occurring underground reservoirs of hot water or the stable temperature of the subsurface can be used to heat and cool buildings. Geothermal heat pumps provide heating and cooling using the ground as a heat sink, absorbing excess heat when the aboveground temperatures are warmer, and as a heat source when aboveground temperatures are cooler.

1.1 Heat formation and structure of the Earth.

Thermal energy within the Earth is generated through two primary processes. The first is the result of friction and gravitational pull that were present when the Earth was formed over 4 billion years ago. The second process is the decay of radioactive isotopes, including potassium-40 and thorium-232. This is a continual process inside the inner part of Earth, where the heat constantly radiates outward, warming rocks, water, gas, and other geological materials. A comprehensive understanding of the process that leads to the development of the geothermal gradient requires an understanding of the Earth's structure, which is composed of several layers. [2]

On the basis of chemical properties, the Earth can be divided into three layers (Figure 1):

- ***crust:*** is the outward layer, primarily composed of solid rock, predominantly basalt and granite. It is divided in continental and oceanic crust: the first is thicker and composed of minerals richer in silica and the latter is thinner with minerals rich in iron and magnesium.
- ***mantle:*** predominantly solid rock but in constant slow motion. It comprises an upper mantle, cooler and stiffer, and a lower mantle, hotter and more flexible.
- ***core***: is the most internal part and is primarily composed of iron. The outer core of this layer, like the other two, can be divided into two distinct parts: a liquid outer core that is heated to high temperatures and a solid inner core that is under immense pressure, preventing the melting of iron.

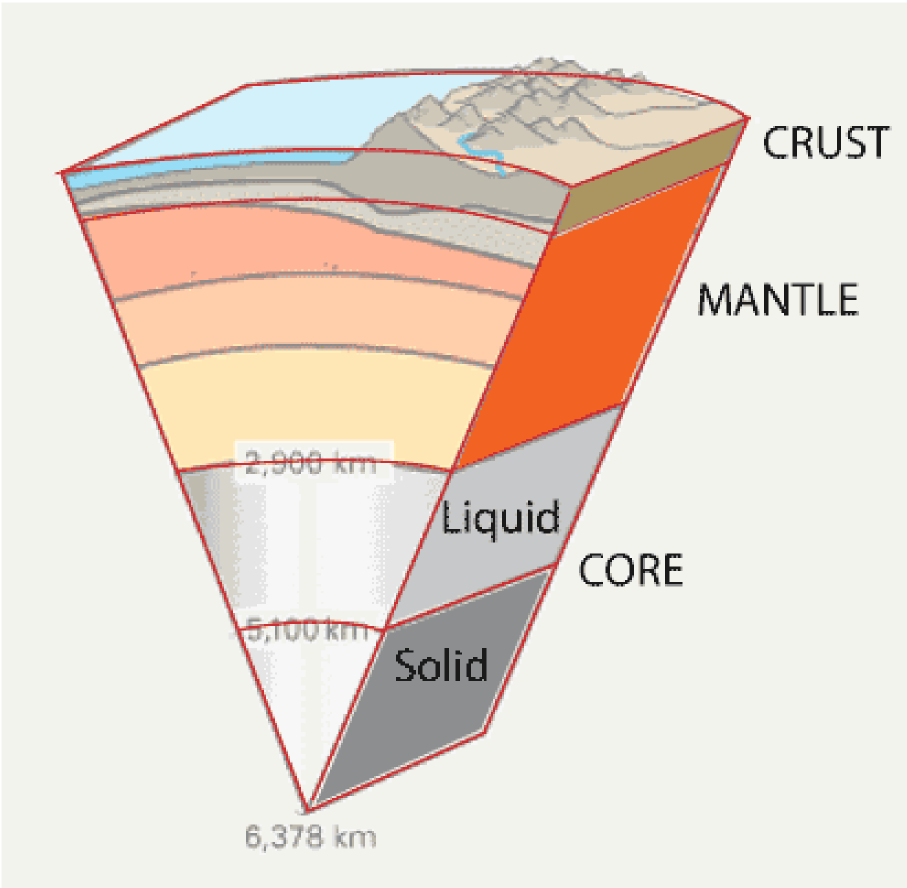

Figure 1 Structure of the Earth based on chemical properties

By considering the physical properties five main regions were derived: [3]

- ***lithosphere (0 to 100 km)***: the rigid outer part of the earth, it is fractured into a few large plates and their movement can facilitate the transfer of heat. This layer remains relatively cool because of the efficient heat dissipation to the surface.
- ***asthenosphere (100 to 660 km)***: located below the lithosphere and is a semi-fluid layer. It is hot and capable of vertical and horizontal flow.
- ***mesosphere (660 to 2900 km)***: a region of very hot solid rock.
- ***outer core (2900 to 5170 km)***: composed of liquid iron and nickel, is responsible for generating the Earth's magnetic field through the convective motion of conducting materials.
- ***inner core (5170 to 6378 km)***: the centre of the earth, it's solid for the extreme pressure despite being at high temperatures. The composition is similar to that of an iron-nickel meteorite.

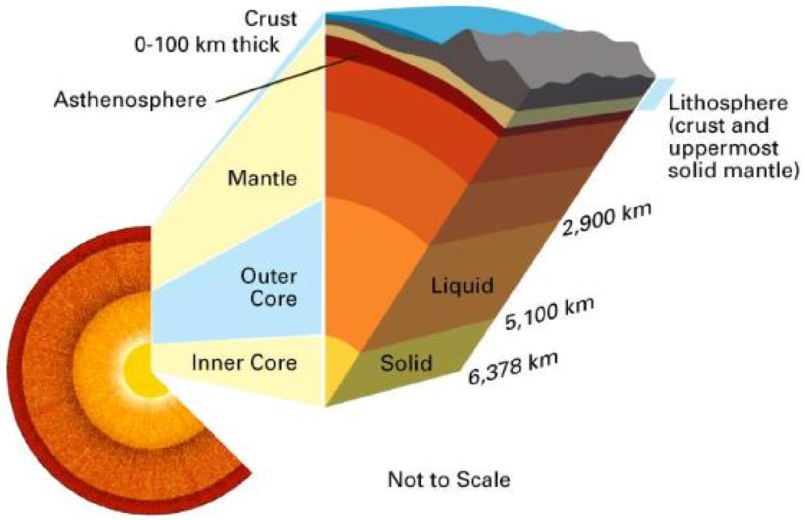

Figure 2: Structure of the Earth based on physical properties

1.2 Geothermal gradient and heat transfer mechanisms.

Going towards the centre of the earth, the temperature continues to rise, leading to a phenomenon known as heat flow, where the heat moves upward. This process, referred to the 'geothermal gradient' is expressed in °C/km:

$$\vec{q} = -\mathrm{k}\frac{dT}{dz}$$

where q is the vector of local heat flux density per m^2 of surface, k is the thermal conductivity and $\frac{dT}{dz}$ is the thermal gradient.

Temperature distribution can vary regionally and over geological time. Typical geothermal gradients in the crust are usually 25-30 °C/km [4]. Once the heat is generated it is transferred through two principal mechanisms:

- ***conduction:*** involves the transmission of heat through collisions between particles within a solid material, without the movement of the material. In the crust, heat transfer is primarily by conduction.
- ***convection:*** heat transfer occurs through the movement of a fluids, such as magma or water, within the Earth's interior. In the mantle, heat is transferred primarily by convection currents.

The technology used to harness this heat can be divided into three categories according to the characteristics reported in the Table 1: high, medium, and low enthalpy.

Table 1 Simplified scheme of geothermal resources, application, and technology

Temperature	Fluid type	Application	Technology
High (> 150°)	Water, vapor	Electricity generation Direct heat use	Dry steam, flash plants Heat exchanger
Medium (90-150 °C)	Water	Electricity generation Direct heat use	Binary cycle Heat exchanger, heat pump
Low (< 90°C)	Water	Direct heat use	Heat exchanger, heat pump Direct heat use

This thesis will focus on the low-enthalpy systems.

1.3 Low enthalpy geothermal energy: applications and future potential

Low-enthalpy geothermal plants allow the use of heat from Earth at relatively shallow depths, typically less than 300 meters. The temperature at this point is generally in a range between 20 and 100 °C. This type of geothermal energy is particularly suitable for heating and cooling applications, especially in buildings. The idea is to transfer the heat from the ground to the buildings during winter season and to extract heat from the buildings to the ground during summer.

Report for Buildings and Construction made by the Global Alliance [5] shows that the construction sector is responsible for 36% of the energy consumption and 37% of the emissions. These emissions are categorized as follows (Figure 3):

- Direct emissions: emitted by the structures themselves.
- Indirect emissions: derived from heating and electric power generation.

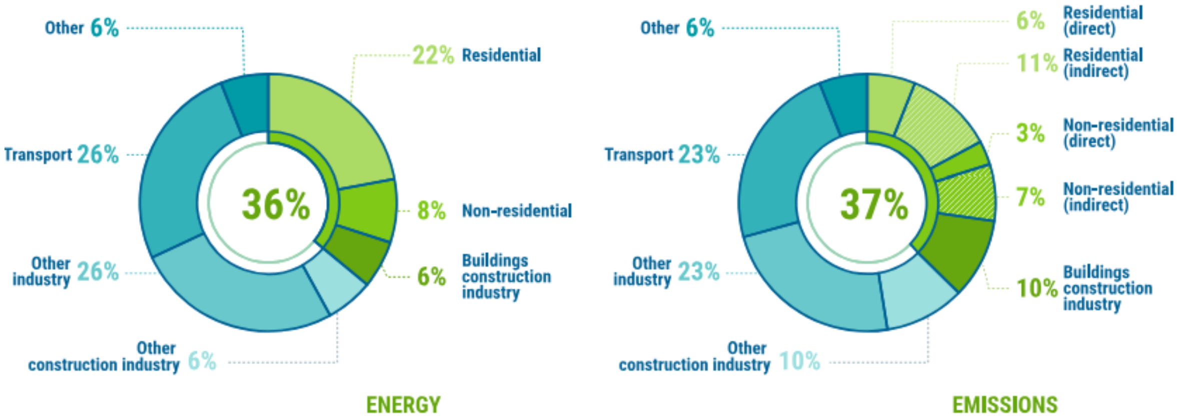

Figure 3: Buildings and construction's share of global energy and energy related CO2emissions,2020

In the future, there will be a rise in demand, almost doubling before 2050, for residential spaces and new facilities, particularly in countries experiencing rapid economic and demographic growth [5]. In already developed countries, it is essential to focus on improving energy efficiency of existing buildings. Building emissions will need to be reduced along their lifecycle through the combination of reducing energy demand (behaviour change and energy efficiency) and decarbonizing the power supply (e.g., electrification through renewable sources and increased use of other zero-carbon heating technologies).

Most of the energy consumed by buildings is related to heating and cooling, with most of this energy being provided by fossil fuel combustion and only a small contribution from renewable energy. In 2021 REN21 [6] reported that only the 14.2% of building heating was covered by renewable sources (REN21) (Figure 4).

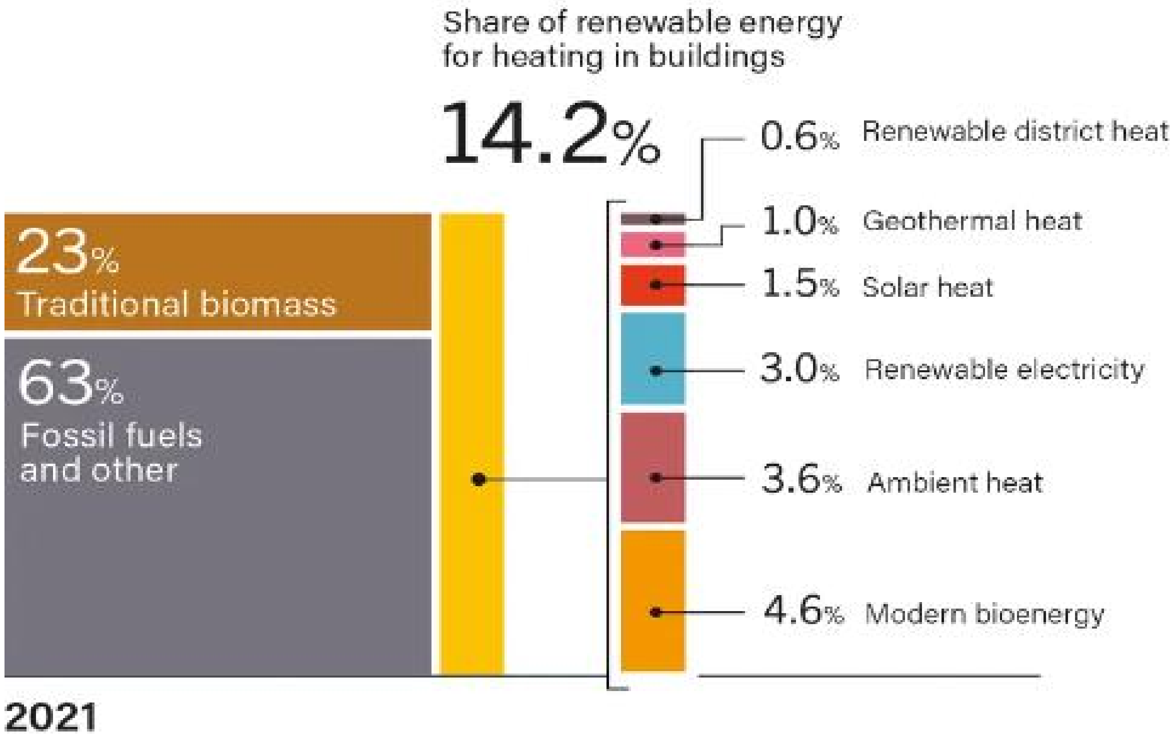

Figure 4: share of renewable energy for heating in buildings

Geothermal energy accounts only the 1%. According to the IEA, the use of heat pumps, will increase significantly in the coming years. As a result the 1% mentioned earlier is expected to increase in the coming years. This increment is related to the financial incentives already available in over 30 countries, which together cover more than 70 % of the heating demand today [7] . The IEA estimates that heat pumps have the potential to reduce global carbon dioxide (CO2) emissions by at least 500 million tons [7].

Shallow-depth system should be highly considered in this energy transition because they are 4-5 times more efficient than fuel-based or electric resistance systems, owing to their ability to move heat in and out of buildings instead of generating it.

In Italy, the situation regarding the utilization of geothermal energy for producing heat is analysed in the text 'Rapporto statistico 2021 energia da fonti rinnovabili', [8] data are reported in the table below:

Table 2 Utilization of geothermal energy for producing heat in Italy.

	2021 (TJ)
DIRECT USE	4.815
-residential	35
-commerce and services	2.946
-industry	57
-agriculture	620
-aquaculture/fish farming	1157
PRODUCTION OF DERIVED HEAT	1.072
-from cogeneration plants	-
-from thermal production plants only	1.072
GEOTHERMAL HEAT PUMPS	3433
Total	9320

In the report, the data may underestimate the actual prevalence of direct-use geothermal resource systems because many of these systems are small, constructed under free building regulations, and operate in closed loops. In Italy, geothermal plants are frequently used in conjunction with heat pumps, so for a comprehensive assessment of the thermal exploitation of geothermal resources for heating purposes also the geothermal heat pumps have been considered.

The market of geothermal plant is still a niche market, especially in comparison to the one of the air heat pumps, as is possible see in the figure 5

	2021			2022		
	Aerothermal HP	Geothermal HP	Total	Aerothermal HP	Geothermal HP	Total
Italy	20 706 000	17 098	20 723 098	20 831 000	17 723	20 848 723

Figure 5 Market of heat pump, air and geothermal ones

data from 'EurObservER-overview-barometer-2023.pdf' [9]. The reasons for this difference can be attributed to several factors, primarily the higher installation costs and longer payback period associated with geothermal heat pumps (GSHPs), a lack of expertise in their installation and maintenance, and a policy framework that does not sufficiently encourage their adoption. Solutions to bridge this gap include implementing better regulations and offering incentives to those who install GSHP systems, additionally, enhancing the efficiency of the systems through improved design and better borehole heat exchangers can help decrease initial costs and make the technology more attractive.

1.4 Key advantages of shallow geothermal energy

The main advantages of ground source heat pump systems can be summarized as follows [10]:

- ***renewable energy***: being related to the Earth, it means that is continuously replenished through natural processes, making it also sustainable for the future.
- ***reduced emissions:*** the systems produce minimal amounts of greenhouse gas emissions compared to fossil fuel-based energy sources, contributing to reducing carbon emissions in line with the goal of achieving net-zero emission by 2050.
- ***weather independent:*** this energy is consistently available, and the systems operate as 'base load' meaning they are not dependent on changing factors such as wind or sunlight. Additionally, their operation is not influenced by season changes.
- ***local energy:*** as fossil fuels are only available in certain areas of the world, many countries rely on imported energy. By using geothermal energy, which is widely available, it will be possible to produce energy locally, increasing energy independence and security for the country.
- ***low space occupied:*** geothermal energy does not require much space compared to other renewable energy sources. Regardless of whether it is a domestic system or a large-scale plant, most of the components (including the heat exchangers) are buried underground.
- ***versatility:*** systems are suitable for various settings, such as residential and commercial buildings, as well as industrial applications.
- ***low maintenance and longevity***: these systems typically have few mechanical parts and a simple design, which contributes to overall cost savings and increases reliability over time.

