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# Feasibility Study of Shallow Geothermal Heat Pumps to Meet the Thermal Demand of a Typical Household in Córdoba, Argentina

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## ABSTRACT

This master thesis is a feasibility study of the use of geothermal energy in typical houses from urban developments in the city of Córdoba, Argentina. Geothermal heat at constant temperature available at shallow depths, is proposed as source of a heat pump coupled to a radiant-floor for air conditioning and a booster tank for domestic hot water supply. The study was carried out considering the characteristics of the local climate, the energy demand of a typical residential house and technical and economic feasibilities in the region. First, the Argentine energy matrix, the demand for residential energy, the renewable technologies applied to supply that demand and the current use of geothermal energy are described. Then, geothermal heat pumps for residential uses are dimensioned, energy savings and greenhouse gas emissions reductions are compared with conventional technologies and an economic evaluation is carried out. It is concluded that heat pumps operating beween shallow geothermal reservoirs and radiant-floor and/or water tank systems, arise as an efficient technology for air conditioning and water heating needs, through use of clean renewable energy.

## RESUMEN

Esta tesis de maestría es un estudio de factibilidad del uso de energía geotérmica, en viviendas tipo de un desarrollo urbano de la ciudad de Córdoba, Argentina. El calor geotérmico a temperatura constante disponible a poca profundidad, se propone como fuente de una bomba de calor acoplada a un piso radiante para aire acondicionado y a un termotanque para suministro de agua caliente sanitaria. El estudio se realizó considerando las características del clima local, la demanda de energía de una casa residencial típica y las factibilidades técnicas y económicas de la región. Primero se describen la matriz energética argentina, la demanda de energía residencial, las tecnologías renovables aplicadas para abastecer esa demanda y el actual uso de la energía geotérmica. Luego se dimensionan bombas de calor geotérmicas para usos residenciales, se comparan los resultados de ahorro energético y de reducción de gases de efecto invernadero con las tecnologías convencionales y se realiza una evaluación económica. Se concluye que bombas de calor operando entre reservorios geotérmicos a baja profundidad y sistemas de suelo radiante y/o termotanques, surgen como una tecnología eficiente para cubrir necesidades de climatización y calentamiento de agua, mediante uso de energía renovable y limpia.

## ZUSAMMENFASSUNG

Diese Masterarbeit ist eine Machbarkeitsstudie zur Nutzung von Geothermie in typischen Häusern einer städtische Entwicklung in der Stadt Córdoba, Argentinien. Erdwärme mit konstanter Temperatur, die in geringer Tiefe verfügbar ist, wird als Quelle einer Wärmepumpe vorgeschlagen, die mit einem Bodenwärmetauscher für die Klimaanlage und einem Druckerhöhungstank für die Warmwasserbereitung im Haushalt gekoppelt ist. Die Studie wurde unter Berücksichtigung der Besonderheiten des lokalen Klimas, des Energiebedarfs eines typischen Wohnhauses sowie der technischen und wirtschaftlichen Machbarkeit in der Region durchgeführt. Zunächst werden die argentinische Energiematrix, die Nachfrage nach Wohnenergie, die zur Deckung dieser Nachfrage eingesetzten erneuerbaren Technologien und die aktuelle Nutzung von Geothermie beschrieben. - Dann werden Erdwärmepumpen für Wohnnutzung dimensioniert, Energieeinsparungen und Reduzierung der Treibhausgasemissionen für konventionelle Technologien verglichen und eine wirtschaftliche Bewertung durchgeführt. Es wird der Schluss gezogen, dass Wärmepumpen, die zwischen flachen Geothermiereservoirs und Bodenwärmetauscher- und/oder Wassertanksystemen betrieben werden, durch die Nutzung sauberer erneuerbarer Energie eine effiziente Technologie für den Klimatisierungs- und Warmwasserbereitungsbedarf darstellen.

## MOTIVATION

Climate change is one of the biggest challenges of our time. Since the endorsement of the Paris Agreement in 2015, the energy transition is playing a central role as a medium to achieve the decarbonization set as an objective target until 2050.

In Argentina, the residential use of energy represents 25% of the national energy demand. Household electricity represents 45% of the national electricity generation and 55% is used for air conditioning and water heating. Thus, the transition to clean residential heat energy plays a relevant role in decarbonization. The use of heat pumps coupled to shallow geothermal sources is in line with recommendations of the International Energy Agency (IEA) (Report 2023) [1] and contributes to energy security.

In Córdoba City, there is a growing interest in the construction of urban developments that offer energy-efficient housing. Currently, the market tends to the construction of houses with energy-efficient materials, solar panels and collectors and high-efficiency equipment for heating and cooling. The large-scale introduction of other renewable sources of energy in the region has not been detected in the last few years. Facing this scenario, the coupling of shallow geothermal resources with heat pumps emerges as an attractive opportunity to provide home-efficient air conditioning and hot water. The efficiency of ground-source heat pumps is 50-70% higher than that of conventional heating systems and 20-40% better than air-to-air heat pumps used in aerothermal systems (Letcher 2013) [2].

Motivated by this challenge, as an inhabitant of the city of Córdoba and by the concern that the company Grupo Conectar expressed to me to incorporate new renewable technologies for residential users, is that this thesis work begins.

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## CONTENTS

# LIST OF ABBREVIATIONS

| | |
|---|---|
| AC | Air Conditioning |
| ARS | Argentinean peso |
| ASHP | Air Source Heat Pump |
| CAMMESA | Compañía Administradora del Mercado Mayorista Eléctrico SA |
| COP | Coefficient Of Performance |
| CSTP | Characteristic Subsurface Temperature Profile |
| DHW | Domestic Hot Water |
| EER | Energy Efficiency Ratio |
| FEA | Finite Element Analysis |
| GHE | Geothermal Heat Exchanger |
| GHG | Greenhouse Gases |
| GSHP | Ground Source Heat Pump |
| GWP | Global Warming Potential |
| HDPE | High Density Polyethylene |
| HVAC | Heating, Ventilation, and Air Conditioning |
| IEA | International Energy Agency |
| INDEC | Instituto Nacional de Estadísticas y Censos de Argentina |
| IPCC | Intergovernmental Panel on Climate Change |
| IRAM | Instituto Argentino de Normalización y Certificación |
| LPG | Liquefied Petroleum Gas |
| NP | Nominal Pressure |
| NPV | Net Present Value |
| RFC | Radiant Floor Cooling |
| RFH | Radiant Floor Heating |
| ROI | Return of Investment |
| SCOP | Seasonal Coefficient of Performance |
| SDR | Standard Dimension Ratio |
| SEER | Seasonal Energy Efficiency Ratio |
| SEGEMAR | Servicio Geológico Minero Argentino |
| SMN | Servicio Meteorológico Nacional |
| USD | US dollar |
| VAT | Value Added Tax |
| WBCSD | World Business Council for Sustainable Development |
| WRI | World Resources Institute |
| WSHP | Water Source Heat Pumps |

# LIST OF SYMBOLS

| | |
|---|---|
| $\Delta H$ | Difference between the specific humidity of outdoor and |
| °D | Degree days of energy demand [K.d] |
| A | Area [m2] |
| c | Specific heat [kj/kg.°C] |
| $CO_2e$ | Mass of equivalent carbon dioxide [g or kg or tonnes] |
| $C_{ti}$ | Thermal coefficient [-] |
| D | Diameter of the pipe [m] |
| E | Energy demand [kwh] |
| f | Friction factor [dimensionless] |
| FE | Solar exposure factor |
| FL | Losses by the floor in contact with the ground [W/K.m] |
| $F_{per}$ | Floor perimeter in contact with outside air [m] |
| G | Volumetric coefficient of heat losses [W/K.m3] |
| g | Gravitational acceleration [m/s2] |
| h | Convection coefficient [W/m2. K] |
| h | Enthalpy values [kj/kg] |
| $h_L$ | Head loss [m] |
| IS | Solar irradiance [W/m$^2$] |
| K | Thermal transmittance values (K) [W/K.m$^2$] |
| $K_{IW}$ | Thermal transmission of the inner walls [W/K.m$^3$] |
| $K_{OW}$ | Thermal transmission of the outer walls [W/K.m$^3$] |
| $K_W$ | Thermal transmission of the windows [W/K.m$^3$] |
| $k_{pipe}$ | Pipe thermal conductivity [W/m.K] |
| $k_{soil}$ | Soil thermal conductivity [W/K.m] |
| L | Length [m] |
| m | Mass flow rate [kg/s] |
| n | Number of air renewals per hour |
| $N_e$ | Number of equipment |
| $N_r$ | Flow rate per person [m3/h.person] |
| p | Pressure [kg/(m.s$^2$)] |
| $P_{cond}$ | Condenser pressure [bar] |
| $P_{evap}$ | Evaporator pressure [bar] |
| Pr | Prandtl number [dimensionless] |
| $q_{air}$ | Flow rate of air renovation [m3/h] |
| $q_{cond}$ | Specific condenser energy load [kj/kg] |
| $Q_{cond}$ | Condenser thermal load [kj] |
| $Q_{cooling}$ | Cooling load [W] |
| $Q_{DHW}$ | Energy demand for heating domestic hot water [kwh] |
| $Q_e$ | Thermal load due to equipment [W] |
| $q_e$ | Thermal energy per equipment [W] |
| $Q_{evap}$ | Evaporator thermal load [kj] |
| $Q_{heating}$ | Thermal power for heating [W] |
| $Q_I$ | Inner energy inputs (equipment, people) [W] |
| $Q_l$ | Thermal load due to lighting [W] |
| $q_l$ | Lighting thermal energy [W/m$^2$] |
| $Q_m$ | Metabolic heat emitted by people |
| $Q_p$ | Thermal load due to people [W] |
| $Q_S$ | Solar energy inputs [W] |
| $Q_T$ | Transmission losses [W] |
| $Q_V$ | Air ventilation losses [W] |
| R | Thermal resistances [mk/W] |
| r | Radius of the pipe [m] |
| Re | Reynold number [dimensionless] |
| S | Conduction shape factor [dimensionless] |
| $S_l$ | Lighting area [m$^2$] |
| $S_{IW}$ | Area of the internal walls [m$^2$]. |
| $S_{OW}$ | Inner area of the outer walls [m$^2$]. |
| $S_W$ | Inner area of the windows [m$^2$]. |
| $S_W$ | Windows surface [m$^2$] |
| T | Temperature [K or °C] |
| TAVE | Average outdoor temperature [°C] |
| $T_{cond}$ | Condenser temperature [°C] |
| $T_{cw}$ | Cold water temperature [°C] |
| TDI | Design indoor temperature [°C] |
| TDO | Design outdoor temperature [°C] |
| $T_{evap}$ | Evaporator temperature [°C] |
| $T_{hw}$ | Hot water temperature [°C] |
| $T_{in}$ | Indoor temperature [°C] |
| V | Indoor volume of the dwelling [m3] |
| V | Volume [m3] |
| v | Fluid velocity [m/s] |
| $w_{comp}$ | Specific compressor power requirement |
| $W_{comp}$ | Compressor work load [kj] |
| $W_r$ | Real total work [kj] |
| z | Pipe depth [m] |
| $\eta_{el}$ | Coefficient due to electric losses |
| $\eta_r$ | Real coefficient of efficiency |
| $\rho$ | Density [kg/m3] |
| $\tau$ | Viscous stress tensor [kg/ (m2.s2)] |

# 1. INTRODUCTION

## 1.1 Analysis of the local energy use

### *1.1.1 National energy use*

Argentina has significant reserves of oil and natural gas, which account for over 80% of the country's energy consumption as fuel, for electricity generation, transportation, and industrial processes. In 2019, the energy consumption was of 25% in the residential sector, 31% in the transportation, 24% in the industry and the rest in commercial and agricultural activities (data from Secretary of Energy of the Nation, 2019) [3].

The electrical matrix includes hydroelectric, nuclear and renewable generation, see Figure 1. According to the 2022 report of CAMMESA (Compañia Administradora del Mercado Mayorista Eléctrico SA) [4], in 2022 the generation was 145 TWh, thermal reached 56%, nuclear 5%, hydro 21%, renewables 13% and imports 4%.  The residential consumption represents the 45% of the total electricity demand and the rest is demanded by commercial and industrial users.  Renewable energy, particularly wind and solar, is a growing sector in Argentina. The government has included feed-in tariffs, net metering, and tax incentives, so the installed capacity of renewable energies increased by 25% from 2020 to 2021.

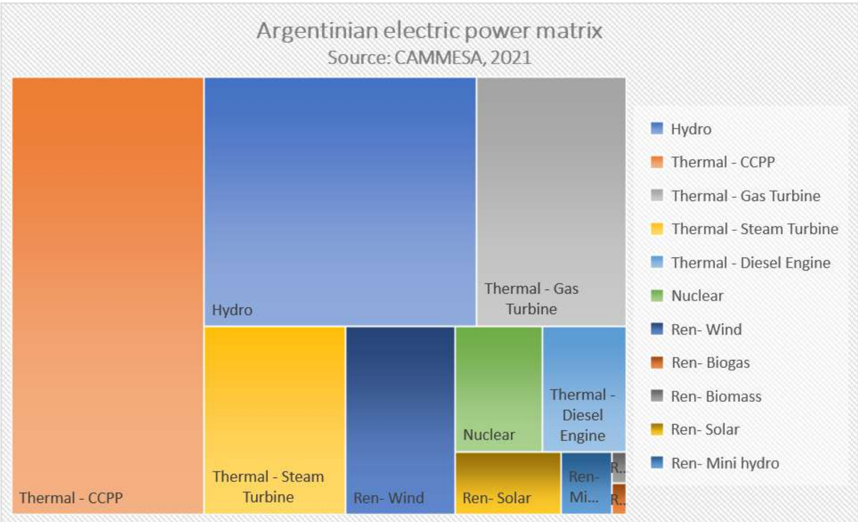



Figure 1. Argentinian electric power matrix. Source: [4]

### *1.1.2 Households' energy use*

The main energy sources used in Argentinean houses are electricity and natural gas, and liquefied petroleum gas (LPG) is the option for those households that do not have access to the natural gas network.

Natural gas and LPG are primarily used for cooking, water heating and space heating. In the last years, to encourage the use of natural gas in households, the Argentinean government has implemented various policies, including subsidies and low-interest loans for households to purchase gas appliances, and programs to expand the national gas distribution network to underserved areas.

Electricity is used for lighting, appliances, electronics and to supply air conditioning and water heating demand. The 2021 report from CAMMESA [5], shows a strong dependence of residential electricity consumption on ambient temperature, which demonstrate the use of this electrical source to meet thermal conditioning needs in homes, especially for cooling.