On the other hand the technology has obviously also disadvantages [11] that can be summarized as follows:

- ***high installation cost:*** the installation of GSHP involves significant upfront expenses, particularly for drilling and excavation required for the ground loops.
- ***installation complexity***: installing this type of system is more complex compared to other heating and cooling systems, the specialized knowledge and equipment are not easy to find.
- ***regulatory and permitting challenges:*** the GSHP may be subject to regulatory approvals and permits, which can vary by region. Navigating these regulations can add time and complexity to the project and.
- ***potential for surface instability:*** drilling deep into the earth to access geothermal reservoirs can cause underground instability, leading to earthquakes and surface subsidence.

2 Low enthalpy geothermal system

The plants used for the extraction of shallow geothermal resources are built to harness the potential of geothermal energy up to 300 meters. Since they utilize low-temperature geothermal resources they are more commonly used for heating and cooling purposes than to produce electricity therefore are better suited for residential and commercial control application. These technologies effectively exchange heat, giving heating in the winter and cooling in the summer, by taking advantage of the sub-surface's constant temperature throughout the year.

Two main groups of low-enthalpy geothermal systems exist: open-loop and closed-loop. In open-loop systems, water is extracted directly from a natural source, such as an aquifer, circulated through the system to extract heat, and then returned to the environment. These systems are highly efficient but depend on the availability of water sources and must comply with environmental regulations regarding water extraction and discharge. In closed-loop systems, a heat transfer fluid circulates within a sealed network of underground pipes, exchanging heat with the ground without direct contact with the soil or groundwater. In this thesis, only the closed-loop system was analysed. [12]

Closed-loop systems can have two configurations: vertical or horizontal. In vertical closed-loop systems, a fluid circulates within a sealed piping loop that extends vertically into the ground. In horizontal closed-loop systems, the piping network is spread over a larger area at shallower depths. Horizontal system offers significant advantages in terms of installation flexibility, but vertical systems require less surface area while accessing deeper, more thermally stable ground layers. [13]

While vertical systems need less surface area to access deeper, more thermally stable ground layers, horizontal systems have substantial installation flexibility advantages. Differently from the direct distribution systems, where the refrigerant liquid is circulated directly through the earth, vertical closed-loop work in a sealed loop avoiding this potential problem.

The main components (Figure 6) of these plants are as follows.

- **borehole heat exchanger** (BHE)**:** is a vertical pipe system installed in the ground used to extract or inject heat from/into the subsurface. The diameter and the depth of the boreholes are important design factors for determining the quantity of heat managed by the system.

- **heat pump** is a device that uses a fluid cycle of compression and expansion to transport heat from a low-temperature source to a high-temperature source.
- **circulating fluid:** the fluid that circulates through the BHE and acts as the medium for the transfer between the ground and the heat pump, the choice of fluid and its properties are essential considerations for ensuring efficient heating and preventing freezing under cold conditions.
- **building heating/cooling system:** the building heating or cooling system is connected to the heat pump in order to maintain the ideal temperature and guarantee the occupants comfort by using the heat or coolness produced by the heat pump.

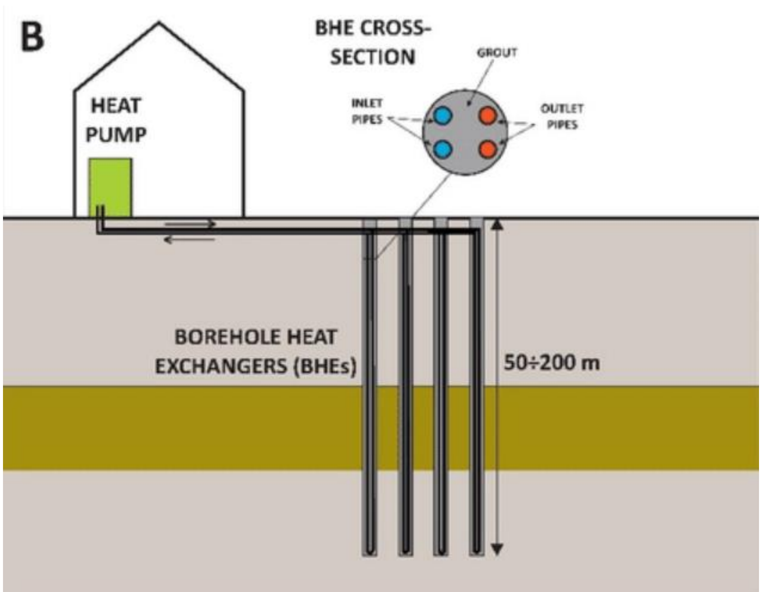

Figure 6 representation of a vertical closed loop system

In heating mode (Figure 7), the chilled carrier fluid exiting the heat pump absorbs heat (by conduction) from the subsurface and conveys it back to the heat pump, where the heat is extracted. The carrier fluid is then cooled again and begins its next cycle through the Earth. In cooling mode (Figure 7), the process is reversed: the warm carrier fluid from the reversed heat pump (or from a free cooling scheme in a building) is circulated into the subsurface, where it releases a portion of its heat load to the cooler ground.

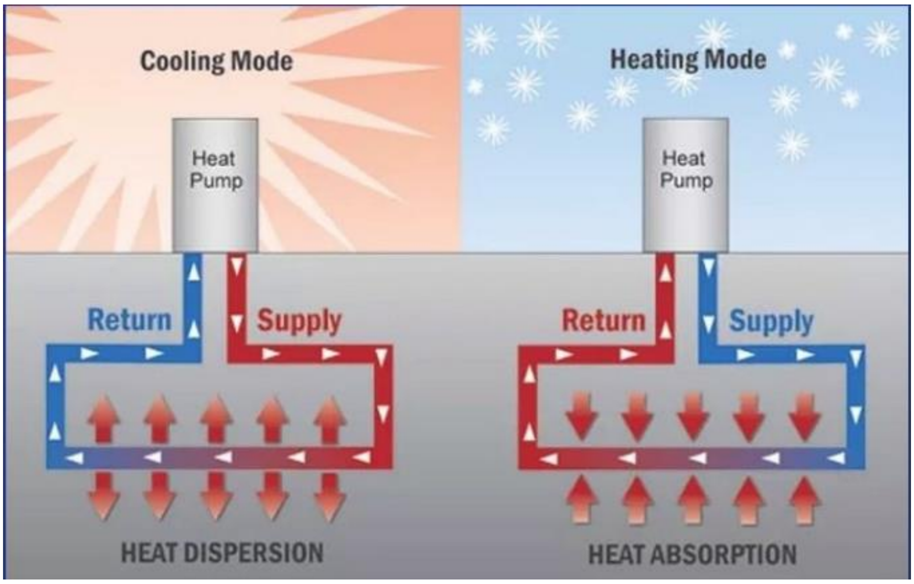

Figure 7 heating and cooling mode operation

2.1 Borehole Heat Exchanger

A BHE typically consists of a series of pipes inserted into a borehole drilled in the ground. These pipes can be configured in different arrangements, such as U tubes (single or double), coaxial designs, or multipipe systems, each of which offers distinct advantages depending on the specific application and geological conditions.

U-tube configuration consists of two parallel pipes connected at the bottom of the borehole, forming a U-shape, which is the most used configuration for practical and performance reasons. Thanks to its shape, the surface area available for heat exchange between the fluid inside the tube and surrounding ground is maximized and this enhances the heat transfer efficiency, other advantages include stability and durability of the configuration, easy installation, and standardization. [14]

Pipes are typically made of high-density polyethylene because of their durability, flexibility, and resistance to corrosion and environmental stress. The material is an excellent choice for this application because it can tolerate the pressure and temperature changes seen in the subterranean environment, which will prolong the system's operational life. In some cases, pipes can be manufactured with coatings or material with increased thermal conductivity to increase the effectiveness of heat transfer between the surrounding ground and the circulating fluid. Once drilling is completed, a U-shaped closed loop is usually emplaced down the length of the borehole, after that grout material is used to fill the space between the ground and the tube, ensuring efficient thermal conductivity.

The grout should ideally have a high thermal conductivity (to facilitate the transfer of heat) and a low hydraulic conductivity (to prevent fluid leakage) it serves also to seal the borehole, preventing groundwater contamination and ensuring that the borehole remains stable over time. High thermal conductivity and low hydraulic conductivity are the characteristics requested for the grout, they allow heat to be transferred more easily and stop fluid leaks. Grout also acts as a sealer keeping groundwater clean and guaranteeing the stability of the borehole over time [15]. The diameter and depth of this geothermal system component are crucial factors that influence the performance of the BHE, which are design parameters, and their values depend on the required heat exchange capacity. Generally, a borehole is drilled to a depth of 50-150 meters, although deeper boreholes can be used under certain conditions, and the diameter is in the range of 100-150 millimetres.

A proper installation is important to guarantee the correct functioning of the system, it ensures that pipes are correctly positioned, the borehole is effectively sealed and circulating flows efficiently circulate through the system.

In a system with multiple boreholes, the spacing between boreholes is carefully planned to prevent thermal interference, where the heat extracted from one borehole affects the temperature in adjacent boreholes, and adequate spacing ensures optimal performance of the entire geothermal field.

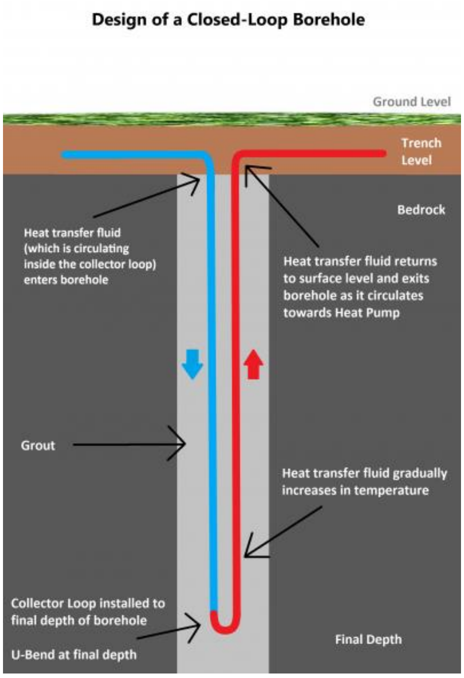

Figure 8 Design of a closed-loop borehole

2.2 Heat Pump

Heat pumps are primarily used for space heating and cooling, though many models are also made to provide hot water for household use. They work by taking heat from a low-temperature source, like the ground, and transferring it to a high-temperature sink, like a central heating system. A heat pump is a cyclical device that transfer heat against its natural gradient by using electrical energy, in this way heat is transmitted from a low-temperature medium to a high-temperature medium. By cycling a refrigerant fluid through a compression-expansion cycle, the device raises the temperature of the available heat from an unusable level to one that is suitable for heating or cooling. A key advantage of heat pumps is that they transfer heat between a heat source and sink instead of generating heat through the combustion of fossil fuels, which qualifies them as renewable energy applications.

A key advantage of heat pumps is that they transfer heat between a heat source and sink, rather than generating heat through the combustion of fossil fuels, which qualifies them as renewable energy applications, contributing to their growing adoption in sustainable energy systems.

Among the various types of heat pumps, ground-source heat pumps (GSHPs), which were used in this project, and air-source heat pumps (ASHP) stand out because of their ability to harness renewable energy from the environment. When comparing Ground Source Heat Pumps (GSHPs) with Air Source Heat Pumps (ASHPs), several critical considerations emerge despite the lower initial capital cost associated with ASHPs. The primary distinction between GSHPs and ASHPs is the stability of their respective heat source. GSHP systems utilize the relatively constant temperature of the underground environment as their heat sink/source, whereas the ASHP performance is significantly influenced by atmospheric conditions, making their efficiency highly variable with changing temperatures. From this consideration, it is possible to notice how the smaller difference in temperature between the subsurface and interior of the building in the GSHP results in a lower needed electrical energy compared to the ASHP, where there are substantial outdoor-indoor temperature differences. For instance, an ASHP's effectiveness is decreased in hotter temperatures because it needs to work harder to reject heat into an already warm environment. Moreover, air, the medium used in ASHP systems, is not as good at transferring heat as the circulating fluids in GSHP systems, which are usually water or a mixture incorporating antifreeze. Unlike its ASHP cousins, which are subjected to weather-related wear and tears, GSHPs are typically housed indoors, shielding them from such elements. Furthermore, compared to the noise usually associated with ASHPs, GSHPs work softly and are almost noise-free. Furthermore, compared to ASHPs, GSHPs have been demonstrated to lower peak load demands and electricity expenditures; this is especially true in colder areas. Moreover, GSHPs have been shown to reduce peak load demands and electricity costs compared with ASHPs, which is particularly evident in colder climates, as demonstrated by a Canadian study where the economic and operational advantages of GSHPs are more pronounced.

All the differences between GSHP and ASHP have been studied and analysed in the article

'A Review of Vertical Closed-Loop Geothermal Heating and Cooling Systems with an Emphasis on the Importance of the Subsurface' [16].

Key components of the heat pump cycle can be summarized as follows (Figure 9):

- **evaporator:** the evaporator is responsible for extracting heat from the ground and transferring it to the refrigerant fluid, which induces a phase transition from the liquid to vapor phase, enabling the refrigerant to enter the compressor.
- **compressor:** The refrigerant is received as low-pressure vapor. Through adiabatic compression, the refrigerant temperature and pressure were significantly increased, requiring a certain amount of electrical energy for this process.
- **condenser:** functioning as a heat exchanger, the condenser is responsible for removing heat from the refrigerant and transferring it to the external medium on the opposite side of the heat-pump cycle.
- **expansion Valve:** this part separates the high-pressure and low-pressure stages of the cycle; it regulates the amount of refrigerant that reaches the evaporator. Upon passing through the valve, the refrigerant undergoes isenthalpic expansion, resulting in a decrease in both the temperature and pressure, thereby preparing it for re-entry into the evaporator. The expansion process also caused the fluid to cool.

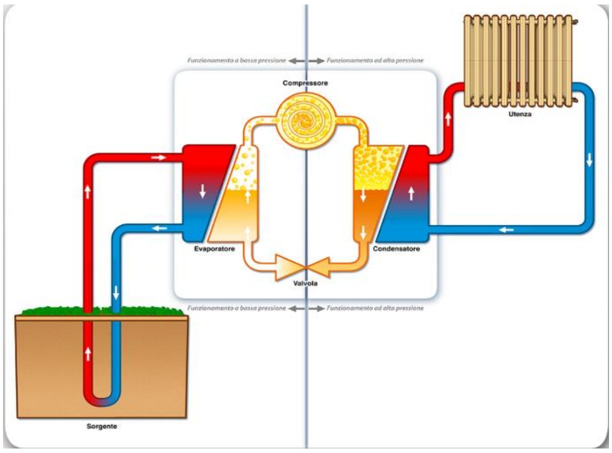

Figure 9 Operating scheme of an heat pump

To describe The To performance factors related to the heating and cooling operations of the heat pump, two key metrics are used: the Coefficient of Performance (COP) for heating and the Energy Efficiency Ratio (EER) for cooling. These parameters provided insights into the efficiency of the machine under different operational modes. The COP measures the ratio of useful heating output to electrical energy input [17].

$$COP = \frac{Useful\ Heating}{Electricity\ Consumption}$$

Equation 1 definition of COP

A higher COP indicates a more efficient system, that is, it can deliver more heating for each unit of electricity consumed. The theoretical maximum COP depends on the temperature difference between the heat source and the heat sink, denoted as θ2 and θ1, respectively.

$$COP = \frac{1}{1 - \frac{\theta_2}{\theta_1}}$$

Equation 2 definition of COP with temperature

In general, the efficiency of a heat pump decreases as the temperature difference increases, specifically, as the delivery temperature increases or the source temperature decreases. It is important to note that the COP is not a fixed value; it varies according to the operating conditions and temperature [17]. Therefore, when assessing a system's efficiency, it may be more appropriate to use a long-term average COP, which is often referred to as the seasonal COP (SCOP). The SCOP provides a more comprehensive measure of heat pump efficiency over the entire heating season, accounting for fluctuations in outdoor temperatures and varying operating conditions. In regions with significant temperature variations, SCOP is particularly relevant because it offers a more accurate representation of the system's overall performance and potential energy savings. This metric is invaluable for comparing different heat-pump models and making informed decisions about the most suitable system for a specific application. For the cooling operations, the Energy Efficiency Ratio (EER) was used to evaluate the efficiency of the system. For cooling operations, the Energy Efficiency Ratio (EER) is a measure of the ratio of the cooling output to the electrical input, is used to evaluate system efficiency under specific, steady-state conditions, similar to how the COP is used for heating.

2.3 Circulating fluid:

In a vertical closed-loop geothermal system, thermal energy is transferred from the earth to the heat pump through the circulating fluid. When choosing the right fluid, it's important to consider a number of important characteristics, including freezing point, thermal conductivity, viscosity, and environmental impact. The choice of circulating fluid has a considerable impact on system efficiency, dependability, and environmental impact [18] .

- **Freezing Point:** even in the lowest operating temperatures, it needs to be low enough to avoid freezing. To do this, antifreeze substances like propylene glycol are added, which guarantees that fluid will stay liquid even at extremely low temperatures.
- **Thermal Conductivity**: this concern to the fluid’s ability to transfer heat, having high thermal conductivity is preferred because it increases the heat exchange efficiency.
- **Viscosity:** the viscosity of the circulating fluid affects the energy required to pump it through the system; a lower viscosity reduces the pumping energy and increases the overall efficiency of the system.
- **Environmental impact:** to minimize corrosion and degradation over time, the circulating fluid must not to be poisonous and must be compatible with the material used in pipeline and heat exchangers to avoid possible contamination of soil or groundwater through leaks.

Propylene glycol-water mixes, ethanol-water mixtures, and methanol-water mixtures are currently the most widely available solutions on the market. Among these, the propylene glycol-water mixture is the most widely used because offers a balanced combination of efficiency, safety, and environmental compatibility, as it is non-toxic and has good thermal properties, making it suitable for a wide range of applications.

2.4 Distribution systems:

Once heat is generated by the heat pump, it must be distributed throughout the house via the distribution system, which is key component that determine the efficiency of the heat exchange, and it must guarantee comfort to the building's occupants. Several considerations are necessary when selecting a distribution system:

- **compatibility with geothermal Systems:** geothermal system generally offers a low temperature output, so distribution system has to manage these temperatures to produce useful effect.
- **energy efficiency:** the efficiency of the distribution system directly affects the overall performance of the geothermal setup. Systems that operate at lower temperatures are generally more efficient and align better with the moderate temperature ranges provided by geothermal heat pumps, thereby maximizing energy savings.
- **installation and maintenance costs:** installation and ongoing maintenance requirements can vary significantly among different distribution systems. Some systems may have higher upfront costs but offer lower operating costs and longer lifespans, whereas others might be more affordable initially but require more frequent maintenance or have shorter lifespans.

Radiant floor heating is a popular distribution system that circulates warm water through a system of pipes buried in the floor. This method is particularly efficient because operates at low temperatures, which aligns with the moderate temperature output of geothermal heat pumps and allows heat to rise evenly through the space.

An additional choice is fan coil units, which are small, space-saving devices that may be placed in specific rooms or zones. They have a fan and a heat exchanger (coil) that circulate air over to heat or cool the air before it is distributed throughout the area.

The primary distinction between the two systems lies in their operating temperatures, with radiant floor systems functioning at a lower temperature range of 29-35°C, whereas fan coil units typically operate at a higher temperature range (40 to 70 °C for heating mode) [19] . Other notable differences include noise levels, with radiant floor systems generating lower levels of noise than fan coil units, and flexibility, as fan coil units are more adaptable to changing needs or layouts and can be easily adjusted or replaced if necessary.

2.5 Regulatory Framework for the Installation and Management of Geothermal Probes in the Piedmont Region

Regarding the regulations for the installation of geothermal probes, the applicable guidelines are established at the regional level, and not all regions are equipped with specific regulations. For this project, the relevant regulations are those set by the Piedmont Region. The document titled "Regional Guidelines for the Installation and Management of Geothermal Probes" outlines the administrative and technical prerequisites for the use of low-enthalpy geothermal probes. In the absence of clear national regulations, these guidelines were established to handle the increasing use of low-enthalpy geothermal systems and to ensure the protection of subsurface water resources.

The aforementioned document is based on various legislative decrees, including D.Lgs. 22/2010 and D.Lgs. 28/2011, which govern the use of geothermal resources and promote renewable energy. These decrees delegate the responsibility for regulating geothermal installations, including simplified procedures for authorization and management, to the Regions.

The guidelines differentiate between small-scale systems, with a useful power ≤ 30 kW, and large-scale systems, with a useful power > 30 kW. The technical specifications that must be followed include the design and installation phases, such as maintaining minimum distances between probes and buildings/trees and using high-quality materials for the pipes to avoid contamination of the subsurface. The same quality standards apply to the cementation process, which is critical to ensure that the materials do not degrade the quality of the underground environment.

Testing and monitoring are required, including pressure and flow tests and temperature measurements, to verify the correct installation of the probes. Decommissioning must then be carried out by washing the pipes and filling them with cement mortar to prevent future contamination.

The documentation required for the evaluation of the systems includes:

- A technical report of the project detailing thermal, hydrogeological, and environmental aspects.

- The location of the system on the regional cartography, with particular attention to the protection of aquifers.
- Characterization of the thermal properties of the soils and hydrogeological analysis, especially for large-scale systems.

This set of guidelines provides a comprehensive framework for ensuring the safe and efficient deployment of geothermal systems in the Piedmont Region.

3 Case study

The Valle Vento Farm Area project, located in Castelboglione, Piedmont (Figure 10) is an innovative initiative focused on enhancing a region that has traditionally been less recognized than the nearby Langhe District, the realization of the project has been assigned to Geonovis.

Geonovis (based in Borgo d'Ale, Vercelli), has been dedicated to designing and installing geothermal heat pump systems for over 15 years. The company specializes in delivering 'turnkey' geothermal solutions, from feasibility studies to post-installation support. The company works with an experienced team and partners with top companies in the sector to ensure high-quality results.

The main goal of the Valle Vento Farm Area is to improve regional wineries by implementing sustainable methods that support environmental stewardship and biodiversity. This concept emphasizes the fusion of contemporary and traditional methods, utilizing state-of-the-art methods, including renewable energy systems, zero-emission applications, and environmentally responsible building practices. The Valle Vento Farm Area project features a collection of purpose-built structures (Figure 12) support various functions essential to sustainable farming and research, including a greenhouse for cultivating diverse crops, which includes offices and meeting rooms to facilitate the administrative and collaborative aspects of farm operations. These buildings will be heated and cooled through a low-enthalpy geothermal system, which is the primary reason for writing this thesis.

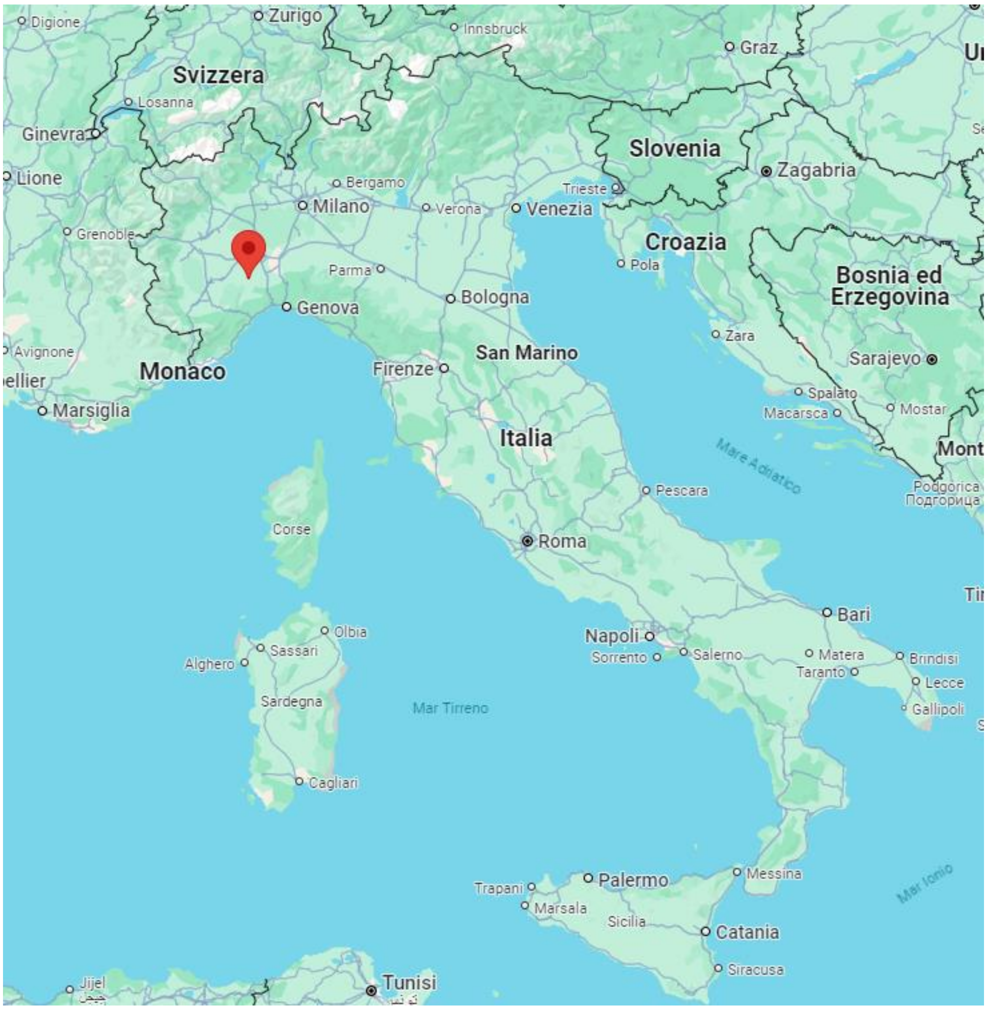

Figure 10 location marker on the map of Italy

Figure 11 Geographical location of the site (Google Maps ©2024)

Figure 12 Buildings under construction

3.1 Ground characteristics and climate zone

Determining the feasibility, efficacy, and safety of geothermal low-enthalpy system design and execution requires an understanding of the Earth's subsurface geological layers. Because of this, the ground's stratigraphy plays a crucial role in these systems, offering information on both the possible existence of aquifers and the thermal properties of the soil. The thermal characteristics of the materials under the surface play a major role in determining a geothermal system's effectiveness since the thermal conductivities of the various geological strata affect the process of heat exchange and the ground's unaltered temperature.

This data is essential for designing the system's layout to maximize effectiveness and reduce environmental impact, as well as for figuring out the best location and depth for geothermal wells. Additionally, understanding the climate zone is fundamental for assessing a building's energy needs. The climate zone provides context for the heating and cooling demands of a building, which complements the geological data and helps in designing a geothermal system that aligns with both the thermal properties of the ground and the specific energy requirements dictated by the local climate. Integrating both geological and climatic considerations ensures a well-rounded approach to optimizing geothermal system performance.

3.2 Geological settings

According to geological study, the site is in the Tertiary Piedmont Basin (TPB), with lithologies belonging to the "Formazione di Cassinasco" (Figure 13). The Alpine chain developed because of tectonic the collision, leading to the formation of an orogenic prism, which is how the TPB was formed. Over time, the opening of the Ligurian-Provencal Basin and the creation of a new Apennine-verging chain caused significant changes in regional geodynamics. This shift transformed the TPB from a configuration of multiple interconnected sub-basins into distinct tecno-stratigraphic regions characterised by predominantly sedimentary sequences. The incorporation of the western portion of the Alpine retro-foreland basin into the Apennine range contributed to this reorganisation. The sedimentary sequences of TPB, which span the late Eocene to the late Miocene, are predominantly terrigenous-siliciclastic and can exceed 4,000 meters in thickness [20].

Figure 13 sketch of the geological map at 1:100000 scale (Foglio 69 – ASTI of the geological map of Italy at the scale 1:1000000)

Based on lithostratigraphic investigations conducted by the geologist associated with Geonovis, Dr. Paolo Momo, the site is characterized by an alternation of marls and sandstones, along with clayey materials and a cover of loose materials with predictability-limited granulometry.

The stratigraphy of boreholes (Figure 14) shows that, especially below 100 m above ground, there is a discernible alternation of grey clays and sandstones following the early yellow clay layers.

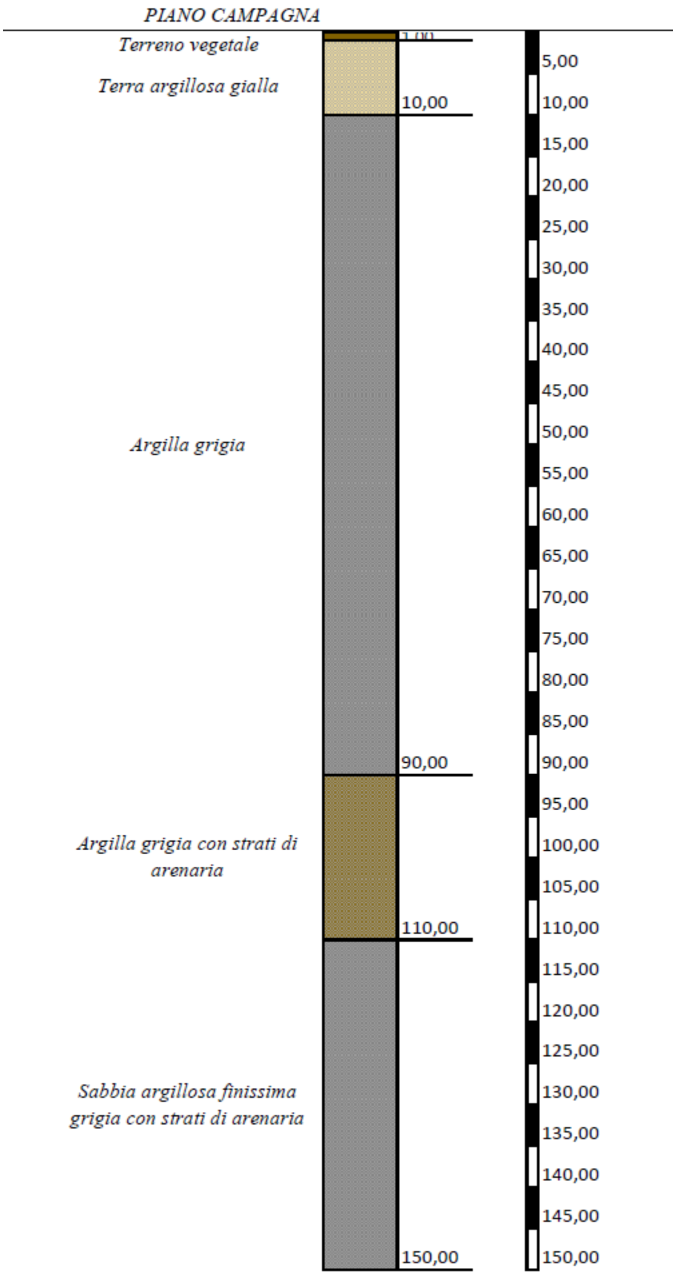

Figure 14 Stratigraphy of the ground

The ground composition begins with approximately 10 m of organic soil, followed by alternating layers of yellow and grey clay down to a depth of 150 m. At greater depths, sandstone strata are interspersed with yellow clay.
The top layer consists of organic soil, which contain loose sediments and organic matter. This layer has moderate thermal conductivity, and its effectiveness is influenced by moisture content.

As one descends, the layer of yellow and grey clay become more prevalent, with grey clay covering the majority of the area. Yellow clay is known for its small particles and fluidity when wet. It also has moderate to low permeability, good moisture retention, fair thermal conductivity, and large variation in moisture content. The grey clay has similar water-retention capacity and thermal characteristics to those analysed, with its properties also being influenced by moisture content. (table 3).

Material	**Thermal conductivity** $(\lambda \frac{W}{mK})$
Organic soil	0.1-0.4
Yellow clay	1.2-1.8
Grey clay	1.5 – 2.0

Table 3 Thermal conductivity of soil materials
Source: "Comparison of Clay Soils" (2020)

The undisturbed ground temperature is a fundamental parameter in the design and operation of geothermal systems. It represents the natural temperature of the subsurface at various depths, unaffected by external influences such as seasonal temperature variations or geothermal activity. The temperature serves as a benchmark for the site's inherent thermal conditions. The temperature difference between the ground and the circulating fluid plays a crucial role in determining the efficiency of the geothermal system. [21]

To determine the undisturbed ground temperature, a test was conducted at the test site by circulating fluid within the geothermal probe without any external heating. Pressurized water was first injected into the probe, replacing the existing fluid, while temperatures were continually recorded. The fluid was then circulated in a closed loop until temperatures of the supply and return lines equalize with the ambient undisturbed ground temperature.

The steps performed on-site were:

- **setup:** a U shape probe was installed to the desired depth of 150 meters. The probes material was PE100 (a type of polyethylene), rated for a nominal pressure of 16 bar and with a diameter of 32 mm.
- **initial water insertion:** pressurized water was introduced at one end of the probe, and temperature sensors recorded the temperature at frequent intervals to monitor the displacement of the existing fluid.
- **displacement monitoring:** as the new water replaced the old water, the system tracks the temperature change to determine when the entire volume of the probe had been filled with the new water. This ensured accurate temperature readings reflective of the current conditions.
- **data collection:** the system continued to record the temperature to build a profile of the ground's thermal gradient. The peak temperature corresponded to the deepest point reached by the probe, providing insight into the thermal properties at various depths.
- **closed-loop circulation:** the fluid was then circulated within the probe in a closed loop until the temperatures at the inlet and outlet stabilized, indicating that undisturbed ground temperature had been reached.

The test was conducted using multiple probes to ensure consistency in the data obtained. The probes were spaced sufficiently apart to avoid interference, with 3 probes being used in this case (Figure 15). Once the data were collected, different temperature results were observed for each probe. As a result, the mean value of these results was considered for further analysis.