### 1.1.3 Legal framework of renewable energies in the country

There are a series of regulations in Argentina that regulate and promote the implementation of projects for the use of renewable energy sources. Law N°27.191 [6], which promotes the use of renewable energy for the generation of electricity, defines that the country must have 20% of electricity from renewable sources by 2025. The law defines as renewable wind, solar thermal, solar photovoltaic, geothermal, tidal (generated by waves), marine currents, biomass, landfill gases, gases from treatment plants, biogas and biofuels, and small-scale hydroelectric energy. The province of Córdoba adheres to Law N°27.191 through Provincial Law N°10.397 [6].

In the province of Córdoba, the Law N° 8.810 [6] refers to the use of renewable energies and the rational use of energy. The objectives of this law are the reduction of greenhouse gases, the efficient use of resources, reducing the risk of global warming and promoting investments for the development of less favored regions. The law establishes a set of tax benefits for renewable energy investments.

The province of Córdoba has specific laws that promote the development of renewable energies and the efficient use of energy. For example, Law N°10.573 [6] encourages the development of solar thermal energy for the supply of hot water and Law N°10.572 [6]. promotes the rational and efficient use of energy.

There are no regulations in the region that establish specific guidelines for the development of low enthalpy geothermal energy projects.

### 1.1.4 Use of renewable energy technologies in households

The use of renewable energy in Argentinean households is increasing, driven by the need to reduce dependence on fossil fuels, increase energy security, and reduce greenhouse gas emissions. However, the adoption of renewable energy in households is still relatively low compared to other countries, and there is still significant potential for growth in this sector. Some of the most common renewable energy sources used in Argentinean households include solar, wind, and biomass energy.

The most widely used renewable energy source in households in Córdoba is solar energy. Photovoltaic panels to generate electricity and solar collectors to heat water are technologies increasingly used in homes. The use of this technology over other renewable options is based on the solar irradiance values in the city, the cost-effectiveness of its installation, the low maintenance, the modular design, the availability of equipment and technical specialists in the local market and the acceptation of the technology by the community.

It is common to use in Córdoba Heating, Ventilation, and Air Conditioning (HVAC) units, which work in cooling and heating mode for air conditioning. The heating function is performed by an Air Source Heat Pump (ASHP). There is an incipient market of heat pumps to heat water, especially focused on uses for heating swimming pools.

While many applications currently use ASHP, there is no widespread knowledge about the possibility of using a heat pump that takes advantage of geothermal energy to maximize its performance, which is a Geothermal Source Heat Pump (GSHP).

Currently, the main motivation for incorporating a renewable technology in the home is the economic benefit that can be obtained in return, mainly due to the savings by replacing the energy source, such as gas or electricity from the grid. The possibility of having a stable and own source of energy, which makes the home independent of supply shortages from other sources is a driver for the installation of renewable sources.

No less important is the growing interest in incorporating environmentally friendly technologies. Many real estate development companies have focused their interest on implementing sustainable urban developments. This interest is mainly based on the demand for residential housing sought by middle- and upper-class sectors.

#### *1.1.5 Air conditioning and water heating of households in the region of interest*

In accordance with data published by the Ministry of Energy of the Argentinean Nation [7], heating constitutes 35% of the energy demand of a typical family home, cooling 6% and domestic hot water 14%, see Figure 2. In total, the air conditioning of the spaces and the Domestic Hot Water (DHW) represent 55% of the total energy demand of a household.

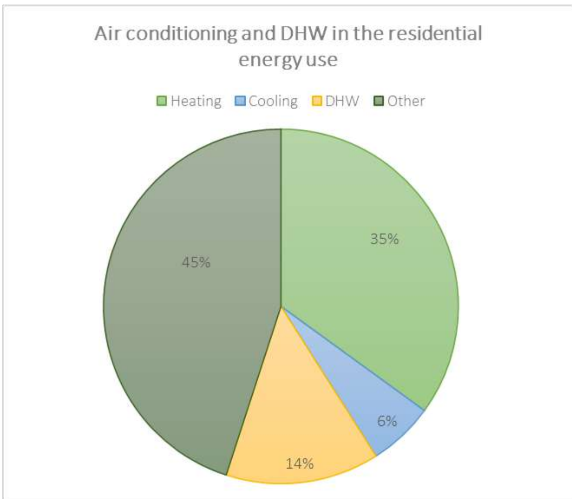



Figure 2. Air conditioning and DHW in the residential energy use. Source: [7]

According to the report published in 2022 by the National Institute of Statistics and Censuses of Argentina (INDEC) [8] in reference to the residential use of energy, the air conditioning and the water heating are supplied as described below in the central region of the country, to which Córdoba belongs:

- Cooling: 86.6% of the households have some type of equipment for cooling the spaces. 46.9% own an AC or HVAC ("split") type equipment. The latter equipment is mainly used in higher-income housing.
- Heating: 85.0% of the households have some type of equipment for space heating. 48.9% reported using gas stoves and 20.0% electric stoves.
- DHW: 37.4% of households use gas-based thermotanks and 29.1% gas heating. The proportion of those who use electrical appliances reaches 8.0% for thermotanks and 18.7% for water heaters.

### 1.2 Geothermal energy

#### *1.2.1 Geothermal energy description*

This work proposes the use of shallow geothermal energy as a source of renewable energy to meet the needs of air conditioning and water heating of the home.

Geothermal energy refers to the internal energy of geological materials contained between the earth's surface and down to the earths' core itself (García Gil A. et al.) [9]. It represents the potential ability of a geological system to transfer thermal energy in the form of heat or to perform work.

The core of the planet has temperatures around 6000°C, and the surface temperature is hundred times lowers than these values. The internal energy difference between these extremes induces an energy flow from the core to the earth's surface. The geological temperature shows a decreasing profile from the core to the surface.

High-temperature or high-enthalpy geothermal energy is characterized by geothermal gradient of approximately 25-32 °C/km and temperatures exceeding 175°C. This energy source it is used for electricity generation and district heating on a commercial scale. As the formation approaches the surface, the geothermal energy becomes lower, and it is known as medium or low temperature or enthalpy geothermal source.

This study is centered in the shallow geothermal energy, characterized as a very low temperature or enthalpy energy source. It contains the energy located between the surface and a depth of around 400m.

All the thermal energy that can be transferred as heat to this thermal reservoir, either by heat dissipation or heat absorption, is called shallow geothermal energy [9].

It should be noted that while medium and deep geothermal energy (cogeneration) can provide heat for heating, only shallow geothermal energy has potential for cooling, since the subsurface temperature in the shallow domain roughly coincides with the annual average atmospheric temperature of the region. Therefore, the shallower ground (<400 m) can provide heating and cooling, including domestic hot water (DHW), all year round [9].

Another advantage of shallow geothermal energy is their ubiquity. It is available everywhere, independent of geological formations.

### *1.2.2 Underground temperature profile*

The interaction of the geothermal gradient with atmospheric dynamics generates a characteristic subsurface temperature profile (CSTP), see Figure 3. The depth at which the annual seasonal temperature variation disappears is between 10 and 20 m depth. This depth marks the boundary where the shallow or transitional terrain domain ends and the purely geothermal thermal domain begins [9]. The depth where the geothermal begins, below the thermal influence of the atmosphere, tends to have a stationary thermal and hydraulic regime. The Figure 3 shows the spatio-temporal distribution of relative temperature changes in the subsurface.

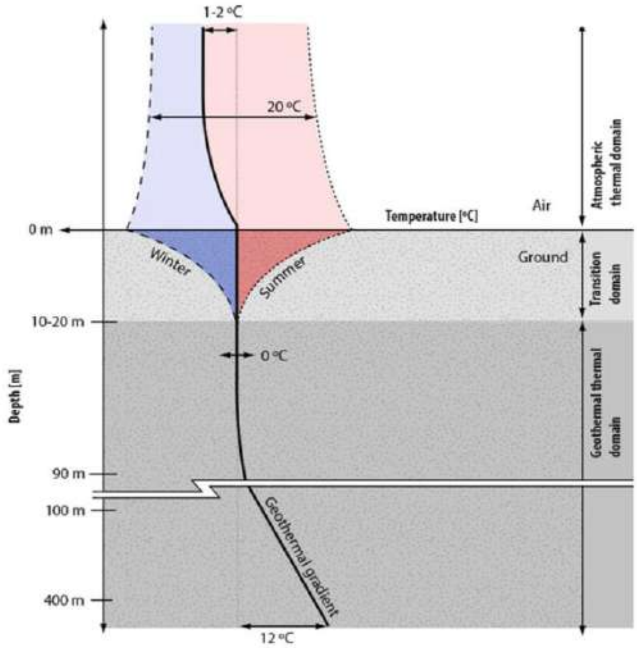



Figure 3. Characteristic subsurface temperature profile (CSTP) with the spatio-temporal distribution of temperatures in the atmosphere and in the ground over the course of a year. Source: [9].

Soil temperature is affected by meteorological variables. Meteorological elements such as solar radiation and air temperature influence the temperature of the surface and subsurface. Other weather factors such as wind and rain can cause local variations as well. The existence of vegetation or the presence of buildings on the ground will also affect the energy exchange with the environment.

The temperature of the soil surface remains practically in phase with that of the air. Below the surface, however, the maximum or minimum occurs later than the corresponding values on the surface, increasing the time lag with depth. It is possible to identify a larger-scale or annual cyclicity, and a diurnal cyclicity, associated with seasonal variations and day/night cycles respectively. These variations are limited to the region near the surface: daily cycles penetrate about 0.5 m, while the temperature of the earth beyond a depth of 1.0 m is usually insensitive to the diurnal cycle of air temperature and solar radiation and the annual fluctuation (seasonal variations) of the earth's temperature extends to a depth of about 10.0 m depending on the area. From there, the subsoil has the capacity to store the heat it receives and maintain it seasonally (practically constant ground temperature throughout the year) (Carro Pérez M. et al) [10].

### *1.2.3 Geothermal energy in Argentina*

According to a 2019 publication of the Secretary of Renewable Energies and Energy Efficiency of the Nation [11], in Argentina there are more than 300 spots of geothermal interest for electricity generation. The western region of the country concentrates the points of greatest interest for the development of medium and high enthalpy projects. The geothermal potential for electricity generation in Argentina is estimated at 2.000 MW (SEGEMAR) [12] distributed in different provinces of the country: Catamarca, Jujuy, La Rioja, Mendoza, Neuquén, Salta, San Juan and Tucumán.

In recent times, public institutions such as the Argentine Geological Mining Service (SEGEMAR) [12] have begun to pay attention to the potential of low and very low enthalpy projects. These projects focus on residential or commercial heating applications and water heating for home or industrial use.

SEGEMAR indicates in its report "Geothermal energy in Argentina: state, areas of interest and potential" [12] that the exploitation of medium and low temperature geothermal resources can be crucial in solving local problems and offer opportunities to improve the quality of life of small, isolated communities. In recent years there has been a positive increase in the presence of multiple ventures of direct uses of geothermal energy in Argentina. Proof of this are the various projects that have been developed in the country ranging from the use of thermal waters for therapeutic or leisure purposes, greenhouses, fish farming, industrial uses and domestic uses of heating and air conditioning of homes and official buildings) [12]

### *1.2.4 Very low enthalpy projects in Argentina*

From the literature review, the existence of antecedents in the country emerges regarding the use of very low enthalpy geothermal to meet the needs of air conditioning in homes. Below are detailed some of the antecedents found:

- Application of very low enthalpy geothermal energy for air conditioning. Olivos, Buenos Aires (2018). Author: Sticco, M., et.al. Technology: Canadian Wells. [13]
- Low enthalpy geothermal energy in loess soils: case study. Córdoba, Córdoba (2017). Author: Peiretti, A. Technology: Canadian Wells. [14]
- Geothermal Energy in Loess: A Detailed Numerical Case Study for Cordoba. Córdoba, Córdoba (2015). Author: Narsilio G., et. al. Technology: GHE design to couple with a heat pump. [15]
- Low enthalpy geothermal energy in loess soils: calculation and design for case study. Córdoba, Córdoba (2018). Author: Carro Pérez M., et. al. Technology: Canadian Wells. [16]

No case studies were found regarding the use of a heat pump coupled to a geothermal heat exchanger (GHE) to supply air conditioning and water heating for a household. The only reference to the heat pump is mentioned in the work of Narsilio G. [15], that focuses on the design of the GHE through numerical analysis.

### 1.3 Ground Source Heat Pump thermal installation

A thermal installation includes the systems and equipment to produce, distribute, store and exchange heat to satisfy the thermal energy demand of the building. Below are described the main components of a geothermal installation.

a. Heat production system

A heat production system is a thermal device or machine designed to generate one or more sources of heat, capable of acting as a source and/or sink [9]. In a geothermal heat pump installation, the heat pump is the device in charge of doing this function.

b. Heat distribution system

The distribution system includes all the elements required for transporting the heat carrier fluid. The system includes not only the pipelines but also all the accessories and instrumentation for controlling the operation, such as valves and expansion compensators.

Another important element is the circulating pumps. Most applications use electric motor-driven centrifugal pumps to impulse the heat carrier fluid through the heat exchanger and the internal distribution system.

The part of the distribution system in charge of the operation with the heat reservoir is the external heat exchange system, also known as the operating distribution system, and the part of the thermal installation that transfer heat to the domestic system is called the domestic distribution system.

- External heat exchange system: it is the system in charge to maximize the heat transfer between the distribution system and the external ambient heat reservoir, in this case, the ground. The heat exchanger can be direct contact, an open thermodynamic system in which the fluid is in direct contact with the medium. The more commons are the indirect-contact heat exchangers. In this last case, the fluid exchange energy through the enclosure walls, this constitutes a closed system.
- Internal heat exchange system: it constitutes the end point of the thermal installation. It is the system designed to maximize the heat exchange between the residence and the thermal installation. Common devices used to comply with the heat exchange are fan coils, air conditioning or air handling units, and radiators systems.

The table below summarizes the different elements that conforms a geothermal installation like the one proposed for the current analysis case.

Table 1. Summary of elements of the geothermal installation

| External exchange system | Production system | Domestic distribution system | Internal exchange system |
|---|---|---|---|
| Geothermal heat exchanger: closed-loop heat exchanger in horizontal trenches.<br>Circulating pump. | Geothermal heat pump. | Pipelines to heat transfer fluid flow.<br>Circulating pump. | Fan coils<br>Air handling units<br>Radiators<br>DHW systems |

## 1.4 State of the art in Heat Pumps

### *1.4.1 General description of heat pumps*

A heat pump is a machine or device capable of applying electromechanical work to generate a transfer of thermal energy (heat) between two thermodynamic systems. The device is based on the reverse Carnot cycle, which generates by work a thermal gradient capable of inducing such a transfer of thermal energy between two systems [9]. Using a heat pump, it is possible to transfer thermal energy by means of work from one thermodynamic system to another even if they have the same (or even higher) internal energy, without contradicting the second law of thermodynamics [9]. Part of the system from which is desired to dissipate or absorb heat is defined as the "domestic system" and, the other part from which the heat demanded is to be absorbed or dissipated is called the heat reservoir, see Figure 4.