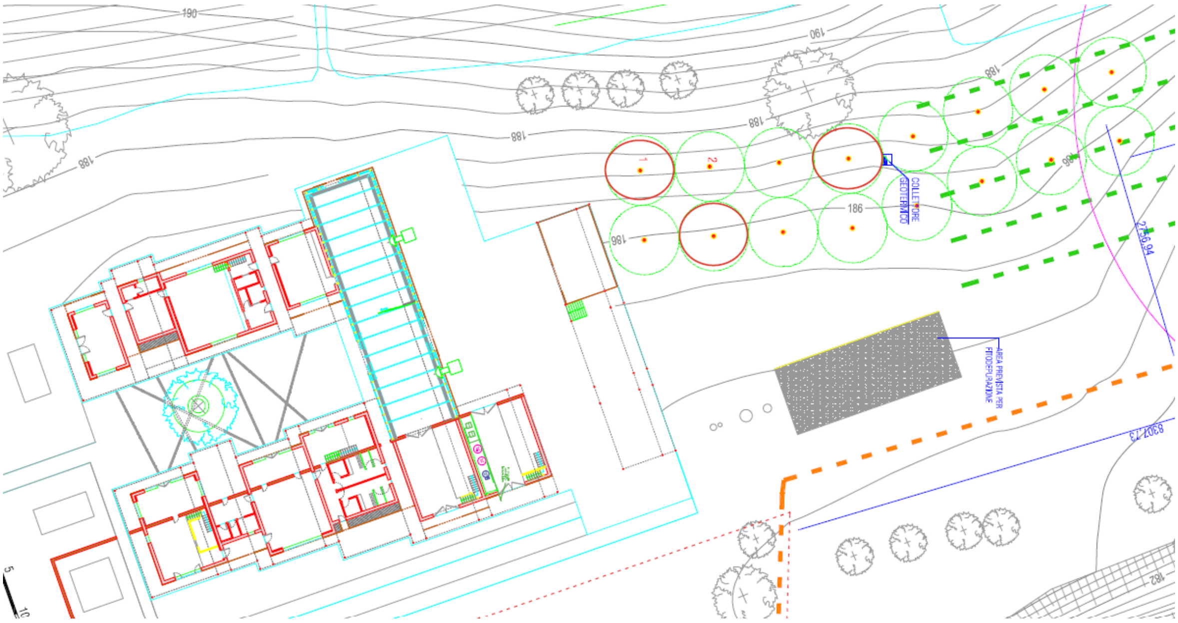

Figure 15 Layout of the probes and of the buildings

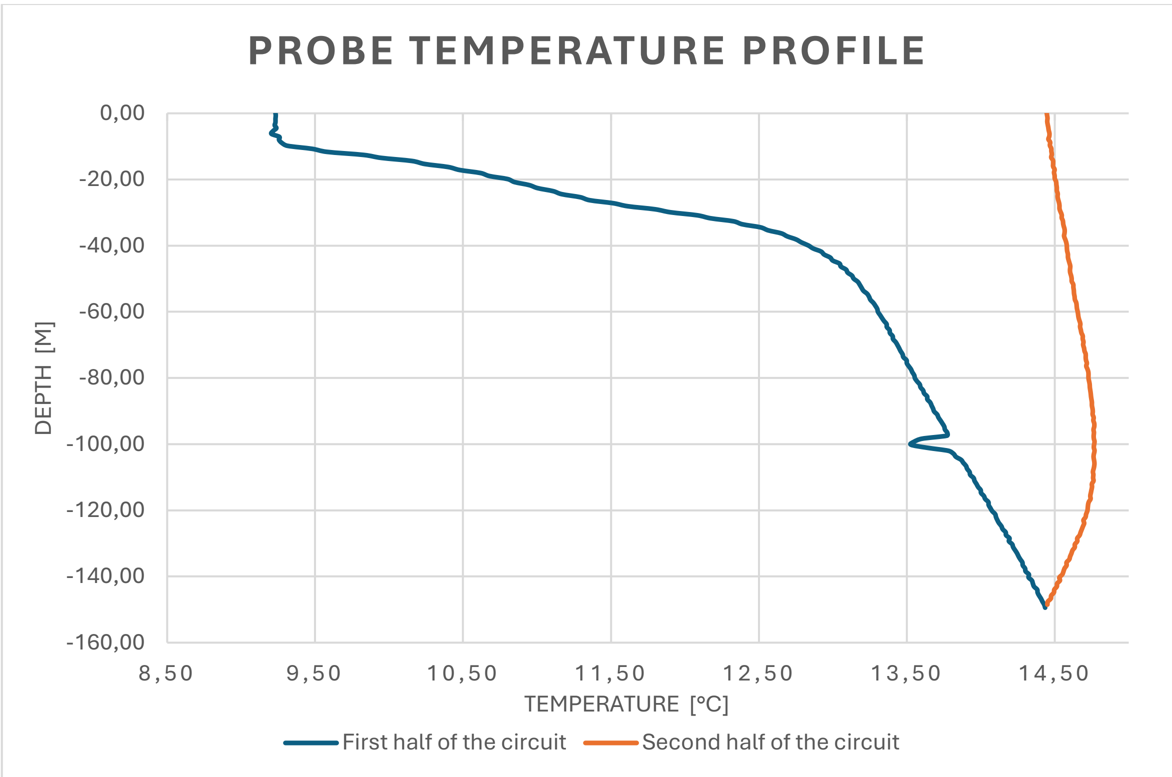

Figure 16 Temperature profile of two half of the circuit

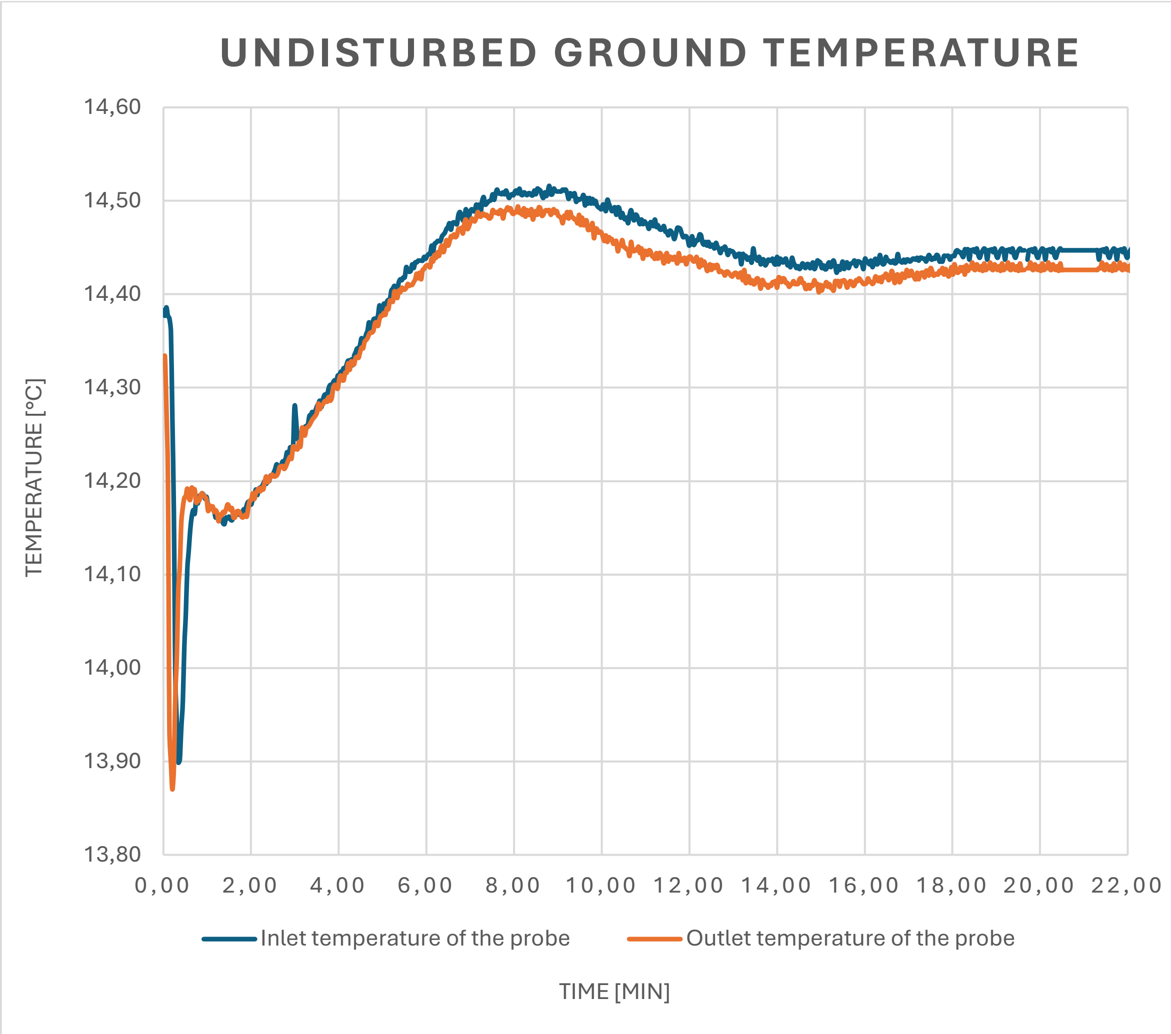

Figure 17 Undisturbed temperature of the ground

In conclusions, the temperatures obtained were 14.51 °C, 14.43 °C and 14.76 °C, with an average value of 14.56 °C. In the first 20 meters, the fluid was influenced by the external air temperature and, particularly by the temperature of the water from the aqueduct that was introduced for the test. Therefore, the behaviour of the curves before a depth of 50 meters should not be considered reliable, as it was affected by external factors. The graph of undisturbed temperatures shows that stabilization occurs after 10-12 minutes (Figure 17), with a very similar value across the three tests.

3.3 TRT Test

A Thermal Response Test (TRT) is a measurement method used to determine the heat transfer properties of a borehole heat exchanger and the surrounding ground. This information is essential for designing the thermal performance of a ground-source energy system. [22]

For an accurate evaluation, it is necessary to know the properties of the fluid, the geometric and thermal characteristics of the tubing, the stratigraphy of the ground, and the "undisturbed" temperature of the ground. These factors significantly affect the accuracy and reliability of the test results, so obtaining precise values for these parameters is crucial.

The values of conductivity and resistance for boreholes are often derived from literature or based on laboratory tests, which have certain limitations [23]. These measurements typically represent samples only a few centimetres in size. However, in an operational ground-source heat system, heat flow must occur through hundreds or thousands of cubic meters of rock. If the rock contains major fractures or discontinuities, these can significantly reduce the overall thermal conductivity, a factor that might not be evident in a small core sample, as such fractures can complicate core recovery. Additionally, ambient groundwater flow within the aquifer can enhance heat transport through advection, a phenomenon that laboratory tests do not account for but can be detected in field tests.

For these reasons, a thermal response test, which simulates real conditions on-site, is preferred over relying solely on literature values. This field test more accurately reflects the actual thermal behaviour of the ground under operational conditions.

The two key parameters identified in a TRT are the effective thermal conductivity (λ) of the ground and the thermal resistance within the borehole (R_b). The TRT equipment is commonly built into a few portable boxes or mounted on a car trailer for easy transportation to test sites (Figure 18).

The test operates by injecting a known amount of heat into the borehole through the circulating fluid within the geothermal loop. Power is supplied to the fluid using a thermal resistance integrated to the test machine, ensuring a maximum difference in dissipated power within the range of 10-15 % and maintaining a constant mass flow rate throughout the tests.

Sensors measure the temperature of the fluid entering and exiting the borehole over time. As the test progresses, the temperature changes in the fluid allow for the analysis of how effectively the heat is being conducted through the ground and the amount of resistance the borehole itself offers to heat transfer.

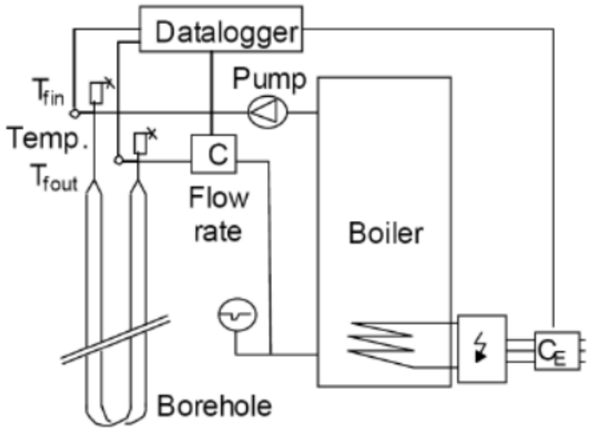

Figure 18 Scheme of operation of the TRT

This process typically runs for a period of several hours to days to ensure that the measurements reflect the steady-state conditions needed to accurately determine thermal properties.

Following the measurement test setup, the system is mathematical modelled. Given the geometry, the probe (a tube filled with heat transfer fluid) is approximated as a wire of infinite length. In this context, the heat transfer occurs mainly in the radial mode, following Eskilson's equation (1987) [23], which describes the evolution of the average temperature of the fluid circulating in the probe over time:

$$T_f(t) - T_m = \frac{Q}{4\pi\lambda}\ln(t) + Q[R_b + \frac{1}{4\pi\lambda}(\ln\left(\frac{4\alpha}{(r_b)^2}\right) - 0.5772]$$

Equation 3 evolution of the average temperature

Where:

- $T_f(t)$: average temperature of the fluid as a function of time t, in K.
- T_m: undisturbed ground temperature, in K.
- t: time in seconds.
- Q: linear thermal power injected into the probe, in W/m.
- r_b : borehole radius, in meters.
- α: thermal diffusivity of the ground, in m²/s.
- λ thermal conductivity of the ground, in W/m/K.
- R_b: thermal resistance of the borehole, in K/(W/m).

The formula shows that the fluid temperature $T_f(t)$ depends linearly on the logarithmic of the time. It is possible to define a parameter ϕ, which corresponds to the slope of the curve when plotting $T_f(t) - T_m$ against the logarithmic of t:

$$\phi = \frac{Q}{4\pi\lambda}$$

Equation 4 mathematical parameter, definition of the curve

If the formula for ϕ is inverted, the thermal conductivity of the ground can be determined:

$$\lambda = \frac{Q}{4\pi\phi}$$

Equation 4 thermal conductivity

In the analysed case study, the TRT test lasted for 50 hours. As with the undisturbed temperature test, three probes were used. However, there were issues with one of them, and data collected from that probe were unreadable.

To evaluate the thermal conductivity results, a step-by-step analysis of the data was conducted. The interpretation was performed several times, each time considering progressively fewer data samples to simulate an early termination of data gathering. The values obtained from the interpretation of the data collected up until each time t was plotted on the resulting graph (Figure 17). It is worth noting that the results normally stabilize 40 to 50 hours after the test begins, which is a relatively long period. For this reason, the TRT typically needs to run for at least 50 hours to produce accurate results.

The thermal conductivity values collected from the experiment were $\lambda_1 = 2.02 \frac{W}{mK}$ and $\lambda_2 = 1.81 \frac{W}{mK}$. Figure 19 shows the conductivity changes during the test time of the two probes.

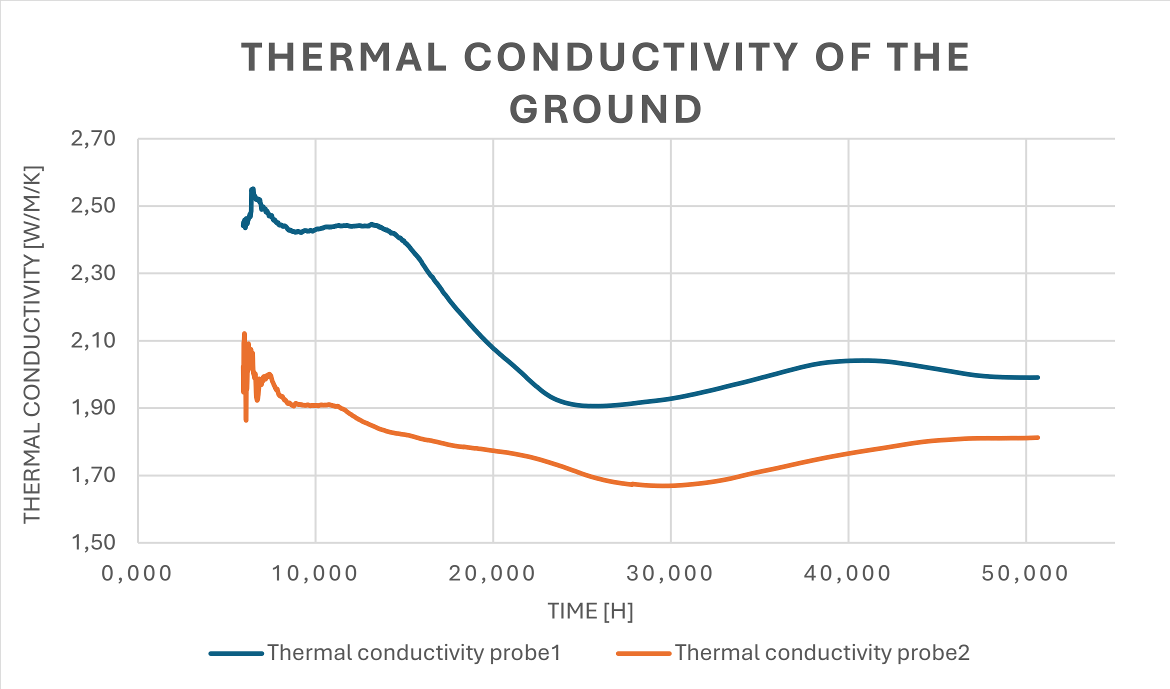

Figure 19 Conductivity of the ground with respect the time

The difference between these two thermal conductivity values from the probes can be attributed to varying boundary conditions, such as differing moisture levels in the ground or minor differences in the materials surroundings each probe. As was done for the undisturbed temperature of the ground, the mean value from the two probes was taken for further analysis $1.915 \frac{W}{mK}$.

Once the conductivity was calculated, it was possible to evaluate the thermal resistance of the borehole using this formula:

$$R_b = \frac{T_f(t) - T_m}{Q} - \frac{1}{4\pi\lambda}\left(\ln(t) + \ln\left(\frac{4\lambda}{(r_b)^2}\right) - 0.5772\right)$$

Equation 5 borehole resistance

The two values obtained from the experiment were $R_{b1} = 0.123 \frac{mK}{W}$ and $R_{b2} = 0.087 \frac{mK}{W}$, with an average value of $0.105 \frac{mK}{W}$.