The cycle in the heat pump can be reversed allowing to switch from operating in heating mode to cooling mode, changing the heat source and sink.

The efficiency of the heat pump will depend on the thermal energy difference between the systems which the heat is transferred. Based on this is that geothermal heat pumps result more efficient that the typical air heat pumps.

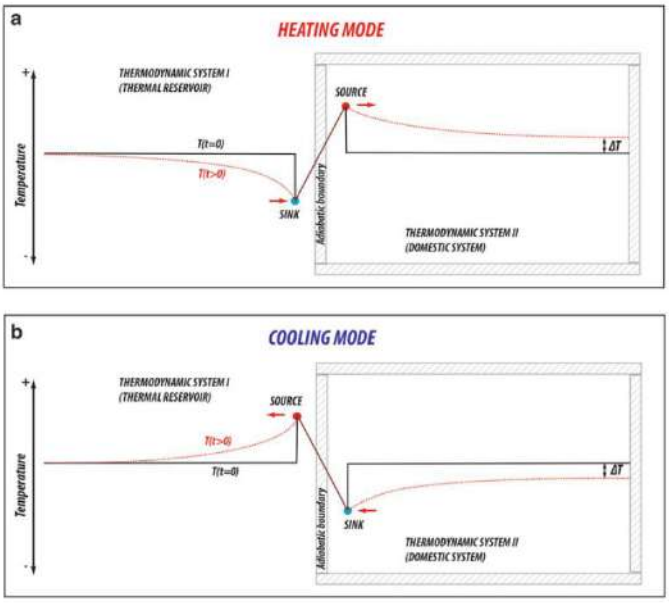



Figure 4. Temperature profiles generated by the generation of artificial heat source and sink by means of a heat pump. Source: [9].

### *1.4.2 Heat pumps use trends*

The heat pumps are considered as a key technology in the clean energy transition scenario according to the International Energy Agency (IEA), in its 2023 Energy Technology Perspectives report [17].

There were more than 1.000 gigawatts thermal (GWth) of heat pump capacity operating worldwide in 2021, up from around 500 GWth in 2010, with sales growing 13% relative to 2020. In 2021, the 1.000 GWth represented around 10% of the total building heating needs [17].

The market grew quickest in the European Union, where sales rose 35%, the United States (15%), Japan (13%) and China (13% for air-source heat pumps). Air-source heat pumps (air-air and air-water) account for most heat pump sales worldwide, making up over 80% of the market in 2021

[17]. The Figure 5 shows the growth expected for the heat pumps use in the Net Zero Emissions scenario.

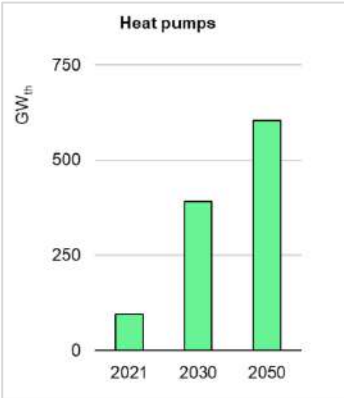



Figure 5. Global deployment of heat pumps in the Net Zero Emissions scenario. Source: [17].

Heat pumps have an upfront price premium when compared with fossil fuel heating equipment, though heat pumps pay back over their lifetime in many regions today. Installation time and costs could decline as heat pumps become more common, and offer greater opportunities in manufacturing [17].Figure 6 details the estimated market price and the installation time for typical heat pump-based systems in 2021.

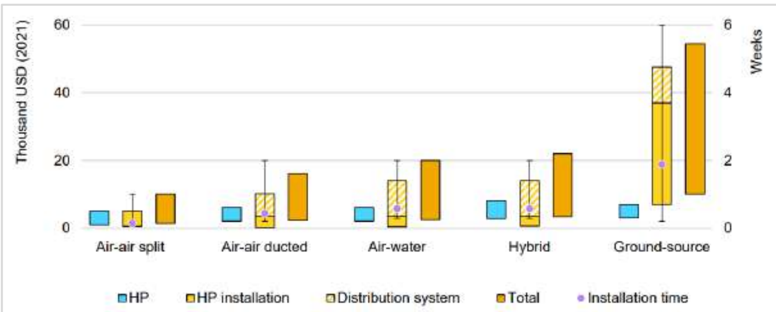



Figure 6. Heat pumps thermal systems market price and installation time for a typical household, 2021. Source: [17].

Nowadays, the manufacturing of heat pumps is centralized in China (40%), Europe (15%), North America (30%) and Other Asia Pacific (over 10%). While China and other Asia Pacific dominate the global heat pump market, in particular for split systems (with both indoor and outdoor units connected by a set of pipes), Europe is the leader in the market for hydronic systems (whereby heat is conveyed via hot water) and large-scale applications [17]. Figure 7 shows that the worldwide market is centralized in China, Europe, North America and Other Asia Pacific. The use of heat pumps is not yet significant in South America, which could represent a potential for future growth.

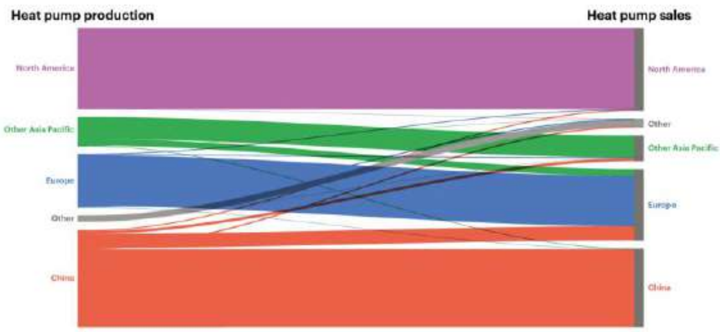



Figure 7. Global inter-regional trade flows of heat pumps. Source: [17].

### 1.4.3 Heat Pump applications

Heat pumps have historically been used in cooling mode as the main component of chillers and air conditioners. Today, the heat pump concept is considered for cooling or heating, depending on the direction of flow of the heat carrier fluid in the primary circuit. By incorporating a four-way valve, heat pumps can transfer heat in both directions without altering the operation of the compressor [9].

The heat pump has the capacity to operate in cooling or heating mode according to the heat transfer demand. The ability to satisfy the demand of a thermal installation will depend on if the required supply temperatures are in the operating range of the device.

Normally, the heat pumps have a maximum working temperature of 55-65°C, which is sufficient to supply DHW and radiators for indoor heating. If a higher temperature is required, then the heat pump must be combined with other heat production system. Based on this, the heat pump can work in monovalent, bivalent and mono-energy mode. Most geothermal heat pumps operate in monovalent regime. It means that the heat pump acts as the only one heat production system and the temperature demand is approximately in the range of -2 to 65 °C.

Nowadays, the biggest challenge for heat pumps is to reach temperatures higher than 70°C, which is needed for some thermal installations with high heating demand or to meet sanitary requirements for DHW.

Heat pumps can be classified according to their use, to the heat reservoir or even to the type of heat transfer fluid used. There are several types of heat pumps available, each with its own set of advantages and disadvantages. Below are described the main used types.

1. Air Source Heat Pumps (ASHP): These heat pumps transfer heat between the outdoor air and the indoor space. They are cost-effective and easy to install, making them a popular choice for residential and commercial buildings. The outdoor heat reservoir of atmospheric air fluctuates seasonally and inversely to the demand of buildings, and this reduces the efficiency of the heat transfer. According to the heat transfer fluids used it can be classified as:
    - Air-to-air heat pump: the evaporator and the condenser are of the thin fin type, designed to optimize metal-to-air surface heat transfer.
    - Air-to water heat pump: atmospheric air is to be used as an external heat reservoir, but the heat is distributed through the thermal installation as a liquid fluid, improving efficiency and reducing the noise produced by fans in overhead distribution circuits.
2. Water Source Heat Pumps (WSHP): These heat pumps transfer heat from water sources such as lakes, rivers, or oceans and the indoor space. They are highly efficient and can be used in large commercial buildings. However, they are expensive to install and require access to a water source.
    - Water-to-water heat pump: the heat carrier fluid, which interacts with one of the heat exchangers of the heat pump (evaporator or condenser), and the fluid used to distribute the heat through the domestic system, which interacts with the other heat exchanger of the heat pump (evaporator or condenser), are liquid water.
3. Ground Source Heat Pumps (GSHP): Also known as geothermal heat pumps, these devices transfer heat between the ground and the indoor space. They are more efficient than ASHPs and can operate in any weather condition. However, they are expensive to install and require a large area of land for installation.
4. Hybrid Heat Pumps: These heat pumps combine two or more types of heat sources to improve efficiency and reduce operating costs. For example, a hybrid heat pump may combine an ASHP and a GSHP to use outdoor air as the primary source of heat and the ground as a backup source.

### 1.4.4 Geothermal heat pumps

Geothermal heat pumps are distinguished from other heat pumps due to their optimal characteristics in terms of energy efficiency. Its operation is based on the efficient vapor compression cycle coupled to a shallow geothermal reservoir.

Shallow geothermal reservoirs can be an ideal heat source or heat sink for thermal installations. The main advantage of these reservoirs is that the temperature is relatively stable throughout the year, which means that the efficiency of the heat pump is more predictable and less affected by seasonal fluctuations. Furthermore, the geothermal reservoir counts with sufficient thermal capacity so that when a finite heat transfer occurs the temperature effectively remains constant.

If it is considered that the efficiency of a heat pump depends on the temperature of the thermal reservoir and the target temperature of the internal system, it is easy to understand how heat pumps coupled to a stable thermal reservoir will give better performance than if coupled to an unstable reservoir with variations of temperature [9].

Geothermal heat pumps refer to water-to-water heat pump coupled to the ground. There are two main types of coupling to the ground:

- Closed-loop geothermal heat exchanger: the heat transfer fluid is circulated through a closed circuit by means of an impulsion pump. Heating SCOP=2.5-4.0 and EER for cooling=10.5-20.0.
- Open-loop geothermal heat exchanger: the heat carrier fluid is the groundwater itself. In this system there is mass exchange. Heating SCOP=3.0-4.0 and EER for cooling=11.0-17.0.

The closed-loop heat exchanger can be of direct or indirect expansion.

- The direct expansions involve the circulation of the heat pump' heat carrier into the ground via a closed loop. The primary circuit is buried in direct contact with the reservoir and the heat carrier fluid used is usually a fluorocarbon refrigerant.
- In the indirect expansion system, a second closed circuit is added which is buried in the ground and circulates an aqueous carrier fluid.

The efficiency of the direct expansion systems is higher, but a disadvantage is the risk of contamination of the reservoir with refrigerant especially in deep vertical boreholes. Indirect expansion installation is widely used, and it constitutes the system chosen for the case of analysis.

### 1.4.5 The thermodynamic cycle

Heat pumps use the ideal vapor compression heat transfer cycle based on the reverse Carnot cycle. The components of the device are a compressor, an evaporator, a condenser, and an expansion system. The compressor is the unit in charge of applying work to generate artificial heat source and sink. The most common source of mechanical work is electrical energy by using electrical motors.

A typical refrigeration cycle works as indicated in the following steps (Figure 8):

- *Compressor:* the compressor increases the pressure of the gaseous heat carrier, and this causes its temperature to rise, for example, from approximately 3°C at 1.7 bar to 73°C at 13.5 bar.
- *Condenser:* The hot compressed gas circulates through the heat exchanger, and it is put in contact with the secondary circuit fluid, which is connected to an external heat reservoir, in this case at a lower temperature. The gas releases sensible heat and reduces its temperature. In this example, condensation temperature is reached at 53°C

and at this point the gas release latent heat to the secondary circuit during phase change. After the condensation isothermal process, the liquid in the primary circuit continues releasing sensible heat until reduce its temperature until around 48 °C, maintaining the pressure at 13.5 bar. The secondary circuit introduces a heat carrier fluid at 45°C and leaves at 50°C.

- *Expansion valve:* the liquid heat carrier fluid passes to the expansion valve and the pressure and temperature are reduced to 1.7 bar and -2 °C.
- *Evaporator:* the low temperature fluid is connected to another heat exchanger from which it absorbs heat (indoor residence) and increases its temperature to its boiling point at 1.7 bar. As in the condenser, it is an isothermal process. The secondary circuit enters the evaporator at a temperature of 12°C and leaves at 7°C.
- *Closing the cycle:* the gas at 3°C and 1.7 bar is returned to the compressor to close and continue the cycle.

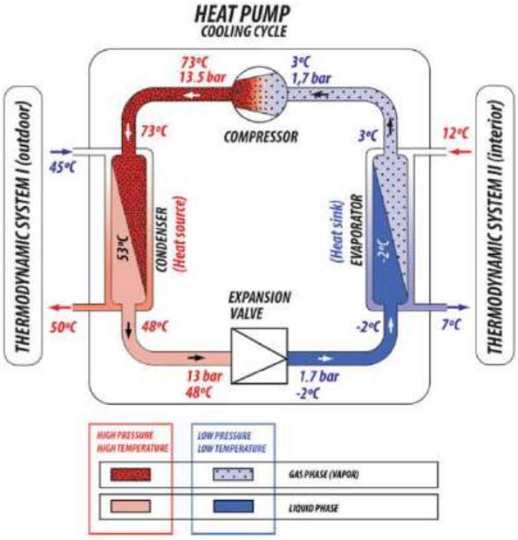



Figure 8. Diagram of a heat pump operating for refrigeration using the vapor compression Cycle. Source: [9].

The device requires a primary and a secondary circuit, it is an indirect heat transfer process. Three thermodynamic subsystems are required to transfer heat between two thermodynamic systems if a heat pump with vapor compression heat transfer is used [9].