The apparent thermal resistance of the geothermal probe depends on the materials used in its construction as well as the installation conditions. These conditions include factors such as the positioning of the pipes within the borehole, any collapses that occurred during drilling, and the care taken during the filling process to avoid internal porosity. A step-by-step analysis of the acquired data was also conducted in this case, correlating the results with the test duration.

Figure 20 tends to stabilize more quickly than the thermal conductivity graph (Figure 19), typically within the first ten hours of testing. This faster stabilization occurs because the test primarily reflects the area immediately surrounding the pipes.

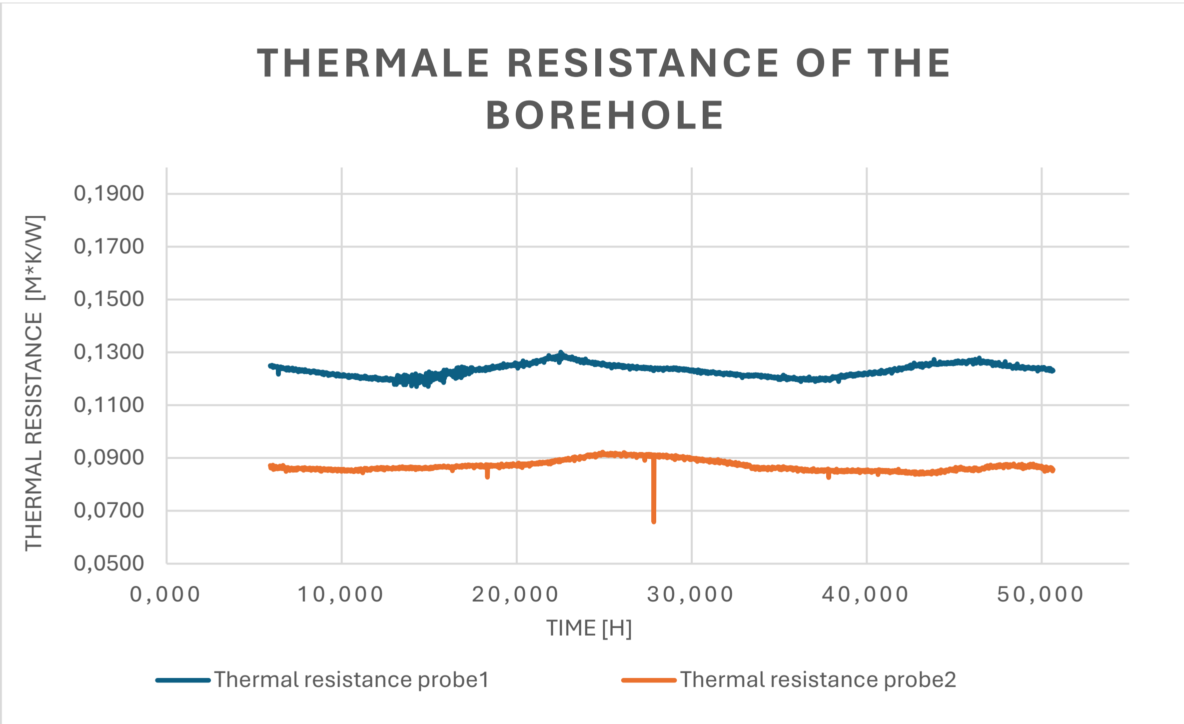

Figure 20 Thermal resistance of the probe with respect time

Both probes performed well, but probe no. 1 showed slightly higher thermal resistance. Since identical materials were used, this suggests that the installation of probe no. 1 may have been slightly less precise, potentially due to small air pockets in the cementation or asymmetrical positioning of the pipes within the borehole. Despite this, the thermal resistance remains within the acceptable limits, indicating that the probe will perform effectively and provide the expected heat exchange without issues.

The final values considered are reported in Table 4 and represent the mean value between the two probes. As can be observed, the thermal yield of the soil is not very high but is still adequate for the system's functionality, provided that the field probes are designed correctly.

	Value
Thermal conductivity ($\boldsymbol{\lambda \frac{W}{mK}}$)	1.92
Thermal resistance ($\boldsymbol{R_b \frac{mK}{W}}$)	0.105

Table 4 Mean value of thermal conductivity and Thermal resistance

3.4 Climate Zone:

Climate zones in Italy are used to group areas according to annual degree days, which indicates how much energy is needed for heating during the winter. This system helps regulate energy consumption, establish guidelines for heating and cooling systems, and ensure both comfort and energy efficiency. Degree days are calculated by summing the positive differences between the indoor temperature (typically set at 20 °C for heating and 26° C for cooling) and the outdoor temperature for each day of the year when the outdoor temperature is below 20 °C (or above 26 °C for cooling).

$$Degree\ Days = \sum_{e=1}^{n} (20 - T_e)$$

A municipality's climatic zone, which ranges from A (warmest) to F (coldest), is determined by the total annual degree days. The classification reflects the varying energy needs across Italy and helps regulate the dates when heating systems can be turned on.
The case study area falls within zone 'E,' where the degree days range between 2101 and 3000. For this zone, heating is recommended from October 15 to April 15, for up to 14 h per day [24].

These recommendations aim to balance comfort and energy efficiency, although they are not mandatory and can be adjusted according to personal preference or specific building requirements. Furthermore, the Italian government has the authority to modify heating schedules and temperatures during severe weather events to ensure public safety and manage energy consumption.

4 Buildings and thermal load

To correctly size a geothermal plant, it is essential to calculate the energy requirements of buildings in both summer and winter. Understanding these requirements allows for the design of a geothermal loop that efficiently meets heating and cooling demands without over- or under-sizing of the plant. A properly sized system ensures year-round comfort in buildings while minimizing the energy consumption and operational costs.

During winter, the primary energy requirement is heating. The system must compensate for heat loss through the building envelope, which includes walls, windows, roofs, and ventilation. In summer, the system's focus shifts to cooling, requiring the geothermal loop to effectively remove heat gained from solar radiation, internal sources (such as occupants, lighting, and equipment), and outdoor air [25].

Thermal loads can be divided into two components: sensible and latent heat [26]. Sensible heat is related to the temperature difference between outdoor and indoor environments, whereas latent heat is associated with the difference in moisture levels between external and internal environments. Both components must be considered when designing geothermal systems capable of maintaining optimal indoor conditions year-round.

Several factors influence a building's energy needs, including size, insulation, construction materials, and orientation. The thermal load of a space is defined as the amount of thermal power that must be supplied or removed to maintain the desired temperature and humidity.

4.1 Buildings characteristics

As mentioned in the introduction of the case study (chapter 3), several buildings serve different functions: some are designed as offices, while others serve as shops, meeting rooms or bathrooms. Additionally, there is a greenhouse aimed at promoting sustainable and eco-friendly production. The figures below (figure 21 and figure 22) illustrate the functions and layouts of these buildings.

Figure 21 building arrangement and their use

All the structures are newly constructed using cross-laminated timber (CLT), commonly known as XLAM. Figure 22 shows the internal space of one of the buildings. XLAM is a sustainable material renowned for its excellent thermal insulation, fire resistance, rapid drying, and acoustic properties. Made from 99.4% timber and 0.6% adhesives, XLAM panels consist of layered, cross-bonded timber, providing exceptional stability, strength, and resistance to seismic activity. These panels were selected not only for their practicality but also for their aesthetic appeal, ensuring a balance between structural performance and visual elegance.

Figure 23 Internal view of one of the buildings

Each structure is primarily composed of the same material, with only minimal variations among them. For practical reasons, only the materials used in Building A (an office) will be detailed.

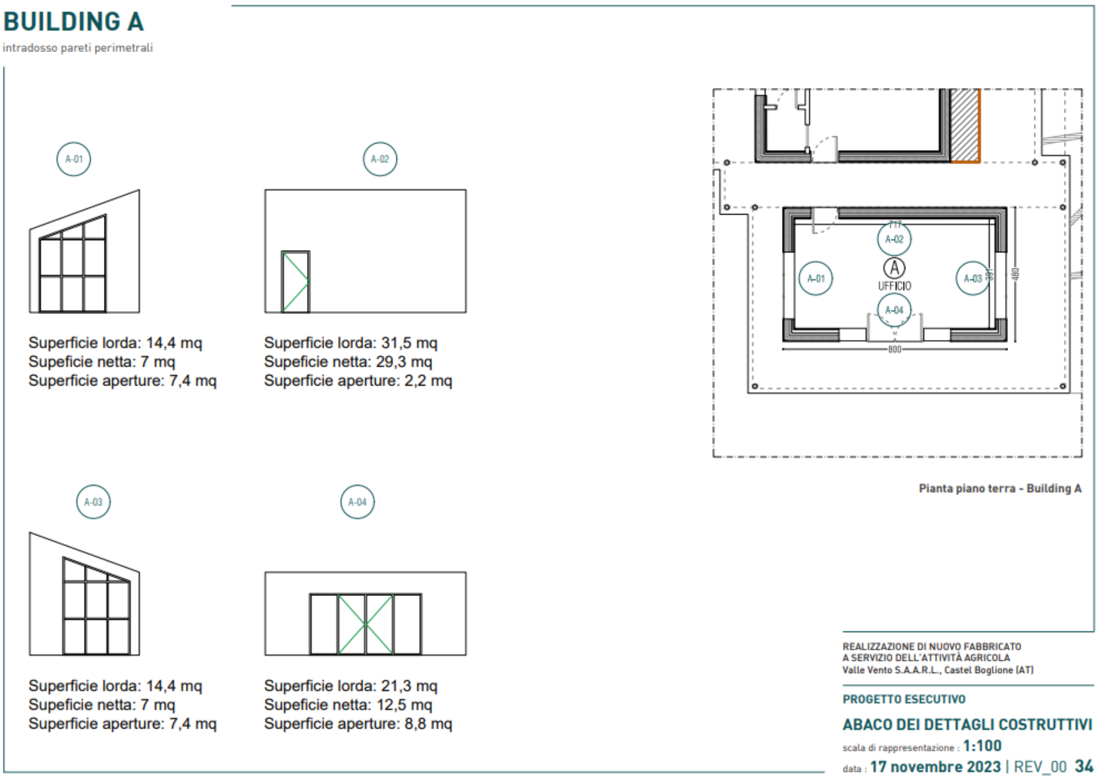

Figure 24 Building A structure

For the material used in Building A the stratigraphy of the external insulation walls is represented below, which are distinguished by their unique characteristics and play a crucial role in defining the building's distinctiveness and thermal load.

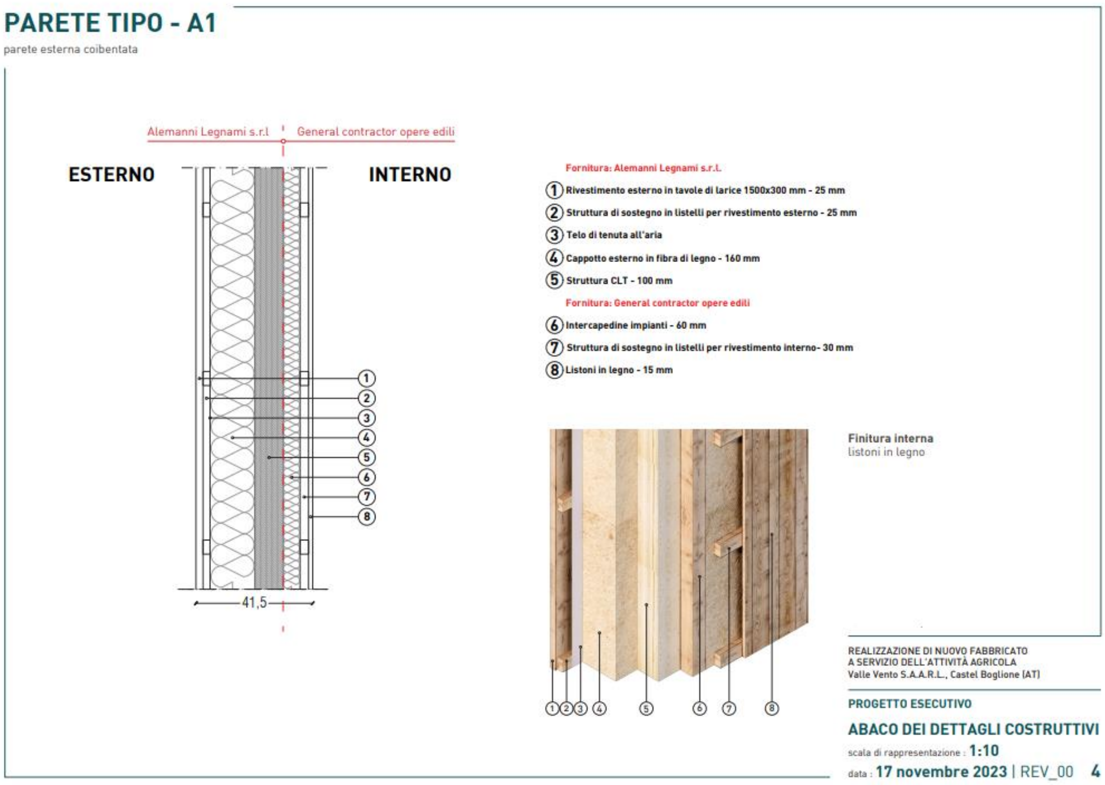

Figure 25 Stratigraphy of the walls

The material used and their characteristics are shorty describe:

- **External cladding:** larch boards are used for their durability and natural resistance to decay, providing a robust and attractive exterior finish.
- **Support structure:** the framework ensures secure attachment of the larch boards and proper ventilation behind the cladding to maintain the exterior's integrity.
- **Air barrier membrane:** installed to prevent air leakage, this membrane enhances the building's efficiency by minimizing heat loss and moisture issues.
- **External insulation:** a 160 mm thick layer of fibreboard insulation offers excellent thermal resistance and energy efficiency.
- **CLT structure:** the building's core is made from 100 mm thick Cross-Laminated Timber (CLT), known for its strength, stability, and eco-friendly properties.
- **Utility cavity:** a 60 mm cavity is included for the installation of electrical, plumbing, and HVAC systems, facilitating efficient integration.
- **Gypsum-Fiber panel:** interior walls are finished with 15 mm thick Vidiwall gypsum-fibre panels, providing durability, fire resistance, and acoustic performance.

- **Ecological mortar finish:** applied to interior surfaces, this finish enhances aesthetic appeal while aligning with sustainable practices.

4.2 Winter thermal load

During the winter season, it is necessary to heat buildings by introducing into the indoor environment. Considering the climatic zone analysed in the Chapter 3.4, the design indoor and outdoor temperatures for this phase are $T_{in} = 20\ °C$ and $T_{out} = -8\ °C$. The thermal load calculation under design conditions is based on the worst-case external temperature, which in this case is -8°C. This ensures that the heating system is adequately sized to handle the most demanding condition.

The calculation of the winter thermal load considers three main components: transmission, ventilation, and recovery factors.

- **Transmission:** this refers to the process by which heat flows from warmer areas (inside the building) to cooler areas (outside), in accordance with the second law of thermodynamics, which states that heat flows from higher to lower temperature areas until thermal equilibrium is achieved. In winter, heat loss occurs as warm indoor air is transferred through the building envelope (walls, windows, floors, etc.) to the colder outdoor environment. The rate of heat loss is influenced by the thermal conductivity of the materials, the surface area through which the heat is transferred, and the temperature difference between the interior and exterior [26]. This necessitates a heating system that is capable of compensating for these losses to maintain a comfortable indoor temperature.
- **Ventilation:** air exchange occurs both in the outdoor environment and adjacent spaces [26]. When warmer indoor air is replaced by cooler outdoor air, either through ventilation or infiltration, the heating system must compensate by warming the incoming air to the desired temperature, adding to the thermal load of the building. Infiltration occurs unintentionally through leaks or poorly sealed openings, whereas ventilation is the controlled introduction of outdoor air to maintain indoor air quality. In both cases, cooler air requires heating, which increases overall energy demand.
- **Recovery factor:** This factor accounts for the additional thermal power needed to bring the indoor environment back to the design temperature after a period of reduced temperature, such as during an off phase of the heating system. Although intermittent

heating and off phases are not typically considered, it is preferred to include the recovery factor for a more accurate assessment.