In the ideal vapor-compression cycle (

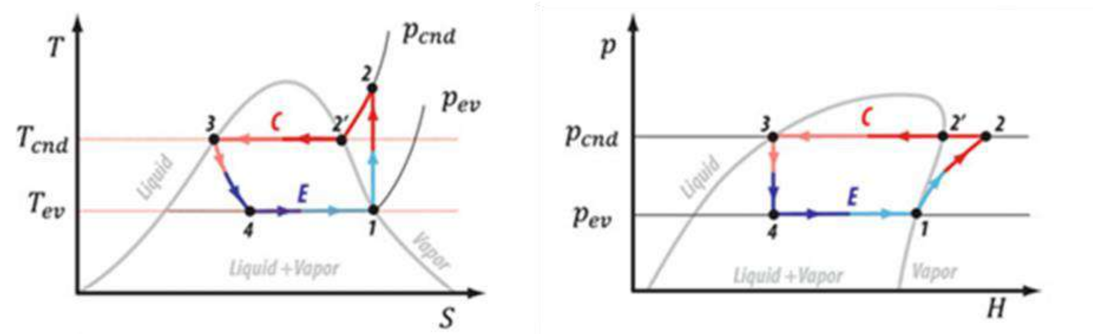



Figure 9), the compression stage is an isentropic process, which means that it is reversible and adiabatic. For this to happen, there should not be heat losses, friction, inelastic deformation…, an ideal process. The condensation and evaporation are isobaric and isothermal processes. In the expansion valve the expansion process it is isenthalpic.

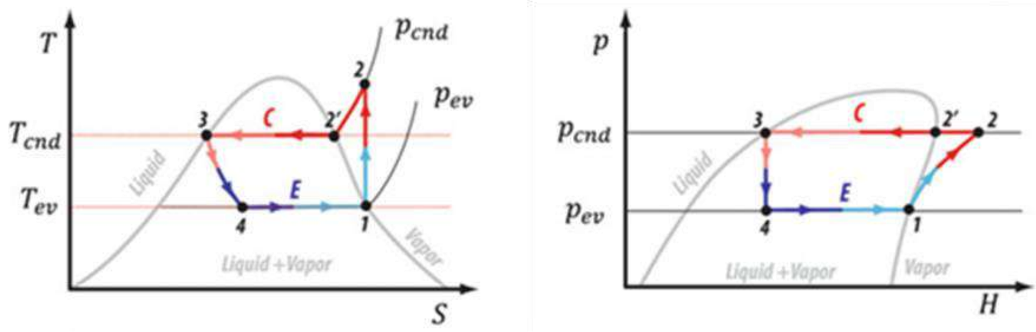



Figure 9. Temperature- Entropy and Pressure-Enthalpy diagrams. Source: [9].

# 2. METHODOLOGY

## 2.1 Case of study

### *2.1.1 Building specifications*

The case of analysis is a residential building located in the city of Córdoba, Argentina. The house is part of an urban development project that proposes the construction of residential units in a residential neighborhood that works in a sustainable way, using clean energy.

The urban development has residential lots with an area of 500$m^2$ each. Each lot is designed to include a house of typical dimensions for a family of 4-6 people. For this analysis, one of the possible construction models was selected. The household counts with 136 $m^2$ of internal habitable spaces divided into two floors. The building on the ground floor has a living room, a kitchen, a toilette, and a gallery with barbecue area, summing a total area of 71 $m^2$. On the upper floor there are three bedrooms and two bathrooms distributed in 62 $m^2$. The stairs occupy an area of 3.4 $m^2$. The floor height is 2.7 m, indicating a total internal volume of 377 $m^3$. The Figure 10 shows the plant view of the model house considered for this analysis.

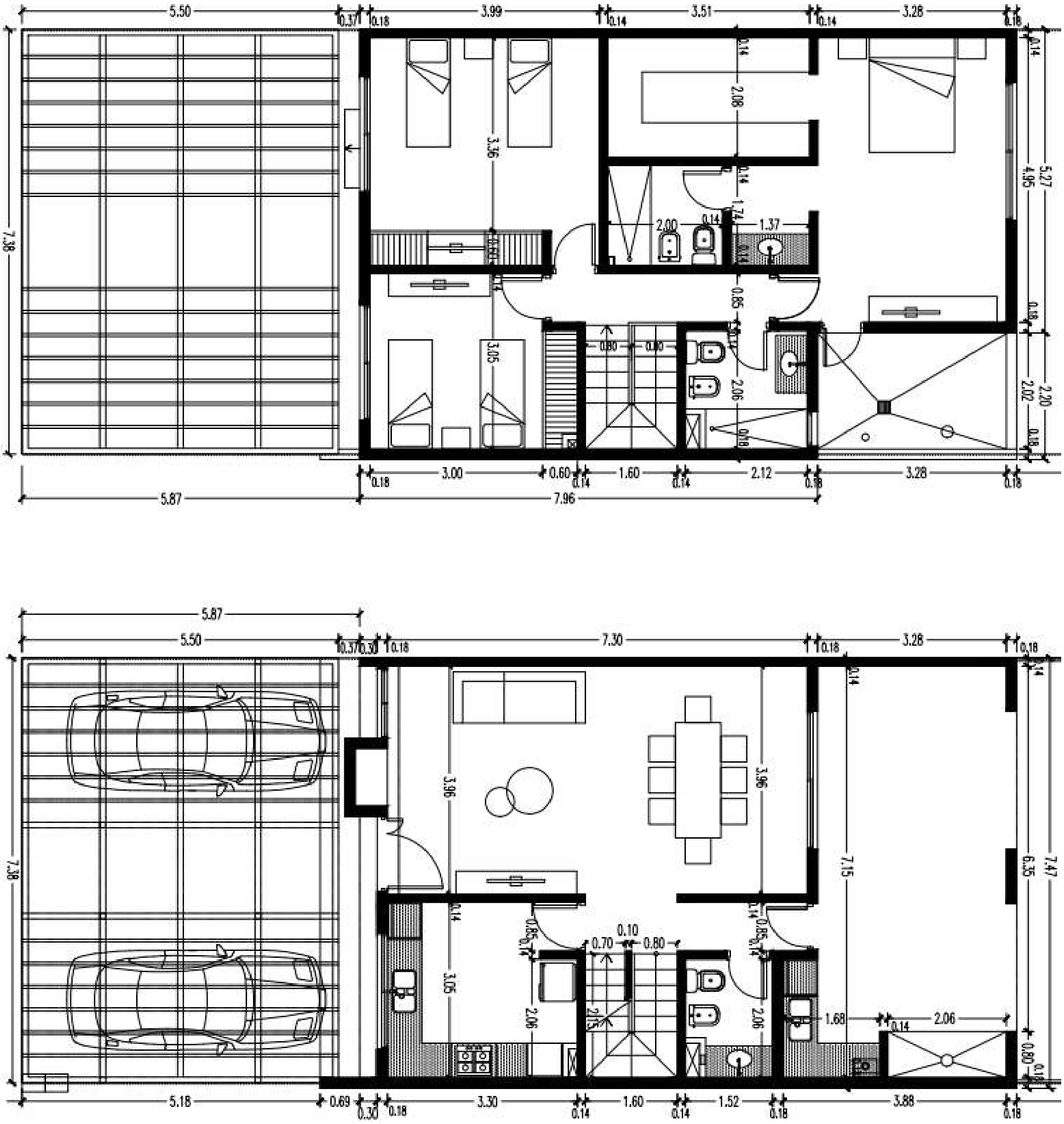


Figure 10. Residential house of study

### 2.1.2 Climate characterization

The city of Córdoba is in the bioenvironmental Zone IIIa that corresponds to the warm temperate zone according to the classification done by the normative IRAM 11603:2012 [18].

Summers are relatively hot and have average temperatures between 20 °C and 26 °C, with average maximums greater than 30 °C, only in the East-West extension belt. Winter is not very cold and has average temperature values between 8 °C and 12 °C, and minimum values that are rarely less than 0 °C. The thermal amplitudes are greater than 14 °C.

The Figure 11 details the average monthly values for the temperature and precipitation considering the period from 1999 to 2020. The data is taken from the National Weather Service (Servicio Meteorológico Nacional – SMN) [19] database. The average annual temperature is 19°C and the accumulated precipitation is around 800 mm per year.

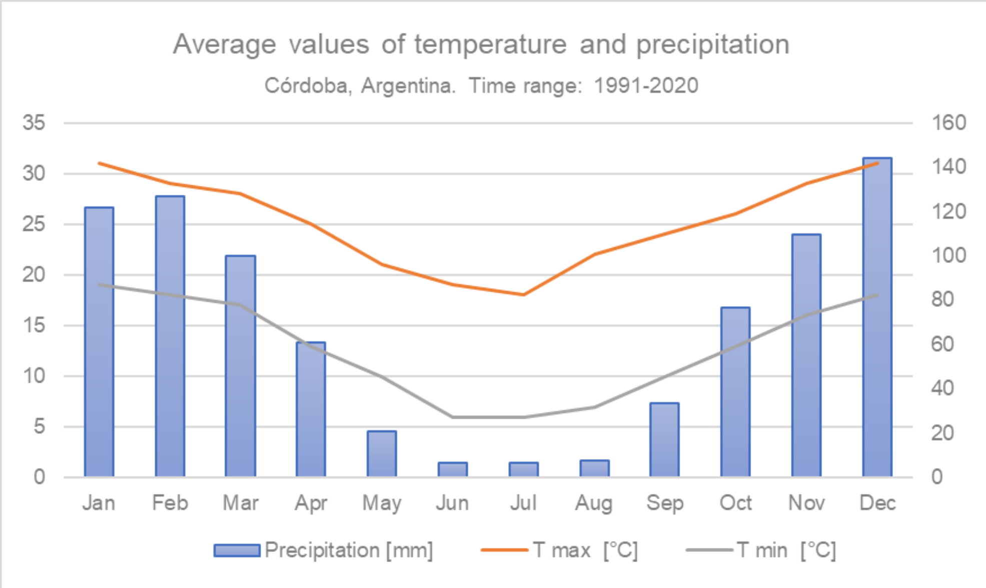



Figure 11. Average climatological values for the city of Córdoba. Source: [19]

### *2.1.3 Thermal installation proposal*

For the case of analysis, a thermal installation based on a shallow geothermal system with closed-loop geothermal heat exchanger coupled to a heat pump is proposed. These installations are known as Ground Source Heat Pump (GSHP) systems. This system is arranged together with an internal radiant floor heating/cooling installation to deliver the thermal comfort needed and with a booster tank to supply domestic hot water requirements.

The efficiency of a closed-loop geothermal heat exchanger system depends on several factors, including the soil composition, the depth of the loop, the size of the loop, and the heat transfer rate of the heat pump. The design of the system requires careful consideration of these factors to ensure that the loop is appropriately sized and located to meet the heating and cooling needs of the building.

The temperature to deliver to the indoor spaces depends on the type of heating or cooling distribution systems used. The Table 2 lists typical delivery temperatures for various heating distribution systems (C82, Energy Saving Trust) [20]. In this case of study, the distribution system is a radiant floor heating/cooling installation. The advantages of this type of hydronic system include their energy efficiency and quiet operation.

Table 2. Typical delivery temperatures for various heating distribution systems. Source: [20].

| Distribution system | Delivery temperature (°C) |
|---|---|
| Underfloor heating | 30-45 |
| Low temperature radiators | 45-55 |
| Conventional radiators | 60-90 |
| Air | 30-50 |

## 2.2 Energy requirement for air conditioning and domestic hot water

### 2.2.1 Heating load

The first step in simulating the performance of a thermal installation is to establish the energy demand for heating, cooling and supply domestic hot water (DHW). The heating load of a house refers to the amount of heat energy that is required to maintain a comfortable indoor temperature. This includes the amount of heat that is gained or lost through the building envelope (e.g., walls, roof, windows), as well as heat generated by occupants, appliances, and lighting.

The determination of the thermal loads allows us to understand the energy demands of a house and thus evaluate the most efficient options to supply them. Knowing the thermal load is important for determining the size of HVAC (heating, ventilation, and air conditioning) systems needed to properly heat and cool the house. Oversized or undersized HVAC systems can lead to poor energy efficiency, higher utility bills, and poor indoor air quality. To determine the heating of a home, an energy balance must be made considering the heat transfers existing in the place. For this, it is necessary to define the conditions listed below [16]:

- Outdoor conditions: maximum and minimum values of ambient temperature and humidity throughout the year.
- Interior conditions: temperature and humidity values that offer the comfort required for the occupation of the house. These conditions depend on the type of activity carried out in the dwelling, the number of occupants, the speed of air renewal.
- Gains and losses of heat by opaque enclosures (walls), translucent enclosures (glasses) due to the ingress of outside air and due to internal heat sources in summer (people, equipment).

The normative IRAM 11603 [18] establishes the exterior and interior design temperatures for the bioenvironmental zone to which Córdoba belongs.

Knowing the thermal properties of the construction materials, thermal balances are carried out considering the design temperatures for summer and winter.

The normative IRAM 11604 [21] defines the calculation of the energy demand (E) [kWh] as follows:

$$\mathrm{E} = \frac{24.\,°D.G.V}{1000}$$

Equation 1

$°D$: : degree days of energy demand [K.d]
$G$: volumetric coefficient of heat losses [W/K.m$^3$].
$V$: indoor volume of the dwelling [m$^3$]
$24$: hours per day [h/d]

The degrees heating day (°D) is an important parameter for the calculation of energy requirement. The °D is the sum, for the winter period, of the difference between the indoor temperature and the average temperature for each day of that period.

$$°\mathrm{D} = (T_{in} - T_{MED}).N°\ of\ winter\ days$$

Equation 2

The normative IRAM 11604 [21] defines the method to calculate the volumetric coefficient of heat losses (G) [W/K.m$^3$]. This is the caloric power lost by the building for each m$^3$ of inner volume and for each degree of temperature difference between indoor and outdoor. The coefficient G is calculated as follows:

$$G = \frac{\sum K_{OW}S_{OW} + \sum K_W S_W + \sum K_{IW}S_{IW} + F_{per}F_L}{V} + 0.35n$$

Equation 3

$K_{OW}$: thermal transmission of the outer walls [W/K.m$^3$]
$S_{OW}$: inner area of the outer walls [m$^2$].
$K_W$: thermal transmission of the windows [W/K.m$^3$]
$S_W$: inner area of the windows [m$^2$].
$K_{IW}$: thermal transmission of the inner walls [W/K.m$^3$]
$S_{IW}$: area of the internal walls [m$^2$].
$F_{per}$: floor perimeter in contact with outside air [m]
$F_L$: losses by the floor in contact with the ground [W/K.m]
$n$: number of air renewals per hour

For the thermal properties of the enclosures, the thermal transmittance values (K) [W/K.m$^2$]indicated in the national regulations IRAM 11605 [22] and 11601 [23] are taken as reference. The inner hydrothermal comfort values are also taken from this normative for the case of the recommended scenario (Level A). The normative defines the recommended values for the summer and winter periods of the case of analysis.

The thermal power for heating ($Q_{heating}$) [W] of the installation is defined as that required for the moment of greatest temperature difference between the interior and exterior. This thermal power demand must be able to replace all the energy that is lost by transmission through walls, ceilings, floors and openings, plus losses due to ventilation.

$$Q_{heating} = Q_T + Q_V$$

Equation 4

$Q_T$: transmission losses [W]
$Q_V$: air ventilation losses [W]

$$Q_T = \sum K_i S_i (T_{in} - T_{out})$$

Equation 5

$$Q_V = 0.35nV(T_{in} - T_{out})$$

Equation 6

### *2.2.2 Cooling load*

To define the cooling load, the heat that must be removed from the house to maintain the comfort conditions shall be estimated. The normative IRAM 11659 [24] defines the different levels of hygrothermal comfort. The cooling load ($Q_{cooling}$) [W] is estimated as follows:

$$Q_{cooling} = Q_C + Q_V + Q_S + Q_I$$

Equation 7

$Q_C$: conduction losses [W]
$Q_V$: air ventilation losses [W]
$Q_S$: solar energy inputs [W]
$Q_I$: inner energy inputs (equipment, people) [W]

$$Q_C = \sum K_i S_i (T_{in} - T_{out})$$

Equation 8

$$Q_V = q_{air}[0.25(T_{out} - T_{in}) + 0.61\Delta H]$$

Equation 9

$q_{air}$: flow rate of air renovation [m3/h]
$0.25$: relation between the air specific heat at 21°C and relative humidity of 50% and the specific volume of the same mixture [Wh/m$^3$°C]
$0.61$: relation between the average heat yielded by the condensation of 1g of water vapor and the specific volume of the same mixture [WhKg$_{dryair}$/m$^3$.g$_{water}$]
$\Delta H$: Difference between the specific humidity of outdoor and indoor air [g$_{water}$ /Kg$_{dryair}$]

$$q_{air} = N°of\ people.N_r$$

Equation 10

$N_r$: flow rate per person [m3/h.person]

$$Q_S = \sum S_W I_S F_E$$

Equation 11

$S_W$: windows surface [m$^2$]
$I_S$: solar irradiance [W/m$^2$]
$F_E$: solar exposure factor [-]

$$Q_I = Q_p + Q_l + Q_e$$

Equation 12

$Q_p$: thermal load due to people [W]
$Q_l$: thermal load due to lighting [W]
$Q_e$: thermal load due to equipment [W]

$$Q_p = N°of\ people.Q_m$$

Equation 13

$Q_m$: metabolic heat emitted by people [W/person]

$$Q_i = \sum q_i S_i C_{ti}$$

Equation 14

$q_i$: lighting thermal energy [W/m$^2$]
$S_i$: lighting area [m$^2$]
$C_{ti}$: thermal coefficient [-]

$$Q_e = \sum q_e N_e$$

Equation 15

$q_e$: thermal energy per equipment [W]
$N_e$: number of equipment [-]

### *2.2.3 Domestic Hot Water energy requirement*

Water heating provides a year-round load and can improve the load factor for the heat pump. For full water heating the heat pump should be capable of supplying water in the range 60°C to 65°C (C82, Energy Saving Trust) [20]. For domestic installations the thermal power output of the heat pump will be inadequate to deliver direct heating of incoming mains water to the required temperature level, so a storage system is required. Heating is usually carried out via a primary coil or jacket to a storage cylinder. For most domestic heat pumps the maximum output temperature is 55°C, and the maximum water storage temperature achievable is 50°C. An auxiliary electric immersion heater is needed to provide a ‘boost’ facility, and also to raise the water temperature periodically to over 60°C to reduce the risk of Legionella.

The energy demand for heating domestic hot water ($Q_{DHW}$) [kWh] is estimated as follows:

$$Q_{DHW} = mc(T_{hw} - T_{cw})$$

Equation 16

$m$: DHW mass flow rate [kg/s]
$c$: water specific heat [kJ/kg.°C]
$T_{hw}$: hot water temperature [°C]
$T_{cw}$: cold water temperature [°C]

For residential buildings, it is recommended to use a DHW consumption value of 55 L/person.day in designs.

### 2.3 Soil characterization in the site of interest

The city of Córdoba is in the middle of Argentina, where the loess soils are characteristic. The loess is a quaternary sediment composed mainly of fine particles that form an open microstructure.

In Argentina, quaternary deposits of loess sediment, known as loess “pampeano”, cover 600.000 $km^2$ of the northeast of the country. Very fine sand, silt and wind-borne clay particles are the main fractions of these sediments (Sayago et al., 2001; Francisca, 2007) [25]. The thicknesses of these loess sediments generally range from a few meters to a maximum of 65 m (Teruggi, 1957) [26]. The geological formation in Córdoba city consists of 4 distinguishable layers, non-plastic silt with some organic matter (z=0 to z=0.6 m below ground surface); collapsible non plastic silt with some clay and sand (z=0.3 m to z=9.5 m) (loess); low plasticity silt with sand (z=9.5 to 13 m); and a sand with silt and gravel layer (z> 13.0 m) [15].

Narsilio G. et. Al [15] performed in 2015 an experimental study to determine the thermal conductivity for loess soil in Córdoba. The thermal needle probe method was used, following the ASTM recommendations. This work yielded values for thermal conductivity that varied from 0.36 and 0.88 W/m.K, depending on the different samples of soil taken which vary in a range of dry densities and water contents (1.2-1.4 g/cm3).

Carro Pérez et. Al. [10] performed in 2020 a research job to determine the temperature distribution in a shallow loess soil profile from Córdoba city. The job consisted in drilling shallow wells of 0.2 m of diameter up to 1.5 m and registering the temperature during annual periods through sensors arranged every 0.3 m (0.3-0.6-0.9-1.2-1.5). The solar radiation [W/m2] as well as the ambient temperature and humidity were also registered during the experiment. Figure 12 shows the temperature profile obtained for summer and winter seasons and the annual average values determined for each depth. In summer months higher temperatures are registered at the shallower depths and since 0.6m the soil does not register diurnal cyclical influence. At 0.05 m, the temperature is higher than the ambient one and this is because of solar radiation. During winter months, in contrast to summer, the maximum temperature in the soil profile is at greater depths.

The literature specifies that the temperature of the soil from the depth that is not affected by the phenomena that occur in the surface soil (which is usually considered from 10 m) is about 2 °C higher than the average annual ambient temperature. According to the experiments of Carro Pérez et. Al. [10], the average annual temperature at 1.5 m of depth is around 20-22°C, which is 2°C higher to the ambient annual average temperature for Córdoba city, which is of 18,5 °C [19].

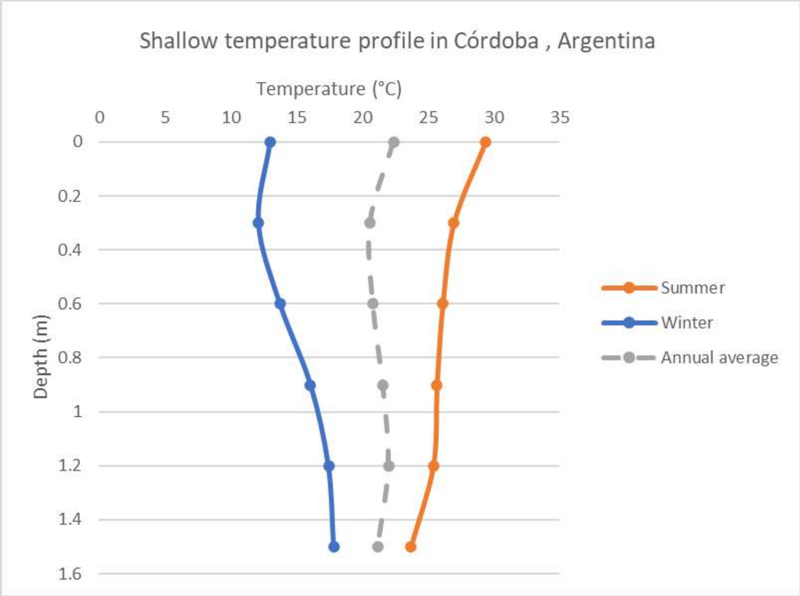



Figure 12. Shallow temperature profile in Córdoba, Argentina. Source: Own elaboration based on [10].

### 2.3.1 Soil thermal parameters

Failure to take ground characteristics into account leads to under- or over-dimensioning installations and, thus, to long term impacts on maintenance costs and payback time of such installations [9].

Before starting a geothermal installation design, it is necessary to have an initial estimation of the hydraulic and thermal parameters of the terrain.

Another way to obtain thermal and hydraulic parameters is from laboratory tests. Thermal conductivity values can be obtained from borehole cores or field samples. A third way to obtain the thermal and hydraulic parameters of the terrain is from different hydraulic and thermal response tests in situ, which are much more representative [9].

Theoretical values are sufficiently representative for small installations. For this analysis, the estimations are done based on theoretical values from the studies performed in the city by Carro Pérez et. Al. [10]and Narsilio G. et. Al [15], see Table 3.

Table 3. Soil properties considered for GHE design.

| Soil properties for GHE design | | | |
|---|---|---|---|
| Thermal conductivity | $k_{soil}$ | 0.8 | W/m.K |
| Winter soil temperature @2m | $T_{soil-winter}$ | 18 | °C |
| Summer soil temperature @2m | $T_{soil-summer}$ | 23 | °C |
| Annual average soil temperature @2m | $T_{soil-annual}$ | 21 | °C |

### 2.4 Engineering design: heat pump

The actual performance of the heat pump system is a function of the water temperature produced by the ground coil (which will depend on the ground temperature, pumping speed and the design of the ground coil) and the output temperature. It is essential that the heat pump and ground heat exchanger are designed together [20].

The heat pump system can be sized to meet the whole design load, but because of the relatively high capital cost it may be economic to size the system to meet only a proportion of the design load, in which case auxiliary heating (usually an in-line direct acting electric heater) is needed [20].

The diagram below shows the main parameters involved in the heat pump sizing (Figure 13).

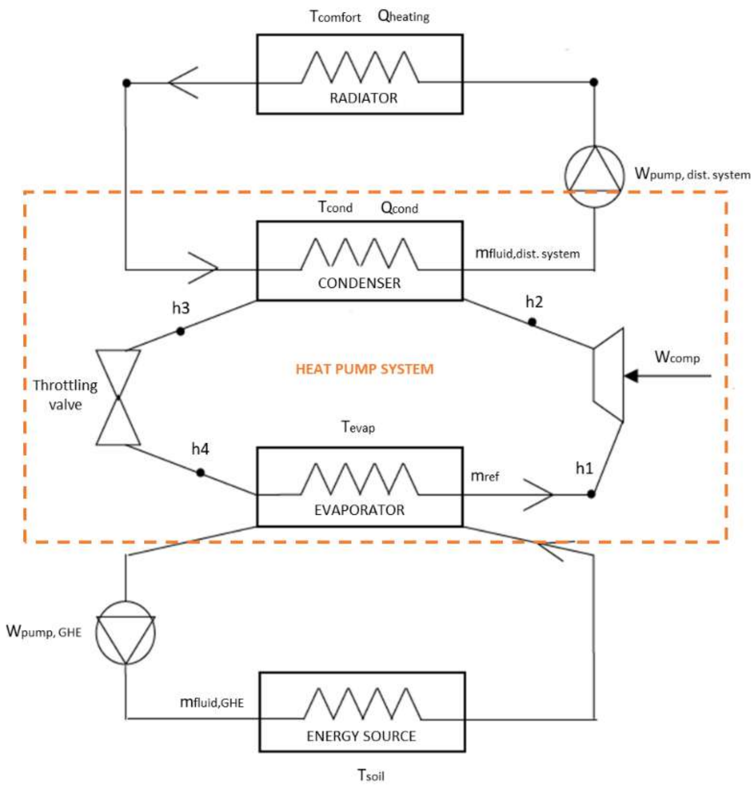



Figure 13. Diagram of a heat pump configuration (heating mode)

To determine the appropriate size of the heat pump, required to supply the energy demand of the building, the calculation steps defined below are followed. The methodology is explained for the case of heating mode.

The thermal power required to deliver in the condenser is equal to the thermal load estimated to supply the building energy demand in heating mode.

The compressor power can be determined based on the enthalpy values of each point of the cycle. The enthalpy values (kJ/kg) can be extracted from the refrigerant phase diagram knowing the condenser and the evaporator temperatures.

The condenser temperature is defined by the distribution system selected, for example, for an underfloor heating, the temperature should be between 30-45°C. The evaporator temperature depends on the fluid enter temperature, which is normally set 7-12°C colder than the soil temperature for the system working in heating mode. With these temperatures values and defining an isentropic compression from h1 to h2 and an isenthalpic expansion from h3 to h4 the enthalpy values for each cycle stage can be defined.

The specific condenser energy load ($q_{cond}$) [kJ/kg], the specific evaporator energy load ($q_{evap}$) [kJ/kg] and the specific compressor power requirement ($w_{comp}$) [kJ/kg] are defined as follows:

$$q_{cond} = h2 - h3$$

Equation 17

$$q_{evap} = h4 - h1$$

Equation 18

$$w_{comp} = h2 - h1$$

Equation 19

Then, known the actual heating load value ($Q_{heating}$) [kJ], which is equal to the condenser energy load ($Q_{cond}$) [kJ] (Equation 20), it is possible to determine the required refrigerant mass flow rate ($m_{ref}$) [kg/s] (Equation 31).

$$Q_{heating} = Q_{cond}$$

Equation 20

$$m_{ref} = \frac{Q_{cond}}{q_{cond}}$$

Equation 21

With the refrigerant flow rate and the specific work that is needed to supply to the cycle it is possible to size the compressor based on the required power ($W_{comp}$) [W] (Equation 22) and to determine the evaporator heat load ($Q_{evap}$) [kJ] (Equation 23), which will be used then to size the GHE.

$$W_{comp} = m_{ref}.w_{comp}$$

Equation 22

$$Q_{evap} = m_{ref}.q_{evap}$$

Equation 23

### *2.4.1 Coefficient of Performance*

The efficiency of the heat pump to transfer the demanded heat between the systems of interest is given by the coefficient of performance (COP). The COP is defined as the ratio between thermal energy transferred (goal) and the mechanical work required to do it. The Equation 24 shows the relation for the heating operation mode.

$$COP = \frac{Thermal\ energy\ transferred}{Mechanical\ work} = \frac{Q\ cond}{W} = \frac{H2 - H3}{H2 - H1}$$

Equation 24

In the real vapor compression cycle, during vapor compression, friction and other irreversible processes take place which, together, make this process irreversible ($\Delta S>0$) [9]. As is showed in Figure 14, the condensing pressure and temperature design conditions are not achieved. To reach these conditions, additional work is required, and so the COP results lower.