Description of the room	T_in [°C]	V [m³]	S [m²]	Φtr [W]	Φve [W]	Φrf [W]	Φtot(Total dispersion of the room) [W]
Office A1	20	124,4	42,82	1690	237	257	2184
Office A1 mezzanine	20	110,9	42,92	992	0	258	1250
Entrance	20	17,5	6,07	283	29	36	348
Toilet 2	20	9	3,14	59	142	19	219
Toilet 1	20	9	3,11	123	141	19	282
Pre-bathroom for Toilet 1-3	20	20,1	6,96	299	315	42	655
Meeting Room	20	183,1	63,01	1515	1360	378	3253
Mezzanine	20	183,3	89,08	1704	0	534	2238
Toilet 4	20	11,8	4,11	246	185	25	456
Toilet 4.1	20	3,9	4,07	107	61	24	193
Pre-bathroom 2	20	6,8	2,36	109	0	14	124
Pre-bathroom 2, Floor 1	20	1	2,42	39	0	15	54
Archive	20	65	22,46	442	91	135	668
Archive, Floor 1	20	16,1	21,61	402	88	130	619
Toilet 3	20	4,4	1,65	8	69	10	87
Shower 1	20	21,3	7,39	189	98	44	332
Storage Ground Floor	20	24,7	8,48	36	34	51	121

Figure 26 Thermal load of every room, in the winter period, data calculated by the external HVAC engineer collaborating with Geonovis

Description of the room	T_in [°C]	V [m³]	S [m²]	Φtr [W]	Φve [W]	Φrf [W]	Φtot(Total dispersion of the room) [W]
Storage Floor 1	20	20,1	8,48	197	22	51	269
Refreshment Area	20	130,3	28,94	1548	521	174	2243
Shower 2	20	16,3	5,64	231	98	34	363
Bathroom 1	20	9,1	3,15	14	142	19	175
Storage 3	20	87,8	20,41	1234	83	122	1439
Group	20	235,9	54,77	1968	223	329	2519
Changing rooms	20	50,7	11,82	571	0	71	642
Toilet 1.1	20	19,6	4,26	308	307	26	641
Pre-bathroom	20	7,5	1,76	73	7	11	91
Toilets 2.1	20	9,5	2,51	95	148	15	258
Viewing Point	20	125,8	27,81	1952	144	167	2264
Bathroom 2	20	8,1	2,81	71	127	17	215
Pre-bathroom 1	20	18,1	6,29	28	59	38	124
Storage 1	20	162,9	37,62	1652	153	226	2030
pre-bahtroom 2	20	17,3	6,02	77	59	36	172
mezzanine	20	116,9	49,28	940	467	296	1703
Office	20	124,5	31,08	2215	246	186	2647
Greenhouse1	20	394,5	239,02	11634	0	4302	15937
Greenhouse2	20	696,1	239,1	9486	2986	4304	16776

Figure 27 Thermal load of every room in winter season, data calculated by the external HVAC engineer collaborating with Geonovi

The total thermal load needed by the buildings is calculated as the sum of the loads for each room, the result is 635191 W that has been rounded up to 65 Kw. This rounding creates a margin of safety, ensuring that the system can handle peak loads without being overstressed.

4.3 Summer thermal load

During the summer season, it is necessary to cool the buildings by removing excess heat. The indoor and outdoor temperatures for this phase are $T_{in} = 26\ °C$ and $T_{out} = 32\ °C$..The thermal load calculation under design conditions is based on the peak external temperature of 32 °C. This ensures that the cooling system is sized to manage the most demanding conditions, maintaining comfort during the hottest days of the year.

The calculation of summer thermal load considers four main components: irradiation, ventilation, transmission and internal loads. The contributions from transmission and ventilation are discussed in the previous section. The key difference between winter and summer scenarios is that, in winter, heat escapes the building, requiring heating, while in summer, however, heat enters the building as it moves from a hotter environment to a cooler one. The contributions unique to the summer case are solar gain and internal loads.

- **Irradiance:** is the contribution given by the solar radiation entering the glass top [26]. The solar radiation affects the building's thermal load, especially in the summer. While natural sunlight provides passive heating in winter, excessive solar gain in the warmer months increases the cooling demand.
- **Internal loads:** heat generated from sources within buildings, these sources typically include occupants, appliances and lighting [26].

Description of the room	T_in [°C]	V [m³]	S [m²]	QIrr [W]	Φtr [W]	Φve [W]	QC [W]	Φtot (Total dispersion of the room) [W]
Office A1	26	124,4	42,82	1989	404	1121	458	3972
Office A1 mezzanine	26	110,9	42,92	197	305	916	258	1676
Entrance	26	17,5	6,07	25	84	48	18	175
Toilet 2	26	9	3,14	0	8	0	27	35
Toilet 1	26	9	3,11	10	19	0	22	51
Pre-bathroom for Toilet 1	26	20,1	6,96	28	45	0	21	94
Meeting Room	26	183,1	63,01	1607	309	1651	3749	7316
Mezzanine	26	183,3	89,08	152	427	1652	134	2365
Toilet 4	26	11,8	4,11	321	68	0	38	427
Toilet 4.1	26	3,9	4,07	0	46	0	21	68
Pre-bathroom 2	26	6,8	2,36	100	98	195	45	438
Pre-bathroom 2, Floor 1	26	1	2,42	16	35	0	37	88
Archive	26	65	22,46	0	12	0	22	34
Archive, Floor 1	26	16,1	21,61	104	86	44	86	321
Toilet 3	26	4,4	1,65	0	0	0	31	31
Shower 1	26	21,3	7,39	5	0	0	168	173
Storage Ground Floor	26	24,7	8,48	0	0	35	42	78

Figure 28 Thermal load in summer season for every room, data calculated by the external HVAC engineer collaborating with Geonovis.

Description of the room	T_in [°C]	V [m³]	S [m²]	QIrr [W]	Φtr [W]	Φve [W]	QC [W]	Φtot (Total dispersion of the room) [W]
Storage Floor 1	26	20,1	8,48	97	23	0	193	313
Refreshment Area	26	130,3	28,94	2058	370	391	476	3296
Shower 2	26	16,3	5,64	4	38	49	97	189
Bathroom 1	26	9,1	3,15	0	0	20	72	92
Storage 3	26	87,8	20,41	464	331	264	59	1117
Group	26	235,9	54,77	711	65	530	794	2100
Changing rooms	26	50,7	11,82	187	123	0	37	346
Toilet 1.1	26	19,6	4,26	260	29	0	26	316
Pre-bathroom	26	7,5	1,76	0	20	0	33	53
Toilets 2.1	26	9,5	2,51	0	25	0	31	57
Viewing Point	26	125,8	27,81	2247	468	1134	266	4115
Bathroom 2	26	8,1	2,81	0	20	0	38	58
Pre-bathroom 1	26	18,1	6,29	0	0	0	84	84
Storage 1	26	162,9	37,62	1639	87	366	312	2404
pre-bahtroom 2	26	17,3	6,02	0	17	0	69	86
mezzanine	26	116,9	49,28	16	188	351	266	821
Office	26	124,5	31,08	1101	505	374	482	2462
Greenhouse1	26	394,5	239,02	51256	2456	725	1004	55442
Greenhouse2	26	696,1	239,1	12043	1804	1280	1004	16131

Figure 29 Thermal load in summer season for every room, data calculated by the external HVAC engineer collaborating with Geonovis.

The sum of the thermal load in summer season is now 106824 W, rounded to 107 kW. In both summer and winter season the room which need the higher amount of power is the greenhouse, especially in summer.

The reason the greenhouse requires cooling during the summer is due to its role as a meeting space as requested by the client. Since people will be present in this room for gatherings or discussions, it is essential to maintain a comfortable indoor temperature. Excess heat, whether from solar gain or internal sources like equipment and occupants, must be effectively removed to ensure a pleasant environment. Cooling the space is crucial to achieving this ideal thermal comfort, especially when hosting events or activities in the greenhouse.

5 Sizing of the plant

5.1 ASHRAE method

The ASHRAE (American Society of Heating, Refrigeration and Air-conditioning Engineers) method is used to design geothermal systems, especially for determining the total borehole length and the space needed for efficient heat exchange.

Building on the ICS (Infinite Cylindrical Source) method, which models heat transfer trough a cylindrical surface, the ASHRAE method introduces new concepts that improve the old model: thermal responses over different periods of time (daily, monthly and annual) and the concept of temperature penalty. These adjustments accounts for the ground's actual thermal behaviour over time [27].

The ASHRAE method evaluates the total length of the borehole required to meet the building's annual energy demand. This calculation takes into account the peak power demands for both summer and winter.

For the analysed case study, the design loads are $65\ kW$ for winter and $-107\ kW$ for summer. The energy required by the buildings are below represented:

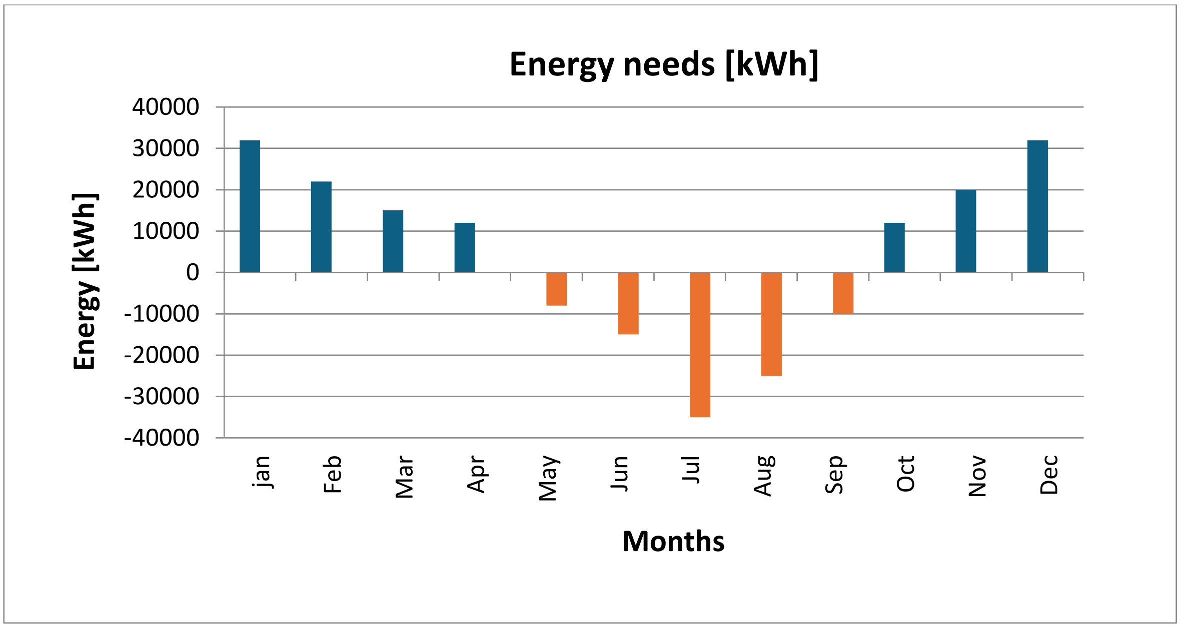

Figure 30 Energy needs of the buildings

The two equation that represents the total length are represented below:

$$L_h = \frac{\dot{Q}_a R_{ga} + \dot{Q}_{g,h_D}[R_b + PLF_{m,h_D} R_{gm} + R_{gd} F_{sc}]}{t_g - \left(\frac{t_{wi} + t_{wo}}{2}\right)_{h_D} - t_p}$$

Equation 6 Total length of BHE in heating mode

$$L_c = \frac{\dot{Q}_a R_{ga} + \dot{Q}_{g,c_D}[R_b + PLF_{m,c_D} R_{gm} + R_{gd} F_{sc}]}{t_g - \left(\frac{t_{wi} + t_{wo}}{2}\right)_{c_D} - t_p}$$

Equation 7 Total length of BHE in cooling mode

Where:

$\dot{Q}_a$ net annual average heat transfer to the ground [W].

$\dot{Q}_{g,h_D}$ design thermal power during heating mode [W]

$\dot{Q}_{g,c_D}$ design thermal power during cooling mode [W]

R_{ga} effective thermal resistance of the ground, annual pulse [mKW^{-1}]

R_{gd} effective thermal resistance of the ground, daily pulse [mKW^{-1}]

R_{gm} effective thermal resistance of the ground, monthly pulse [mKW^{-1}]

R_b thermal resistance of the borehole [mKW^{-1}]

t_g undisturbed temperature of the ground [°C]

t_p temperature penalty for interference of adjacent bores [°C]

t_{wi} liquid temperature at heat pump inlet [°C]

t_{wo} liquid temperature of heat pump outlet [°C]

F_{sc} short-circuit heat loss factor [-]

PLF_{m,c_D} part-load factor during design month for cooling [-]

PLF_{m,h_D} part-load factor during design month for heating [-]

Thermal energy values

$\dot{Q}_a$ represents the total amount of thermal energy exchanged with the ground over the course of a year. The net annual average heat transfer to the ground ($\dot{Q}_a$) can be determined based on the peak heating and cooling loads during summer ($\dot{Q}_{h,hp,out_D}$) and winter ($\dot{Q}_{c,hp,out_D}$). The formula for this calculation is:

$$\dot{Q}_a = \frac{\dot{Q}_{h,hp,out_D}\left(1 - \frac{1}{COP_{ms}}\right)\tau_h + \dot{Q}_{c,hp,out_D}\left(1 - \frac{1}{EER_{ms}}\right)\tau_c}{8760}$$

COP_{ms} , EER_{ms} are design variables regarding the heat pump and its inlet and outlet temperature. τ_h, τ_c corresponding to the equivalent hours at full load.

The heat pump is designed to work with a COP of 4,32 and a EER 4,48, with seasonal value equal to 4,7 and 4,9.

Inlet temperature for the heat pump, in heating mode is 5 °C and 24 °C in summer.

Thermal resistance values

In the ASHRAE method, different thermal response time frames are considered to capture how the ground and the geothermal loop perform over time [22] .

R_{gm}: it is the medium-term resistance over this period the heat injected or extracted by the borehole gradually spreads into the surrounding ground and the thermal properties of the ground, such as conductivity and diffusivity start to dominate the behaviour of the system.

R_{ga}: it incorporates the long-term impact of continuous operation on the surrounding ground and ensures that the borehole design can sustain efficient heat transfer over time without causing significant performance degradation.

R_{gd}: this resistance reflects the immediate heat transfer between the borehole wall and surrounding ground.

R_b: it is the thermal resistance of the borehole, and its value has been experimental determined in the TRT test.

To relate the time defining the heat exchange impulse with the geometric characteristics of the heat exchanger and the thermal properties of the soil, the following relationship is applied, involving the Fourier number:

$$Fo = \frac{4\alpha_g \tau}{{d_b}^2}$$

Equation 8 Fourier number

Where:

α_g diffusivity [m²/s];

τ time of the pulse in second [s];

d_b borehole diameter [m].

τ is a period pulse that can change in accordance with the type of resistance in fact making the hypothesis of 10 years for $R_{ga}(\tau_1)$, 1 month for $R_{gm}(\tau_2)$ and 6 hours for the daily peak associated with $R_{gd}(\tau_f)$ the tau are:

τ_1 = 3650 days.

τ_2 = 3680 days.

τ_f= 3680.25 days.

The three Fourier number related at the different pulses:

$$Fo_1 = \frac{4\alpha_g(\tau_f - \tau_1)}{d_b^2}$$

Equation 9 Fourier number1

$$Fo_2 = \frac{4\alpha_g(\tau_f - \tau_2)}{d_b^2}$$

Equation 10 Fourier number2

$$Fo_f = \frac{4\alpha_g \tau_f}{d_b^2}$$

Equation 11 Fourier number f

For each Fourier number obtained from equations the corresponding G-Factor is calculated using the following equation (valid for Fo>2Fo > 2Fo>2) based on the solution of the cylindrical source (Carslaw & Jaeger, 1959).

$$G = 0.0758 \ln(Fo) + 0.1009$$

Equation 12 G factor related to Fourier number

The ground resistances are then calculated as:

$$R_{ga} = \frac{G_f - G_1}{\lambda}$$

Equation 13 Resistance R_{ga}

$$R_{gm} = \frac{G_1 - G_2}{\lambda}$$

Equation 14 Resistance R_m

$$R_{gd} = \frac{G_2}{\lambda}$$

Equation 15 Resistance R_{gd}

Temperature values

The undisturbed temperature of the ground (t_g) has been calculated experimentally in the previous chapter, the inlet (t_{wi}) and outlet (t_{wo}) temperatures of the heat pump are design value.

Temperature penalty (t_p) allows for the necessary analytical adjustments to the average temperature difference between the ground and the heat transfer fluid, in order to account for the mutual interference of thermal fields induced by active heat exchangers in the ground. Initially the value of t_p can be hypothesized and after the following calculation procedure can be verified if the assumption was correct.

$$t_p = \frac{N_4 + 0.5N_3 + 0.25N_2 + 0.1N_1}{N_{tot}} t_{p1}$$

Equation 16 Temperature penalty

Where:

N4 = number of BHEs surrounded by 4 BHEs.

N3 = number of BHEs surrounded by 3 BHEs.

N2 = number of BHEs surrounded by 2 BHEs.

N1 = number of BHEs surrounded by 1 BHEs.

Ntot = total number of BHEs.

t_{p1} = temperature penalty of a BHE surrounded by 4 BHEs.

t_{p1} can be evaluated by considering the amount of heat that can be stored in the parallelepiped of the ground around the BHE.

$$t_{p1} = \frac{Q_{stored}}{S_{vc} d_s^2 L_D};$$

Equation 17 temperature penalty1

Where:

Q_{stored} = heat stored in the ground after 10 years of functioning of the system [J].

SVC = volumetric heat capacity [J/ (K m^3)].

ds = BHE distance [m].

L = BHE length [m].

In the following scheme, the surface at ds/2 can be considered as adiabatic. If S1 were in free-field conditions, the ground temperature would be affected up to R_{max}. However, with the presence of the adiabatic surface, heat is primarily stored within the parallelepiped with side length equal to d_s. To calculate the stored heat, we use the infinite cylinder solution

(Carslaw, Jaeger 1959), assuming R_{max}=10m (the expected thermal propagation distance over 10 years). The stored heat can be evaluated as follows:

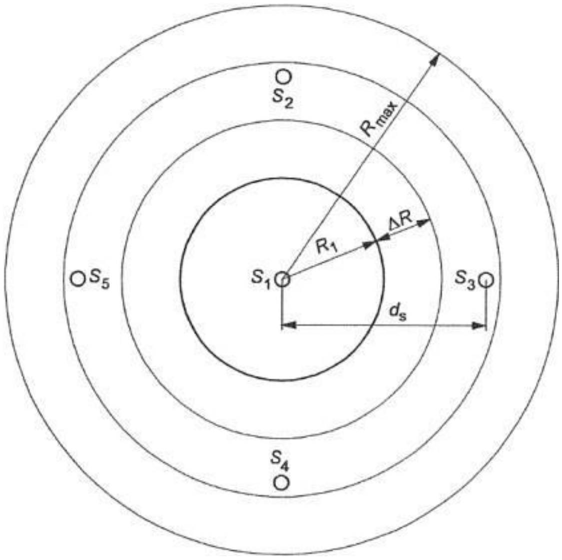

Figure 31 Surface, free field condition

$$Q_{stored} = \sum_{i=1}^{n} S_{vc}\pi L_c[(R_i + \Delta R_i)^2 - R_i^2]\Delta\theta_{gi}$$

Equation 18 Heat stored

Ri = ds 2 [m].

ΔR = radius increase [m].

$\Delta\theta gi$=temperature variation of the i-th surface compare the undisturbed ground temperature [°C]

In which $\Delta\theta_{gi}$ is the temperature variation of the i-th surface compared with the undisturbed ground temperature, that is evaluated as:

$$\Delta\theta_{gi} = \frac{\dot{Q}_a I(X)}{2\pi\lambda_e L_c};$$

$$X = \frac{(R_i + \Delta R_i)}{2\sqrt{\alpha_e \tau_1}};$$

$$I(X) = \begin{cases} -0{,}577078\ln(X) + 0{,}1, & 0{,}5 \le X \le 1 \\ -0{,}932002\ln(X) - 0{,}14601, & 0{,}01 \le X < 0{,}5 \end{cases}$$

Now the length of the BHEs for heating is calculated again using as time penalty the one previously found, iteratively until the time penalty used and the one coming from evaluation is the same.

Initially the value of t_p can be hypothesized and after the calculation procedure can be verified if the assumption was correct.

Short-Circuit heat loss factor (F_{sc})

The thermal interference or heat exchange between the borehole's supply and return flows is considered by this parameter, considering whether the disposal is in parallel or series.

Short-circuiting occurs when heat is transmitted from the supply to the return flow because of the close closeness of these pipes, system's overall heat transfer efficiency may be decreased by this procedure. The value of short-circuit heat loss factor is generally given by literature and for this case is equal to 1,03, from the following table.

Heat exchanger for circuits	**F_{sc}**	
	0,0036 (mass flow rate per unit of power kg/s per kW)	0,0054 (mass flow rate per unit of power kg/s per kW)
1	1,06	1,04
2	1,03	1,02
3	1,02	1,01

Table 5 Short-circuit heat loss factor possibility, Geonovis 2024

Partial Load factor PLF

Represents the fraction of the system's full capacity that is utilized during the design month. It is a dimensionless factor, and its value is between 0 and 1. Geothermal system not always run at full capacity due to variations in buildings load during different time of the month, but this factor is used to ensure that the system operates efficiently even when it's not handling peak loads.

Results and arrangement.

The main results of the calculation procedure are represented in the following table.

	Value
Total length winter case (m)	1112
Total length summer case (m)	2312
Penalty temperature (°C)	-0,02

Table 6 Results of the ASHRAE method

As expected from the energy analysis of the buildings, the required borehole length is greater for the summer load. Therefore, the summer load is taken as the reference point. The penalty temperature is -0.02; since this value is negative, it indicates that the system is heating the ground. Based on the required length, it was decided to construct 16 boreholes in a rectangular arrangement with a base of 2 and a height of 8, distance between boreholes is 8 meters (Figure 32).

The geothermal probes installed in the ground are connected to what is called a geothermal manifold. The geothermal manifold collects all the probes and allows the connection between the underground system and the above ground system

The chosen configuration ensures adequate spacing between the boreholes to minimize thermal interference, allowing each borehole to efficiently exchange heat with the surrounding ground. This setup also makes efficient use of available space for the borehole placement.

The layout ensures balanced heat exchange between the boreholes and the ground, with the longer side of the arrangement allowing heat exchange with undisturbed ground. Additionally, this configuration simplifies the connection of the different boreholes.

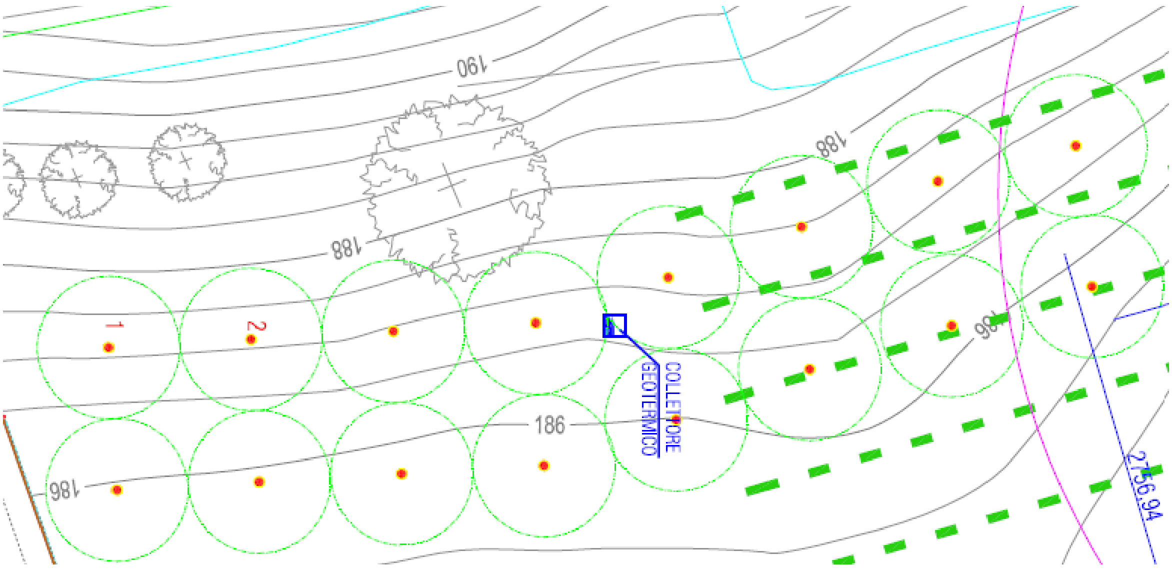

Figure 32 BHE disposition

5.2 Plant description

This section of the thesis presents the final configuration on the geothermal heating and cooling system, which integrates several key components to ensure efficient energy transfer. The focus will be on the main component of the system: heat pumps, buffer tanks, expansion vessel, and HPAC.

Each component works in unison to achieve optimal system performance while maintaining energy efficiency and operational flexibility.

In addition to the main components, the plant is equipped with instruments designed to monitor and control pressure, temperature and flow rate. These components include flow meters, analog thermometers, manometers and different types of valves such as ball valves, safety and check valves.

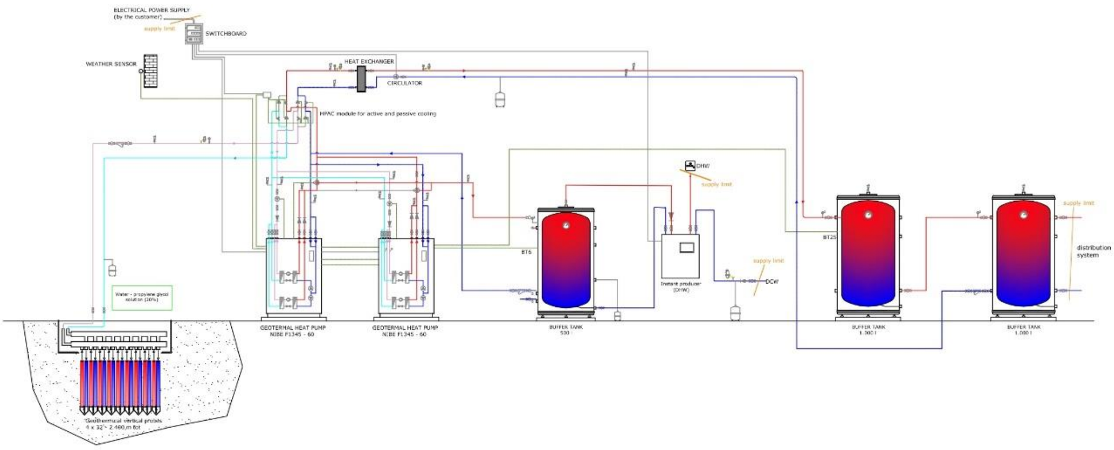

Figure 33 Scheme of the plant, Geonovis 2024

5.3 Buffer tanks

A buffer tank is used in heating and cooling systems to help manage and balance the flow of energy between different components of the system, considering that it is designed to prevent thermal losses and improve efficiency, and is generally equipped with high-quality thermal insulation.

A buffer tank decouples the heat-pump flow requirements from the flow demands of the distribution system [28], and their advantages can be schematized as follows:

- **Prevention of short cycling:** during low-load conditions, the heat pump compressor may frequently turn on and off to meet demand, a phenomenon known as short cycling. This frequent cycling stresses the compressor, which is designed to operate at a full load for extended periods. By adding a buffer tank, additional water volume helps reduce the frequency of these cycles, extending the compressor lifespan and improving reliability.
  -**Temperature regulation:** the buffer tank helps maintain a consistent water temperature within the system by absorbing excess heat or releasing stored heat as needed.
  -**Increased efficiency:** by minimizing compressor cycling, buffer tanks enhance overall system efficiency. The compressor operates at optimal levels for longer periods, which reduces the energy consumption.

Buffer tank for distribution system:

Two buffer tanks were selected for the distribution system: the TANKO-G MIX buffer tank of Pacetti [29] . They are connected to the distribution system that the radiant floor is for this plant and the temperature operation is between 30 and 45 °C. To size the buffer tank, a general rule of 25 L/kW of compressor power was applied. In this case, the electrical power of the compressor was 30 kW, so the following formula was applied:

$$Volume\ of\ the\ buffer\ tank = 30 * 25 = 750\ l$$

Initially, the calculated volume of the buffer tank was 750 L; however, to ensure operational flexibility and accommodate any unforeseen demands, a tank with a capacity of 1000 litres was selected. This sizing approach is repeated also for the second heat pump having as a result again a buffer tank with a capacity of 1000 litres. The tanks used water, not glycol, with glycol separation handled by a dedicated system component, the separation exchanger. This heat exchanger transfers heat between the glycol circuit and the water circuit, maintaining efficient heat transfer. Inside the tank, there is water and not glycol water, and the separation of the glycol circuit from the water circuit is done by another component, the separation exchanger. This heat exchanger transfers heat between the glycol circuit and the water circuit, maintaining efficient heat transfer.

Buffer tank for DHW:

The functioning principles are the same as those of the buffer tanks for the distribution system; however, warm water is now used for domestic hot water. The model of Pacetti TANKO-G in carbon steel has been selected [30].

To determine the appropriate size of the buffer tank, the domestic hot water (DHW) consumption of the building must first be assessed. In this case, the building that requires DHW is primarily the bathroom. *Caleffi* [31] suggests using a formula that takes into account various characteristics.

The hourly heat demand, or the required thermal power, can be estimated by calculating the total heat to be generated during the time interval that includes the preheating period and the peak period.

$$Q_h = C * \frac{T_u - T_f}{t_{pr} + t_{pu}}$$

Equation 19 Hourly heat transfer to the water

Where

C hot water consumption during the peak period [l], for an office equal to 40 l.

Q_h hourly heat transfer to the water [kcal/h]

t_{pu} duration of the peak period [h], for an office 1,5 h.

t_{pr} duration of the preheating period [h], for an office 2 h.

T_f cold water temperature [°C] 10 °C.

T_u hot water usage temperature [°C] 40 °C.

T_a hot water storage temperature [°C] 65 °C.

V_b volume of the boiler [l].

$$V_b = Q_h * \frac{t_{pr}}{T_a - T_f}$$

Equation 20 volume of the boiler

The volume required to meet the demand for hot water is about 13 liters.

As can be seen, this is a small volume. However, the installed buffer tank has a capacity of 500 liters. This size was chosen for two reasons. First, a larger tank was selected to take advantage of thermal recovery during the summer when the geothermal system is used for cooling. Second, the client requested a larger buffer tank to accommodate a greater volume of water, as part of it will be used for agricultural activities.

The water circulating inside the system, as mentioned several times and detailed in Chapter 2.3, is glycol water, which is not suitable for domestic use. Therefore, an instant water heater has been installed.

An instant water heater is a heat exchanger, as shown in the schematic (Figure 34), which acts as an intermediary between the final user (the buildings) and the buffer tank. It heats the cold water from the domestic supply using the heat stored in the buffer tank. The chosen capacity is approximately 40 liters per minute.

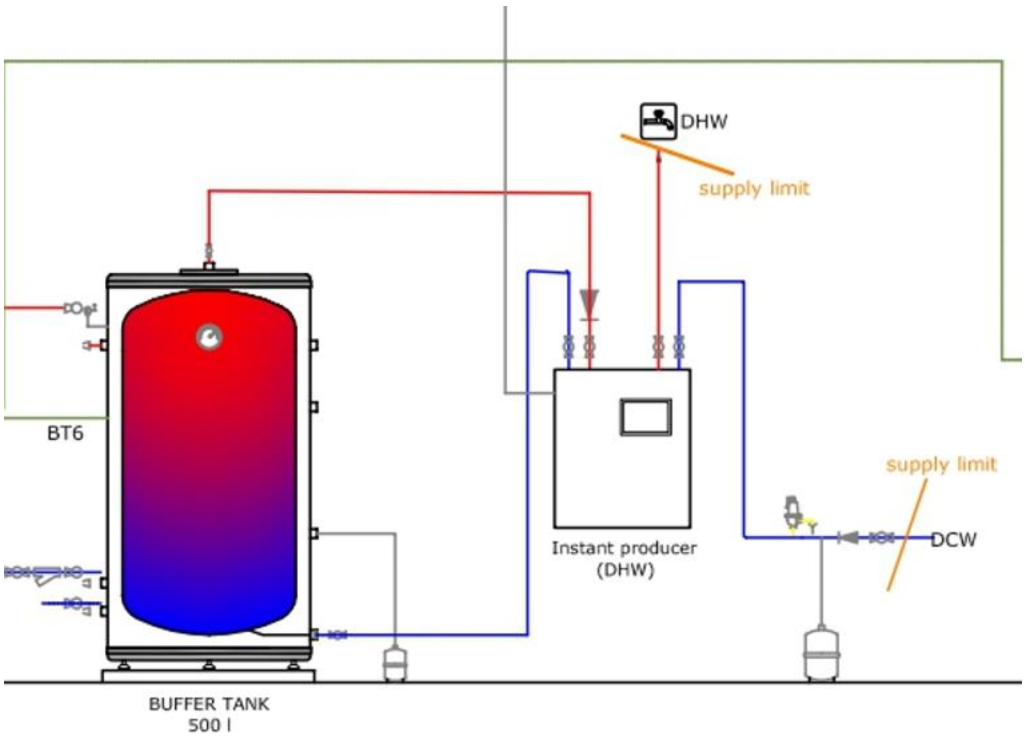

Figure 34 Buffer tank and instant producer, Geonovis 2024

5.4 Heat pumps and HPAC.

The heat pump sets the mass flow rate of the glycol circuit in the geothermal probes to its nominal value of 3.1 l/s. On the plant side, connected to the evaporator, the system operates with a lower flow rate of 1.34 l/s. For the piping system of the two circuits PPR fibrereinforced SDR 11 pipes were selected ($\emptyset 90\ mm$ and $\emptyset 63$ mm).

The power of the heat pump must satisfy this requirement by considering the power required to heat and cool the system. To satisfy this requirement 2 heat pump of 60 kW are chosen. The model of the heat pump was NIBE F1345 (figure 35). The pressure head of the heat pump is set to 78 kPa.

Figure 35 Heat pump NIBE F12345 and buffer tank

Characterized by the four main components on the refrigerant circuit, previously mentioned in the heat pump section (chapter 2.2), another important component that worth to be analysed is the HPAC module for active and passive cooling. The HPAC is an external component connected to the heat pump and is designed to enable the production of chilled water for the cooling phase by inverting the hydraulic circuit [32]. The core mechanism responsible for this transition from heating to cooling is the reversing valve, which changes the direction of the refrigerant flow within the heat pump, effectively reversing the heat-exchange process.

In the cooling mode, the evaporator, which originally extracted heat from the ground, simultaneously extracted heat from the indoor environment, and the condenser released this heat into the ground. Despite the change in the refrigerant flow, the internal component of the heat pump remains in the same position because the trick efficiency of the system is preserved and the components are less worn, providing a significant advantage overheat pumps that require internal component repositioning during mode changes.

HPAC supports two modes of cooling: active and passive.

In passive cooling, heat is extracted from buildings only by the circulation of the fluid within the systems, without activating the heat pump. The heat collected is not directly rejected inside the ground but is used in the thermal buffer dedicated for the DHW so in this way is possible operate a thermal recover. This method leverages the natural temperature difference and offers an energy-efficient solution, as the heat pump remains off during the process. However, active cooling requires the heat pump to be operational. In this mode, the compressor facilitates the heat transfer from the hot source to the cold source. In this plant, the buffer tank acts as an intermediary between the indoor and heat pump, absorbing heat from the indoor space. In this case, in the first instance, the heat is rejected into the buffer tank for the DHW, and the second option is rejected into the ground.