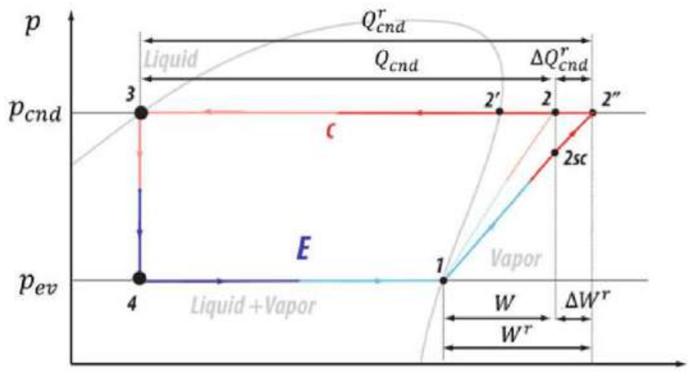



Figure 14. Pressure-Enthalpy diagram of a real vapor compression cycle. Source: [9].

The heat loss during compression is sufficiently low that the actual compression is still considered adiabatic. In any case, a real total work ($W^r$) is required to achieve the same pressure and temperature conditions as in the ideal cycle [9]. The adiabatic compressor efficiency coefficient can be defined as:

$$\eta_{ad} = \frac{W}{W^r} = \frac{W^r - \Delta Q_{cond}}{W^r} = 1 - \frac{\Delta Q_{cond}}{W^r}$$

Equation 25

The irreversible processes make it necessary to correct the COP to obtain the real coefficient of efficiency ($\eta_r$):

$$\eta_r = \frac{Q^r_{cond}}{W^r} = \frac{Q_{cond} + \Delta Q_{cond}}{W + \Delta W} = \frac{Q_{cond} + \Delta Q_{cond}}{W + \Delta Q_{cond}} = \frac{Q_{cond} + W\left(\frac{1}{\eta_{ad}} - 1\right)}{W + W\left(\frac{1}{\eta_{ad}} - 1\right)}$$

Equation 26

Combining with Equation 24:

$$\eta_r = (COP - 1)\eta_{ad} + 1$$

Equation 27

An extra coefficient ($\eta_{el}$) is added to the thermodynamic efficiency losses to contemplate losses that occur in the electric motor that supplies the mechanical energy, so the $COP_{el}$ is defined as:

$$COP_{el} = \eta_{el} . \eta_r$$

Equation 28

Thermal installations operating with an external heat reservoir, in which temperature varies over time, and an internal domestic system, with a temperature that remains constant, will experience varying efficiency over time as a function of the temperature in the external heat reservoir. If the internal system temperature tends to decrease, the heat pump will operate in heating mode, and if it tends to increase, it will operate in cooling mode [9]. Based on this concept is that a seasonal coefficient of performance (SCOP) for heating season is defined as:

$$SCOP = \frac{E_H}{W}$$

Equation 29

Where $E_H$ [J] is the heat energy transferred by the heat pump during the heating season and W [J] is the mechanical energy performed during that period.

For the cooling season, it is defined the seasonal energy efficiency ratio (SEER):

$$SEER = \frac{E_C}{W}$$

Equation 30

Where $E_C$ [J] is the thermal energy transferred by the heat pump during the cooling season. Systems with SEER>8.5 have the highest energy rating.

## 2.5 Engineering design: geothermal heat exchanger

### *2.5.1 Layout and piping*

This project is intended to be implemented for residential houses, which have a low to median energy demand and mostly the cost of the investment is a limitation, because of that the horizontal closed-loop geothermal heat exchanger is chosen to be analyzed. The technology involved is simpler than the one required for vertical BHE.

The horizontal ground heat exchangers (also known as ground loops) typically are buried at depths in a range from 1.2-3 m.

The material used for piping is high-density polyethylene (HDPE) due to its high flexibility, low cost, and acceptable thermal properties. The optimal pipe diameter of the geothermal heat exchanger will generate a turbulent flow regime, a condition that improves the heat exchange between the pipe wall (ground) and the heat carrier fluid in the closed circuit. However, turbulent flow increases frictional pressure losses compared to laminar flow, and a turbulent regime with minimum pressure losses is desirable [9].

The simplest forms of horizontal heat exchangers consist of pairs of straight pipes with a loop or curved fitting at the end of the trench. The pipe assembly consists of 26–40 mm diameter pipe in a single U-shape or slinky coils, see Figure 15. If there is a space constraint and the optimum length required for the heat exchanger is large, the loop type configuration results in a good layout option.

The axis to axis between two pipes placed simultaneously should be at least 1.5 times the diameter of the pipes. This minimum distance should be kept between two pipes so that the effect of the heat transfer of one system does not affect the other pipe in a long term of operation as the heat supplied or extracted from the continuously in change the temperature (Sukhija A. et. Al) [27].

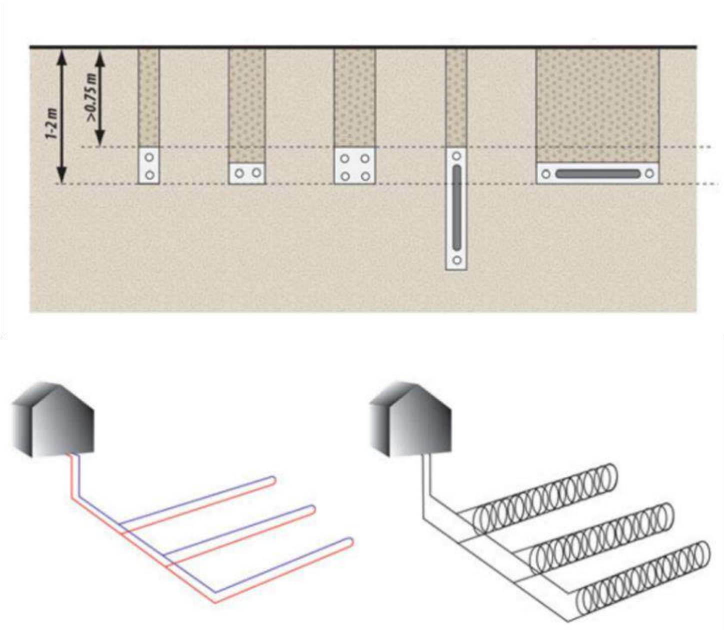



Figure 15. Horizontal geothermal heat exchangers with U-shaped and slinky coils layout. Source: [9].

### 2.5.2 *Sizing*

The sizing of the exchanger is based on the heat transfer process that is intended to be carried out between the heat carrier fluid and the soil. The heat transfer mechanism is complex, and it is done in a porous media with several components, such as, the piping, the heat carrier fluid and the ground. Heat conduction occurs in the soil and HDPE pipe wall, and partially in the carrier fluid (water) circulating in the pipe, while heat convection dominates in the carrier fluid, since there is no groundwater flow in the soil [15].

The governing equations of heat transfer are the three-dimensional Navier-Stokes equations for fluid flow, coupled with the energy equation for heat transfer. These equations are coupled, meaning that the solution for each equation depends on the solution for the others.

Based on the much smaller size of the GHE respect to the geological environment, it is accepted that the temperature changes inside the heat exchanger are fast enough to be considered in equilibrium. If the rate of heat transferred to the GHE from the heat pump is constant, a steady state is reached in a few hours, whereas in the geological environment it will take tens of hours to several days, even up to one or two years. This is an important simplification that facilitates the design of the GHE [9].

Below is described the calculation methodology used for the sizing of the exchanger, applying an analytical solution, under a steady state assumption, and simulation by finite element numerical method.

*Multidimensional steady heat transfer*

Multidimensional steady-state heat transfer refers to the transfer of thermal energy through a material or system that has multiple dimensions (e.g., length, width, and height) and is in a state of thermal equilibrium, meaning that the temperature distribution within the system is constant with respect to time. In such a system, the rate of heat transfer is governed by the Fourier's law of heat conduction, which states that the heat flux is proportional to the temperature gradient across the material or system.

Defining the thermal properties of the soil, fluid and pipe, the fluid mass flow, the pipe diameter and the inlet and outlet temperatures and the energy load, it is possible to define the required length. The assumptions listed below are taken for the estimations:

- The ground’s temperature is constant across the axial direction.
- The ambient water properties are taken at standard temperature and pressure (STP).
- The thermal properties of water and soil are constant.
- The temperature of the pipe’s surface is equal to the ground temperature.

The thermal resistances per pipe length of the water convection, pipe conduction and ground soil conduction are as follows:

$$R_{total} = R_{conv} + R_{pipe} + R_{soil}$$

Equation 31

$$R_{conv} = \frac{1}{\pi D_i h_f}$$

Equation 32

$$R_{pipe} = \frac{\ln \frac{D_o}{D_i}}{2\pi k_{pipe}}$$

Equation 33

$$R_{soil} = \frac{1}{S k_{soil}}$$

Equation 34

$D_i$, $D_o$ : pipe inner and outer diameter [m]
$h_f$ : convection coefficient [W/m$^2$. K]
$k_{pipe}, k_{soil}$ : pipe and soil thermal conductivity [W/ (m.K)]
$S$ : conduction shape factor [dimensionless]

The conduction shape factor (S) is a dimensionless parameter used in heat transfer analysis to describe the thermal resistance between two arbitrary surfaces. Shape factors have been obtained analytically for numerous two- and three-dimensional systems, for the case of analysis the shape factor is defined as follows (Said S.A.M. et. al) [28]:

$$S = \frac{2\pi}{\ln\left[\left(\frac{2z}{D_o}\right) + \sqrt{\left(\frac{2z}{D_o}\right)^2 - 1}\right]}$$

Equation 35

z : pipe depth [m]

The convection coefficient ($h_f$) can be calculated by using the Nusselt number:

$$h = \frac{Nuk}{D}$$

Equation 36

$$Nu = 0.023(Re)^{0.8} Pr^n$$

Equation 37

$k_p$ : thermal conductivity of the heat transfer fluid [W/ (m.K)]
$D$: diameter of the pipe [m]

$\mathrm{Re}$ : Reynold number [dimensionless]
$Pr$: Prandtl number [dimensionless]
$n$: constant value, 0.4 for heating and 0.3 for cooling.

The Equation 37 is valid for 0.7<Pr<160, Re≥ $10^4$ and L/D≥60.

Performing an energy balance on a differential section $dx$ , the differential heat transfer is given as:

$$dq = m_f C_{p,f} dT_f = \frac{T_{f,x} - T_{soil}}{R_{total}} dx$$

Equation 38

Defining $\theta_f$ and $X$ as follows:

$$\theta_f = T_f - T_{soil}$$

Equation 39

$$X = \frac{x}{m_f C_{p,f} R_{total}}$$

Equation 40

Then, the differential heat transfer equation can be written as:

$$\theta_f = \frac{d\theta_f}{dX}$$

Equation 41

Solving Equation 41 with boundary conditions, the equation for length (L) is defined as:

$$L = m_f C_{p,f} R_{total} \ln \frac{\theta_{f,in}}{\theta_{f,out}}$$

Equation 42

To define the length, the heat carrier fluid inlet and outlet temperatures must be defined. These temperatures are determined by defining the GHE outlet temperature, which will enter the heat pump, according to recommendations, and calculating the delta of temperatures required to exchange the energy load with the ground (Equation 43 and Equation 24). The energy load required to gain or lose from the soil corresponds with the energy load calculated for the evaporator in heating mode ($Q_{evap}$) and for the condenser in cooling mode ($Q_{cond}$).

$$Q_{evap} = m_f C_{p,f} \Delta T_{heating}$$

Equation 43

$$Q_{cond} = m_f C_{p,f} \Delta T_{cooling}$$

Equation 44

*Numerical modelling*

The thermal analysis applying a numerical modelling approach was performed using the software SolidWorks Simulation.  The governing equations for fluid flow and heat transfer are coupled numerically within the finite element package SolidWorks Flow Simulation to evaluate thermal performance of GHEs [29].

Below are listed the main steps of the numerical modeling process to simulate heat transfer:

1. Model Geometry: The first step is to create a 3D model of the heat exchanger being analyzed. The model geometry is created in SolidWorks and then imported into SolidWorks Simulation.
2. Boundary Conditions: The next step is to define the boundary conditions for the heat transfer analysis. This includes setting up the initial temperature distribution, specifying the heat sources and sinks, and defining the thermal boundary conditions such as the ground constant temperature.
3. Meshing: Once the boundary conditions are defined, the model is meshed to discretize the geometry into small elements. SolidWorks Simulation uses various types of meshing techniques such as tetrahedral, hexahedral, and triangular.
4. Solver: SolidWorks Simulation uses a finite element analysis (FEA) solver to solve the governing equations of heat transfer.
5. The FEA solver uses numerical techniques to discretize and solve the equations for each element in the mesh. The solver calculates the temperature distribution, heat fluxes, and other thermal properties.

*Circulation pumping*

To size and select the proper circulating pump for a geothermal heat exchanger the head loss must be determined. The head loss is the pressure drop that occurs as the fluid circulates through the geothermal loop. This is affected by factors such as the length and diameter of the pipes, the pipe material specifications, the fluid flow rate, and the properties of the fluid. Once the head loss has been calculated, the appropriate pump can be selected based on its performance characteristics. This will involve choosing a pump that can provide the required flow rate and head pressure, while operating efficiently and reliably.

The head loss ($h_L$) [m] can be calculated using the Darcy-Weisbach equation:

$$h_L = f\left(\frac{L}{D}\right)\left(\frac{v^2}{2g}\right)$$

Equation 45

$f$ : friction factor [dimensionless]
$D$: inner diameter of the pipe [m]
$L$: length of the pipe [m]
$v$: fluid velocity [m/s]
$g$: acceleration due to gravity [m/s$^2$]

The friction factor is a measure of the resistance to flow in the pipe. It can be estimated using empirical correlations or charts based on the Reynolds number and pipe roughness.

The analytical correlations are complex equations that require iterative calculations, such as the Colebrook or the Swamee-Jain equations. On the other hand, graphical methods are simpler to apply and return adequate values. The Moody chart is a graph that shows the friction factor as a function of Reynolds number and relative roughness. The relative roughness is the ratio of the pipe roughness to the diameter of the pipe.

The total head loss is the sum of the individual head losses for each component of the geothermal loop, including the supply and return piping, the heat exchanger, and any valves or fittings.

## 2.6 Energy demand

The thermal installation includes devices that need external energy to perform work. The external energy source is electricity, which can be taken from the grid or from an on-site source. For the case of a GSHP thermal installation, without considering the devices that distribute heat inside the house, the GHE circulation pump and the HP compressor are considered as working machines.

To evaluate the suitability of the proposed system, a comparison is made with respect to the most used systems in the region for air conditioning and DHW. The comparison is based on the energy consumption that each option needs to provide or extract the same amount of energy to the house. The Table 4 details the thermal installations selected for comparison.

Table 4. Comparative thermal installations

| Thermal installations | Option 1 | Option 2 | Option 3 | Option 4 |
|---|---|---|---|---|
| Heating | Gas heater- RFH[1] | Gas heater- RFH[1] | Electric heater- RFH[1] | GSHP- RFH[1] |
| Cooling | Split AC | Split AC | Split AC | GSHP- RFC[2] |
| DHW | Gas Thermotank | Gas Thermotank | Electric Thermotank | GSHP- Thermotank |
| Energy source 1 | Natural gas | LPG | Grid electricity | Geothermal |
| Energy source 2 | Grid electricity | Grid electricity | - | Grid electricity |

[1] *RFH: radiant floor heating*
[2] *RFC: radiant floor cooling*

The thermal load used for comparison is the same for the four options. The values correspond to those defined according to what is specified in the section 2.2. The energy use in kwh is determined through the degree days for heating, and assuming a daily demand for cooling in summer months and for DHW supply throughout the year.

For systems that operate based on a gas heater, an efficiency of 76% was considered, and for those with an electric heater of 95%. For both cases it was considered an equipment with energy efficiency class A, according to the data published by the Ministry of Energy of the Argentinean Nation [30]. It is assumed that the internal distribution system for heating the house is the same for all the options, which is radiant floor, so a difference in efficiency with respect to this installation is not included among the options presented.

In the case of cooling, it is considered a split air conditioner equipment with a COP of 3.

## 2.7 Calculation of greenhouse gas emissions

The use and promotion of ground source heat pumps is also justified by the decarbonization of the heating sector as a measure of mitigating climate change. Minimal electricity consumption and low Greenhouse Gases (GHG) emissions are the most important reasons why shallow geothermal energy is in vogue today.

The GHG emissions are calculated based on the internationally recognized GHG Protocol [31]. This protocol was created by the World Resources Institute (WRI) and the World Business Council for Sustainable Development (WBCSD) and set the guidelines for carbon accounting.

To analyze the emissions related to the operation of the system studied in this project, an operational control approach is taken, and the boundaries are set at the study site, that is, the air conditioning and DHW system of the analyzed residential building.

The GHG emissions are expressed as carbon dioxide equivalent emissions. This indicator includes the impact of all the GHG as a carbon dioxide equivalent value.

The protocol defines the emissions in categories which are classified between Scope 1, 2 and 3 emissions. This classification is based on whether the emissions and direct or indirect and whether they originated at the analysis site or at another location by third-parties. The operative emissions are included in scope 1 and scope 2 categories. Scope 3 categories are excluded from this analysis. It would be good to include the impact of the production of the equipment and the construction and installation of each alternative, but given the variability of the data found, it was decided to make the comparison considering only the emissions over which there is operational control as a user (S1+S2).

The total emissions are calculated applying an emission factor (kg CO2e/unit) to the functional unit of each category. The emission factors are taken from public and recognized databases.

The climate impact of the system proposed for the climatization and DHW of a dwelling is estimated together with the impact of the more common alternatives implemented in the region to compare and analyze the benefits of the proposed technology. The HVAC technologies considered for the comparison are the same as those defined in section 2.6, see Table 4.

The Table 5 lists the emissions that must be considered to evaluate climate performance based on the equivalent carbon emissions for the GSHP energy facility and the comparative alternatives: air source heat pump for cooling, electrical and gas heaters for heating and DHW production, considering natural gas and LPG as a fuel source.

Table 5. Emission categories included in the analysis.

| Emissions by scope | Description | Activity data | Emission factor |
|---|---|---|---|
| Scope 1 | Direct emissions. | | |
| Fossil fuel use | Emissions from the combustion of fossil fuels in the gas heaters. | Gas consumption in kwh/year | kg CO2e/kwh (LPG and NG) |
| Fugitive emissions | These emissions result from intentional or unintentional releases during the use of refrigeration and air conditioning equipment. | Quantity of refrigerant leakage in kg per year | kg CO2e/kg of released refrigerant |
| Scope 2 | Indirect emissions sources | | |
| Grid electricity | Emissions from the consumption of purchased electricity. | Grid electricity consumption in kwh/year | kg CO2e/kwh |

## 2.8 Economic evaluation

One of the deciding factors to move forward with new technology in the home is the economic convenience of its implementation. An economic evaluation is a way to compare the costs and benefits of different technologies. For this reason, an economic analysis is carried out comparing the economic convenience of the proposed GSHP installation with other conventional thermal installations used in the region. The comparative options are the same as those defined in the previous sections.

For each option it is calculated the annual monetary benefits in terms of the energy savings. Based on this value and the estimated initial investment to install the systems, it is calculated the payback period. The payback period is the number of years needed to recover an investment. It is the amount of time it takes for the cash inflows generated by the investment to equal the initial cost of the investment.

The payback period is a useful tool for evaluating the short-term viability of an investment. However, it does not consider the time value of money or the long-term profitability of the investment. As such, it should be used in conjunction with other financial metrics, such as Return of Investment (ROI), to make informed investment decisions.

Some assumptions to perform the economic evaluation:

- The analysis is carried out considering the US dollar currency (USD). This is because the variability of the Argentinean peso (ARS) is not reliable to make an economic evaluation and it is common practice in the country to reference operations to the US dollar.
- The conversions of the amounts in Argentine pesos to US dollar are done considering the value of the official dollar on 04/24/2023.
- Energy prices in the city of Córdoba are taken from the official sources of supply on 04/24/2023.
- The investment values for each technology are defined considering market values.
- The internal distribution system is not included in the evaluation, considering that it is the same for all the options analyzed.

Once the investment and operating costs for each alternative of thermal installation are estimated, the economic evaluation considering a period of analysis of 10 years is performed. For the economic analysis it is calculated for each comparative option the Net Present Value (NPV), the Return of Investment (ROI) and the payback period.

Net Present Value (NPV) is a financial concept used to determine the current value of an investment's future cash inflows and outflows. It is a discounted cash flow analysis that takes into account the time value of money by applying a discount rate to future cash flows to adjust for inflation and the opportunity cost of capital. In this case, the annual energy savings constitutes the inflows and the initial investment the outflow. Based on these values and with a discount rate of 8% the NPV is calculated.

Return on Investment (ROI) is a financial metric used to measure the profitability of an investment relative to its cost. It is expressed as a percentage and calculated by dividing the net profit or gain from the investment by the investment cost.

The payback period is carried out to determine the time to recover the investment that the proposed option would have, compared with the other options.

These metrics are used in finance and investment analysis to evaluate the feasibility of a project or investment opportunity, and to compare alternative investment options.

# 3. RESULTS

## 3.1 Energy requirement for residential air conditioning and DHW

The energy requirements are determined according to the guidelines defined in section 2.2. The Table 6 details the parameters considered to carry out the energy balances that guarantee the thermal comfort of the living throughout the year.

Table 6. General data for energy balances

| General data | | | |
|---|---|---|---|
| House volume (V) | $m^3$ | 376.8 | |
| N° People | | 4 | |
| **Climate data** | **Unit** | **Winter** | **Summer** |
| Average outdoor temperature (TAVE) | °C | 12.5 | 22.4 |
| Design outdoor temperature (TDO) | °C | -4.3 | 36.6 |
| Design indoor temperature (TDI) | °C | 25.0 | 25.0 |
| $\Delta$T design | °C | 29.3 | 11.6 |

The results obtained for heating are displayed in Table 7. The thermal properties of the enclosures (walls, windows, roof…), are defined considering the maximum thermal transmittance values defined in the IRAM 11.605 standard [22] for a household of class A, which corresponds with the most energy efficient one.

Table 7. Heating – Energy balance

| Heating – Energy balance | | | | |
|---|---|---|---|---|
| Transmission losses (QT) | | | | |
| *Enclosure elements* | *S (m2)* | *K (W/m2. K)* | *$Q_{ti}$ (W)* | |
| Outdoor walls | 161 | 0.33 | 1558 | |
| Windows | 20 | 0.28 | 163 | |
| Outer doors | 10 | 0.28 | 83 | |
| Roof | 65 | 0.28 | 535 | |
| Indoor walls to non-AC spaces | 45 | 0.33 | 434 | |
| *Floor perimeter* | *P (m)* | *K (W/m. K)* | *$Q_{ti}$ (W)* | |
| Floor | 38 | 0.93 | 1035 | |
| QT (W) | | | 3809 | |
| Ventilation losses (QV) | | | | |
| n | 2 | | | |
| QV (W) | | | 7729 | |
| Heating energy demand ($E_H$) | | | | |
| Month | TMED | N°D | °D | Q (kwh) |
| Jan | 24 | 31 | 0 | 0 |
| Feb | 23 | 28 | 0 | 0 |
| Mar | 21 | 31 | 31 | 1172 |
| Apr | 18 | 30 | 120 | 1985 |
| May | 14 | 31 | 248 | 3223 |
| Jun | 11 | 30 | 330 | 3969 |
| Jul | 11 | 31 | 341 | 4101 |
| Aug | 13 | 31 | 279 | 3516 |
| Sep | 15 | 30 | 210 | 2835 |
| Oct | 19 | 31 | 93 | 1758 |
| Nov | 21 | 30 | 30 | 0 |
| Dec | 23 | 31 | 0 | 0 |
| HEATING- SUMMARY | | | | |
| Degree days | °D | 2357 | | |
| Volumetric coefficient of heat losses | G | 1.04 | W/m3K | |
| Heating thermal load | $Q_H$ | 11.5 | kW | |
| Energy demand | $E_H$ | 22275 | kWh | |

The IRAM 11.604 [21] standard defines that the calculated volumetric coefficient (G) must be less than or equal to the value admissible by the standard ($G_{adm}$). For the household volume and the degree days value, the standard defines a $G_{adm}$ of 1.5 W / $m^3$.K, according to the data presented in Table 7 this value is corroborated.

The results obtained for cooling are presented in Table 8.

Table 8. Cooling – Energy balance

| Cooling – Energy balance | | | |
|---|---|---|---|
| Transmission losses (QT) | | | |
| Enclosure elements | S (m2) | K (W/m2. K) | Qti (W) |
| Outdoor walls | 161 | 0.33 | 617 |
| Windows | 20 | 0.28 | 64 |
| Outer doors | 10 | 0.28 | 33 |
| Roof | 65 | 0.28 | 212 |
| Indoor walls to non-AC spaces | 45 | 0.33 | 172 |
| QT (W) | | | 1098 |
| Ventilation losses (QV) | | | |
| Flow rate per person | $N_r$ | 15 | $m^3$/h.person |
| Flow rate of air renovation | $q_{air}$ | 60 | $m^3$/h |
| Factor 1[1] | F1 | 0.25 | Wh/ $m^3$°C |
| Factor 2[2] | F2 | 0.61 | $Whkg_{dryair}/m^3g$ |
| Humidity difference[3] | ΔH | 3.0 | $g_{water}/g_{dryair}$ |
| QV (W) | | 283.8 | W |
| Solar energy inputs (QS) | | | |
| Windows surface | $S_W$ | 19.81 | $m^2$ |
| Solar irradiance | $I_S$ | 274 | W/$m^2$ |
| Solar exposure | $F_E$ | 0.89 | |
| QS (W) | | 4828.4 | W |
| Energy inputs from inner sources (QI) | | | |
| Metabolic heat emitted by people | $Q_m$ | 47 | W/person |
| Thermal load due to people | $Q_p$ | 188 | W |
| Lighting thermal energy | $q_l$ | 10 | W/$m^2$ |
| Lighting area | $S_l$ | 136.1 | $m^2$ |
| Thermal coefficient | $C_{tl}$ | 1.25 | |
| Thermal load due to lighting | $Q_l$ | 1701.6 | W |
| N° of equipment[4] | | 10 | |
| Thermal energy per equipment | $q_e$ | 300 | W/unit |
| Thermal load due to equipment | $Q_e$ | 3000 | W |
| Energy inputs from inner sources | QI | 4889.6 | W |
| Cooling energy demand ($E_C$) | | | |
| Month | N°D | Cooling time (h/d) | Q (kwh) |
| Jan | 31 | 6 | 2065 |
| Feb | 28 | 4 | 1243 |
| Mar | 31 | 2 | 688 |
| Apr | 30 | 0 | 0 |
| May | 31 | 0 | 0 |
| Jun | 30 | 0 | 0 |

| | | | | |
|---|---|---|---|---|
| Jul | 31 | | 0 | 0 |
| Aug | 31 | | 0 | 0 |
| Sep | 30 | | 0 | 0 |
| Oct | 31 | | 2 | 688 |
| Nov | 30 | | 4 | 1332 |
| Dec | 31 | | 6 | 2065 |
| COOLING- SUMMARY | | | | |
| Volumetric coefficient of heat losses | G | 29.5 | W/m3K | |
| Cooling thermal load | $Q_C$ | 11.1 | kW | |
| Energy demand | $E_C$ | 8081 | kWh | |

*1 Relation between the air specific heat at 21°C and relative humidity of 50% and the specific volume of the same mixture*
*2 Relation between the average heat yielded by the condensation of 1g of water vapor and the specific volume of the same mixture.*
*3 Difference between the specific humidity of outdoor and indoor air*
*4 Average thermal energy including common equipment such as refrigerator, TV, computer, vacuum cleaner, washing machine.*

For the case of DHW supply, the calculated values are presented in Table 9.

Table 9. DHW energy requirement

| DHW energy requirement | | |
|---|---|---|
| General data | | |
| DHW consumption | 55 | L/day.person |
| Occupation | 4 | people/house |
| DHW consumption | 220 | L/day.house |
| $T_{DHW}$ | 60 | °C |
| Specific heat (c) | 4.187 | kJ/kg.°C |
| Water density | 1000 | kg/m3 |
| GSHP energy requirement | | |
| $T_{ext. average}$ | 18 | °C |
| $T_{DHW -step 1}$ | 50 | °C |
| $E_{DHW}$ | 10835 | MJ/year |
| $E_{DHW}$ | 3010 | kWh/year |
| Accumulator additional energy requirement | | |
| $T_{DHW -step 1}$ | 50 | °C |
| $T_{DHW -step 2}$ | 60 | °C |
| $E_{DHW}$ | 3360 | MJ/year |
| $E_{DHW}$ | 933 | kWh/year |

## 3.2 Engineering design: heat pump

### *3.2.1 Sizing*

The sizing of the heat pump is carried out considering the thermal load previously defined to maintain the comfort of the house throughout the year and provide the required amount of DHW.

The refrigerant selected for the analysis is R410A. This selection is because it is one of the most widely used refrigerants in domestic applications. The thermodynamics properties of the refrigerant are detailed in the Table 10.