In summary, the HPAC module has three major advantages:

- **Component longevity:** the internal component inside the heat pump remains in fixed positions during the switch from heating to cooling, which changes the direction of the hydraulic circuit. Therefore, the wear caused by frequent repositioning is avoided when the worn component is avoided.
- **Dual cooling modes:** the HPAC module enables the heat pump to operate in both active and passive cooling. While active cooling requires a compressor, passive

cooling can be achieved with the heat pump turned off, offering an energy-saving solution.

- **Heat recovery:** the system allows the possibility of recovering excess heat, which can be utilized to warm DHW before any heat is rejected to the ground, improving overall system efficiency and reducing energy waste.

5.5 Expansion vessels

Expansion vessels are important components in heating and plumbing systems and are designed to accommodate the expansion and contraction of the fluid due to temperature changes [33]. These fluctuations are managed by realizing or absorbing pressure as required, ensuring the correct functioning of the systems.

It is a container with two chambers separated by a flexible membrane such as a diaphragm. One chamber was filled with air or an inert gas such as nitrogen, and the other chamber was connected to the fluid circuit of the heating or plumbing system. This type of vessel is used for several reasons: it protects the buffer tanks and plumbing system from damage due to excessive pressure, improving the longevity of the system [33]. It also makes the system more efficient because, without an expansion vessel, the pump and valves must work harder to maintain the desired flow and temperature of the fluid, increasing the energy needed for the system. In the presence of expansion vessels, these changes are managed independently. More than one expansion vessel is placed inside the system, and they are typically installed at various locations within the system. In this case, there is an expansion vessel in each buffer tank as well as other expansion vessels connected to the pipes. They are placed near each buffer tank and at points along the pipeline that transfers the water, which helps effectively manage pressure changes throughout the system.

To correctly size the expansion vessel, it is possible to divide the total circuits operating in the water transfer into sub-systems. The three main sub-systems in which the circuit is divided are: borehole side, buffer tank, and domestic hot water (DHW) side.

As an example, the sizing of the expansion vessel associated with one of the 1000-liter buffer tanks is illustrated below. The remaining values for other expansion vessels were calculated in the same way. The formulas provided are based on the Caleffi guidelines for dimensioning the expansion vessel [34]. The following formula is applied:

$$V_n = \frac{e * (V_a + V_V)}{1 - \frac{P_a}{P_e}}$$

Equation 21 volume of the expansion vessel

Where:

V_n nominal volume of the expansion vessel, in litres.

V_a absolute atmospheric pressure, in bar.

V_v expansion volume due to water heating.

P_a initial absolute pressure on the gas side (bar) equal to pressure P0 plus atmospheric pressure (1 bar).

P_e final absolute pressure on the gas side (bar), given by pressure Per plus atmospheric pressure (1 bar). $P_e = P_{vs} - 0{,}5\ bar + 1$.

P_{st} set pressure of the safety valve (bar).

P_{vs} pre-charged pressure of the vessel on the gas side (bar).

P_o total system volume, in litres. $P_o = P_{st} + 0{,}3\ bar$

$n = 0{,}31 + 3{,}9 * 10^{-4} * t_m^2$.

$e = \frac{n}{100}$.

t_m maximum allowable temperature in °C related to the activation of safety devices.

Variable (side buffer tank)	Value
V_a [l]	1000
V_v [l]	5
t_m [°C]	50
n	1,285
P_{st} [bar]	1,5
P_{vs} [bar]	3,0
P_0 [bar]	1,8
e	0,012
P_a [bar]	2,8
P_e [bar]	3,5
V_n [l]	65

An expansion vessel of 80 litters has been chosen for the circuit related to one of the 1000-liter buffer tanks. The calculated expansion volume required was 65 litters; therefore, a 80-liter vessel was selected to provide a safety margin. This additional capacity ensures that the vessel can accommodate unexpected fluctuations in pressure and temperature, allowing for a more reliable and stable operation over time. Choosing a slightly larger vessel than the calculated minimum also reduces the risk of over-pressurization, which could otherwise lead to premature wear or system failures. Additionally, the choice of an 80-liter vessel aligns with practical considerations, as Caleffi offers this configuration (Serie 556) . This availability simplifies installation and integration into the system, making it a convenient option while still enhancing the overall performance and longevity of the components involved.

6 Borehole thermal energy storage (BTES)

All the buildings in this project are designed to accommodate both photovoltaic panels and hybrid solar panels that produce both heat and electricity. The electricity generated by the photovoltaic panels will power the buildings' systems, including the two compressors of the heat pumps, with the goal of covering all the site’s electricity consumption. Solar thermal collectors absorb the sunlight and convert it in heat. This heat will first be used to warm up the buffer tanks, and once their demand is met, any excess heat will be transferred to the borehole thermal energy storage (BTES) system for long-term storage.

BTES are an efficient solution for managing thermal energy, utilizing the ground’s natural insulating properties to store heat with minimal losses. The BTES (figure 36) involves a network of borehole drilled vertically into the ground with a U-tube structure embedded in the soil. A working fluid passes through a heat exchanger, transferring heat between the fluid and the surrounding soil.

This stored thermal energy can be extracted during the colder months, either directly or with the assistance of a ground-source heat pump. As a result, the operation time of the vertical closed-loop geothermal system already installed is reduced, along with the associated costs [35].

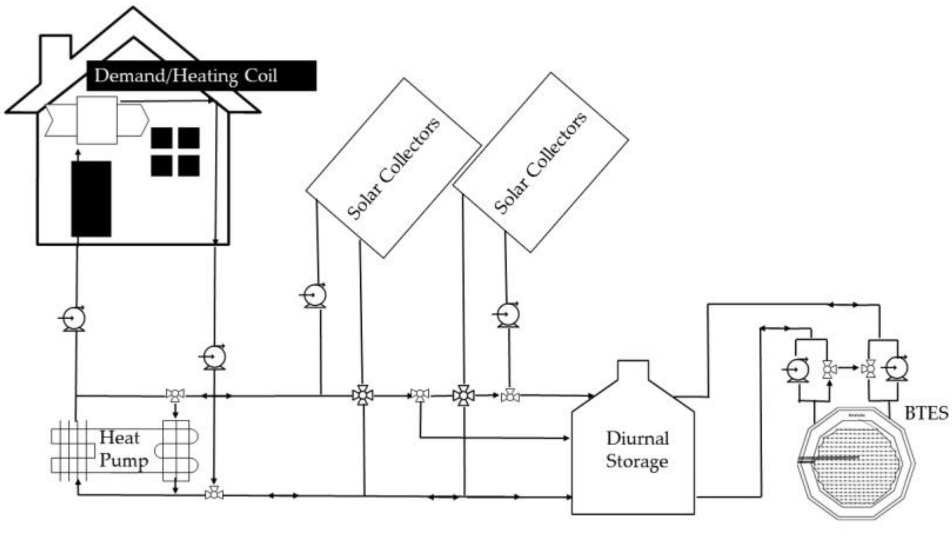

Figure 36 Concept diagram of BTES connected with solar collector and GSHP

The two key parameters for assessing the effectiveness of a BTES system are its efficiency and outlet temperature. The outlet temperature, also referred to as the extraction temperature, typically ranges between 25 and 45 °C [35].

Skarphagen et al. (2020) [36] provide important insight about the recovery efficiency. The thermal recovery factor was defined as

$$\eta = \frac{Heat\ extracted\ over\ an\ annual\ cycle}{Heat\ recharged\ over\ an\ annual\ cycle}$$

To ensure that the average temperature within the BTES remains stable, the amount of heat charged into the system during the summer usually exceeds the quantity discharged over an annual cycle. Achieving a high thermal recovery factor depends on minimizing steady-state heat losses (a function of temperature, BTES geometry, rock thermal conductivity, and insulation) while maximizing the seasonal heat transfer.

The literature also suggests that BTES efficiency tends to increase during the first few years of operation. As the rock surrounding the BTES warms up, conductive heat losses decrease. For instance, the BTES efficiency of the Canadian Drake Landing project, a well-known example of BTES, has improved from 9% to 40% over the first four years of operation. Generally, BTES recovery efficiency starts at a low level during the initial year but can reach 40% to 60% by the fourth or fifth year [35].

The efficiency of a BTES system is influenced by the design and layout of the borehole heat exchangers (BHEs), the properties of the materials used, the characteristics of the ground, and the system's operational parameters.

The ground characteristics are the same as those described in previous chapters. As for the other parameters, those that can be discussed in more detail include the arrangement of the boreholes, the distance between them, and their depth.

6.1 Design layout considerations

The arrangement of boreholes, their spacing, depth, and overall layout directly affect the effectiveness of heat storage and retrieval. To store heat efficiently, common approaches involve using large arrays of boreholes arranged in geometric patterns, such as square, hexagonal, or cylindrical layouts (figure 37).

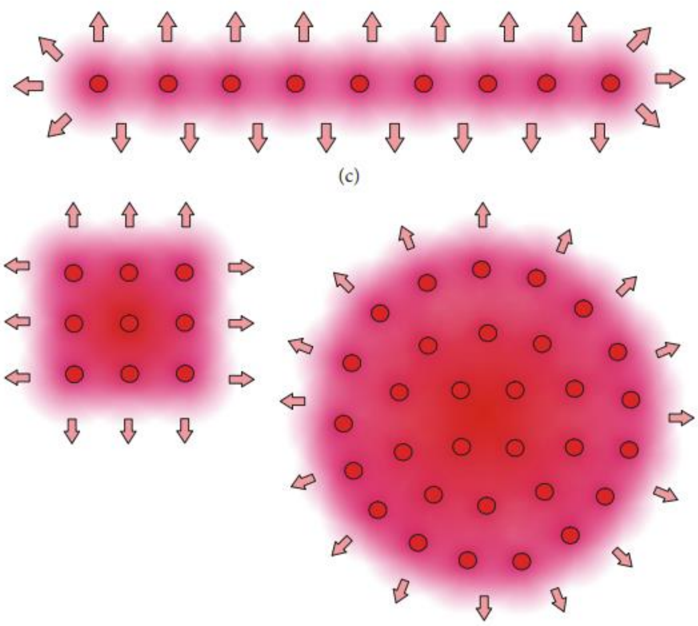

Figure 37 Different array shapes for BTES

Two factors are important in these considerations: surface and volume. The storage capacity, the amount of thermal energy that can be stored, is influenced by the volume of the arrangement, while the area influences the heat losses [37]. A small surface-to-volume ratio is recommended for optimal energy storage. Shape selection is a process wherein theoretical and practical considerations intersect. Although a spherical shape would be optimal for minimizing heat loss owing to its lowest surface-to-volume ratio, constructing a spherical BTES system is impractical. The ideal configuration to reduce the losses at the minimum is a sphere; however, it is not possible to build a sphere for practical reasons, and the most similar geometry is referred to as a cylinder. The goal is to maintain the smallest possible surface-area-to-volume ratio by maintaining the arrangement as compact as possible [37] .

Ideally, the temperature should be highest at the centre of the cylinder and decrease gradually towards the outer edges. For instance, the rectangular shape with two long lines used for the vertical closed loop previously described is not efficient in this situation because its large perimeter results in substantial heat loss to the surrounding ground, thus compromising the effectiveness of energy storage. An example from the Canadian Drake Landing BTES project illustrates this approach: the system includes 144 boreholes disposed in a cylindrical way with a diameter of 34 mm and depth of 35.

The distance between boreholes is a key differentiating factor between vertical closed-loop and BTES systems. In vertical systems, thermal interference must be completely avoided because each borehole needs to maintain a certain efficiency without being affected by others. According to Kumar Kumawat [38] in BTES systems, some degree of thermal interference is desirable so that the boreholes can interact and allow the entire volume of the ground to act as a large thermal storage medium.

6.2 Actual BTES system in site

Estimates have been made regarding the potential energy produced by the solar panels, with a focus on the summer months. This period was chosen because, during the other months of the year, the energy production is relatively low and sufficient only to meet the demand for domestic hot water. For the months from May to September, the expected energy production is as follows: 11.805 kWh, 12.745 kWh, 13.774 kWh, 12.095 kWh, and 8.960 kWh. From this data, which represents conservative estimates, an initial configuration for the system has been designed. The arrangement of the boreholes is circular, allowing for easy expansion to accommodate a potential increase in thermal energy production in the future.

The BTES system is currently under construction and consists of seven boreholes arranged in a circular pattern, spaced 5 m apart, and drilled to a depth of 150 m.

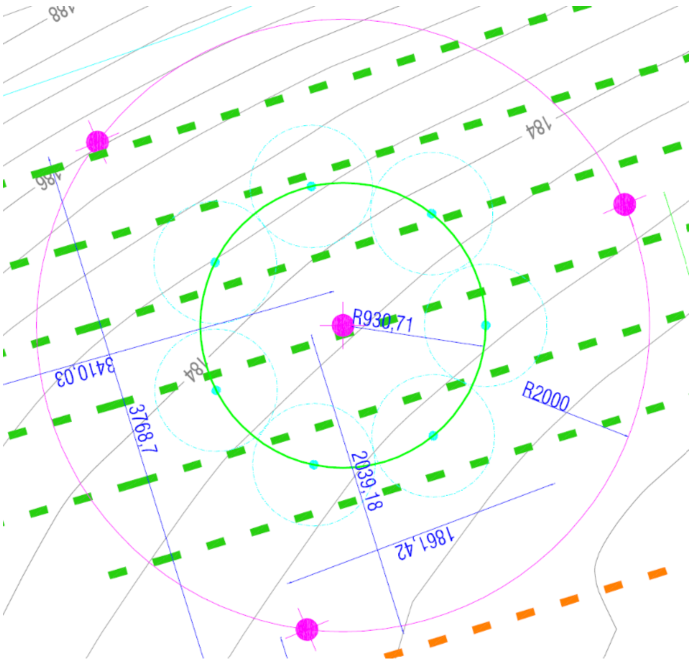

Figure 38 Boreholes layout of the BTES

There are also plans to add an eighth borehole at the centre to serve as a reference point, concentrating heat in the central area. The system is designed so that the hot heat transfer fluid can be directed toward the core of the BTES, where the temperature is the highest, and then radiates outward, gradually warming the surrounding zones.

As discussed earlier, optimization strategies for BTES systems often face practical challenges. A cylindrical configuration is preferred, as constructing a spherical layout with boreholes is impractical. The 5-meter spacing between boreholes was chosen to mitigate the risk of drilling deviations, which can occur due to geological conditions. If boreholes are too closely spaced, deviations in the drilling path can result in intersecting boreholes, compromising their functionality.

The calculated surface-to-volume ratio is 0.22, derived from the previous calculations of the surface area and volume for a cylinder with a radius of 9.3 meters and a height of 150 meters.

This value is not considered particularly low, as the diameter and depth of the boreholes are significant, which contributes to a more favourable heat exchange efficiency. Values closer to 0.1 indicate more efficient heat storage.

Therefore, there is still room for improvement regarding this parameter, aiming to achieve a lower surface-to-volume ratio and minimize heat loss. By optimizing the borehole configuration, such as adjusting the diameter, depth, and spacing of the boreholes, we can enhance the overall efficiency of the BTES system and reduce thermal dispersion.

To extract energy from the BTES, the above-ground portion of the previously described vertical closed-loop system will be utilized. The boreholes in the BTES will connect to the two heat pumps, which will draw heat from the storage system during the winter season. The heat pump benefits from the stable, elevated temperatures within the BTES, making it less energy-intensive to increase the temperature to a usable level, especially compared to a standard vertical closed-loop system.

As long as there is a sufficient temperature difference between the stored energy in the BTES and the heat pump's evaporator, the BTES will be the primary source for heating the buildings. Once the BTES temperature drops below optimal levels, the system will switch to the standard closed-loop system, which draws heat directly from the ground. This setup ensures efficient energy use and maximizes the heat pump's performance, effectively utilizing the seasonal energy stored in the BTES before relying on conventional geothermal resources

One possible strategy could involve injecting heat into the BTES without extracting it during the first few years. This approach would allow the ground to gradually stabilize at a higher temperature, optimizing the system's heat storage capacity and enhancing future heat extraction efficiency. By pre-warming the BTES in this way, the system could reach an optimal thermal equilibrium, providing more reliable performance in the long term.

Future improvements to the system could include adding a new ring of boreholes in a radial arrangement, expanding storage capacity and optimizing the use of available space. This expansion could be particularly beneficial if energy production from the hybrid solar panels increased. Additional boreholes could also help balance the temperature gradient by absorbing excess heat from the inner boreholes. To further enhance storage efficiency, these new boreholes could be shallower and more numerous compared to the first ring, thereby reducing the area-to-volume ratio and improving the overall performance of the system.

7 Conclusion

The thesis presents a vertical closed-loop geothermal system as an extremely efficient and suitable solution to meet today's energy demands. With a single setup, the system can provide hot water for domestic use, cooling, and heating. It offers numerous technical and economic benefits, one of the most significant being its independence from the volatility of the fossil fuel markets, a critical advantage given today's challenges.

Due to its design, the system requires less infrastructure and space, and its lower maintenance needs ensure long-term performance. Compared to conventional solutions, the system offers significant cost savings from an economic perspective.

Vertical closed-loop geothermal systems also provide attractive environmental benefits. The environmental impact of buildings is reduced, as the system emits no CO_2 or particulates. The absence of combustion processes eliminates risks such as fires or carbon monoxide leaks. Additionally, its silent and unobtrusive installation makes it ideal for new construction and renovation projects, including historical or luxury buildings.

In conclusion, adopting this geothermal solution not only enhances comfort and operational simplicity but also makes a substantial contribution toward global sustainability goals. To offer a tangible comparison, the annual CO_2 savings from using this system can be likened to the CO_2 absorption of hundreds of trees or the emission reduction from removing several cars from the road.

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