Table 10. R410A Thermodynamics properties

| R410A Thermodynamics properties | | | |
|---|---|---|---|
| Saturation temperature and pressure[1] | | | |
| Condenser temperature | $T_{cond}$ | 45 | “C |
| Evaporator temperature | $T_{evap}$ | 10 | “C |
| Condenser pressure | $P_{cond}$ | 1082 | kPa |
| Evaporator pressure | $P_{evap}$ | 2717 | kPa |
| Condenser real pressure[2] | $P_{Rcond}$ | 974 | kPa |
| Evaporator real pressure[2] | $P_{Revap}$ | 2853 | kPa |
| R410 – Thermodynamic properties – Enthalpy [3] | | | |
| Saturated vapor | h1 | 424 | kJ/kg |
| Superheated vapor | h2 | 450 | kJ/kg |
| Saturated liquid | h3 | 281 | kJ/kg |
| Liquid-vapor mix | h4 | 281 | kJ/kg |

*[1] Evaporator and condenser values of pressure and temperature set based on normal values applied in GSHP for R410A.*
*[2] The saturation pressure values are adjusted considering a pressure drop of 10% of the absolute working pressure in the evaporator and 5% in the condenser.*
*[3] Source: [32].*

The

Table 11 and Table 12 detail the heat pump sizing results obtained for heating and cooling mode. The calculations were done following the guidelines described in section 2.4.

Table 11. Heat Pump Sizing- Heating

| HP Sizing-Winter | | | |
|---|---|---|---|
| Condenser thermal load[1] | $Q_{cond}$ | 11.5 | kW |
| Specific condenser thermal load | $q_{cond}$ | 169 | kJ/kg |
| Specific evaporator thermal load | $q_{evap}$ | 143 | kJ/kg |
| Specific compressor workload | $w_{comp}$ | 26 | kJ/kg |
| Refrigerant mass flow rate | $m_{ref}$ | 0.07 | kg/s |
| Compressor workload | $W_{comp}$ | 1.8 | kW |
| Evaporator thermal load | $Q_{evap}$ | 9.8 | kW |
| Ideal coefficient of performance | $COP_{ideal}$ | 6.5 | |
| Real coefficient of performance[2] | $COP_{real}$ | 4.7 | |

[1] *Equivalent to the heating thermal load.*
[2] *Considering a mechanical and electrical efficiency of 85% for the compressor.*

Table 12. Heat Pump Sizing- Cooling

| HP Sizing-Winter | | | |
|---|---|---|---|
| Evaporator thermal load[1] | $Q_{evap}$ | 11.1 | kW |
| Specific condenser thermal load | $q_{cond}$ | 143 | kJ/kg |
| Specific evaporator thermal load | $q_{evap}$ | 169 | kJ/kg |
| Specific compressor workload | $w_{comp}$ | 26 | kJ/kg |
| Refrigerant mass flow rate | $m_{ref}$ | 0.07 | kg/s |
| Compressor workload | $W_{comp}$ | 2.02 | kW |
| Condenser thermal load | $Q_{cond}$ | 13.1 | kW |
| Ideal coefficient of performance | $COP_{ideal}$ | 5.5 | |
| Real coefficient of performance[2] | $COP_{real}$ | 4.5 | |

[1] *Equivalent to the cooling thermal load.*
[2] *Considering a mechanical and electrical efficiency of 85% for the compressor.*

### *3.2.2 Equipment selection*

Based on the previous sizing, the heat pump module is selected considering the equipment available at the local market. Table 13 presents the characteristics of a heat pump model that fits the requirement of the current case study. A model of the equipment is presented in Figure 16 and Figure 17 shows the typical performance curves for the selected GSHP.

Table 13. Heat Pump Selection. Source: EcoForest [33].

| HP Selection | |
|---|---|
| Model | EcoGEO+ B3/C3 3-12[1] |
| Manufacturer | Ecoforest |
| Technology | Inverter + scroll compressor |
| Type | Water-water, GSHP |
| Application | Heating, cooling, DHW |
| Refrigerant | R410A |
| Heating power output | 2.5-16 kw |
| $COP_{heating}$ | 4.6 |
| Cooling power output | 3.1-15 kw |
| EER | 5.2 |
| Max. DHW temperature without / with support | 63/70 |
| Max. consumption | 5 kW/7.2 A |

| | |
|---|---|
| Dimensions (height x width x depth) | 1060 x 600 x 710 mm |


Figure 16. Ecoforest Ground Source Heat Pump thermal installation. Source: [33]

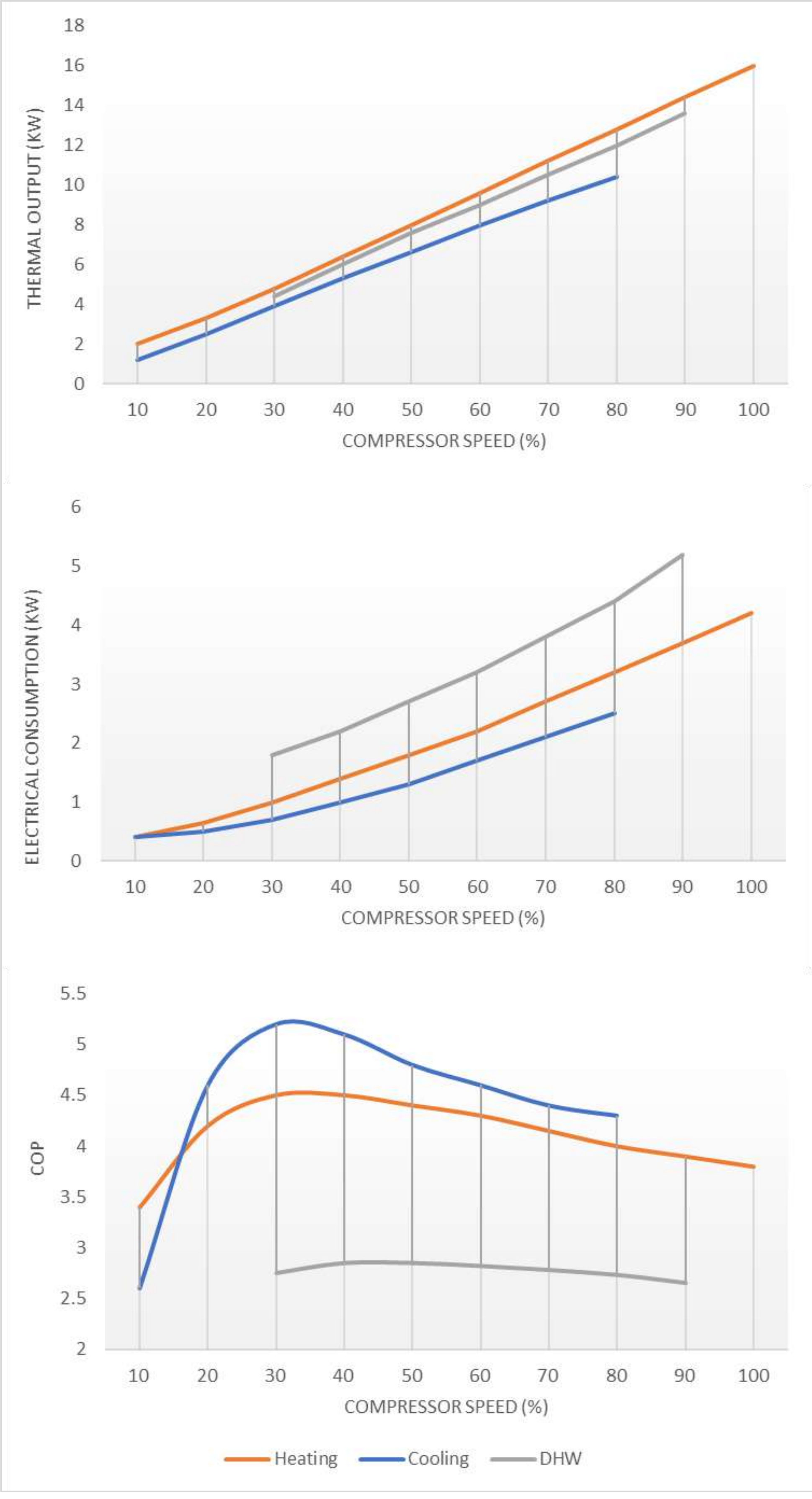



Figure 17. GSHP performance curves. Source: own elaboration with data taken from [33]

### 3.3 Engineering design: geothermal heat exchanger

#### *3.3.1 Piping specifications*

If the pipe material had to be selected based on its capacity to maximize heat exchange, a metal pipe would be chosen. However, corrosion problems and the high cost of these materials make this option not suitable for an HGHE. The versatility of plastic materials and their appropriate thermal conductivity make them the most suitable materials for this application. In this case 40 mm HDPE pipe is chosen, this selection is based on its wide use in similar applications. Pipe properties are listed in Table 14 and an illustration of the piping is showed in Figure 18.

Table 14. Piping specifications. Source: TIGRE products brochure [34].

| Piping specifications | | | |
|---|---|---|---|
| Material | HDPE | | |
| Diameter | D | 40 | mm |
| Thickness | t | 2 | mm |
| Standard Dimension Ratio | SDR | 21 | |
| Nominal Pressure | NP | 8 | MPa |

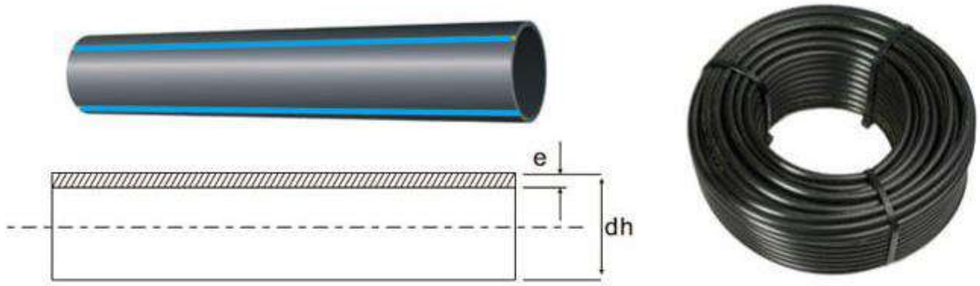



Figure 18. HDPE piping for HGHE. Source: [34].

#### *3.3.2 Heat carrier fluid temperatures design*

The GHE design is performed based on the dimensions that allow the required thermal load to be extracted or transferred to the ground. To implement the sizing methodologies, it is necessary to know the difference in temperatures of the inlet and outlet of the exchanger. The delta of temperatures is calculated based on the amount of energy that is required to exchange with the ground and the heat capacity of the carrier fluid.

Selecting the design inlet water temperature is an iterative process. The key is to find the balance between the supply water temperature, which improves heat pump performance as it is lowered and ground loop size, which for the heating mode becomes larger and more costly as the supply water temperature is decreased. Raising the temperature will have the opposite effect. A good starting point is the supply fluid temperature should be 1-7°C warmer than the undisturbed ground temperature for cooling and 7-12°C colder for heating (McQuay International, 2002) [35].

The ground temperature is defined for the depth of 2 m, as detailed in section 0.

The water flow rate is also an iterative process. Lower flow rates will reduce the pump and piping size, but they will also de-rate the performance of the heat pump [35]. Based on experiences collected from literature, it is proposed a water flow rate of 1.5 $m^3$/h.

The thermal load that is exchanged with the ground in cooling mode corresponds to the thermal load of the heat pump condenser ($Q_{cond}$) and, in heating mood, this load corresponds to that of the evaporator ($Q_{evap}$).

The Table 15 presents the proposed temperature values for the GHE inlet and the obtained ones for the outlet in cooling and heating mode.

Table 15. GHE inlet and outlet temperatures

| GHE inlet and outlet temperatures | | | | |
|---|---|---|---|---|
| Parameters | | Summer | Winter | |
| Thermal load | $Q_{cond}/Q_{evap}$ | 13118 | 9762 | W |
| Ground temperature | $T_{soil}$ | 23.0 | 18.0 | °C |
| GHE outlet temperature | $T_{f,out}$ | 30.0 | 10.0 | °C |
| Difference of temperatures | $\Delta T$ | 7.5 | 5.6 | °C |
| GHE inlet temperature | $T_{f,in}$ | 37.5 | 4.4 | °C |

*A specific heat capacity (Cp) for water of 4184 J/kg.K was taken for calculations and the fluid flow rate is 0.4 kg/s.*

### *3.3.3 Sizing*

*Multidimensional steady heat transfer. Results.*

This analytical solution to estimate the required length for the GHE is performed following the equations defined in the section of Multidimensional steady heat transfer inside the title 2.5.2.

The pipe depth is defined at 2 meters below the surface.

The calculation is done for the case of the heating and cooling mode of the thermal installation. The Table 16 details the results.

Table 16. GHE sizing. Methodology: multidimensional steady heat transfer

| GHE sizing. Methodology: multidimensional steady heat transfer. | | | | |
|---|---|---|---|---|
| Parameters | | | | |
| Nusselt number | Nu | 119 | | |
| Reynold number | Re | 16325 | | |
| Prandtl number | Pr | 7.2 | | |
| Convection coefficient | $h_f$ | 1726 | W/m$^2$K | |
| Pipe thermal conductivity | $K_{pipe}$ | 0.48 | W/mK | |
| Soil thermal conductivity | $k_{soil}$ | 0.80 | W/mK | |
| Conduction shape factor | S | 1.19 | | |
| Thermal resistances | | | | |
| Convection resistance | $R_{conv}$ | 5.1E-3 | mK/W | |
| Pipe resistance | $R_{pipe}$ | 3.5E-2 | mK/W | |
| Soil resistance | $R_{soil}$ | 1.05 | mK/W | |
| Total resistance | $R_{total}$ | 1.09 | mK/W | |
| Temperatures | | Winter | Summer | |
| Inlet temperature difference | $\theta_{f,in}$ | 13.6 | 14.5 | °C |
| Outlet temperature difference | $\theta_{f,out}$ | 8.0 | 7.0 | °C |
| GHE length | | | | |
| Length | $L_{GHE}$ | 1012 | 1392 | m |

As can be seen in Figure 19 and Figure 20, the design method is affected by the length of the pipe and the fluid velocity. The length of the pipe determines the surface area available for heat transfer. As the length of the pipe increases, the surface area for heat transfer also increases, which increases the overall heat transfer rate. However, longer pipes can also increase the pressure drop and increase the cost of the heat exchanger.

The fluid velocity affects the convective heat transfer coefficient between the heat transfer fluid and the piping walls. As the fluid velocity increases, the convective heat transfer coefficient also increases, which can increase the overall heat transfer rate. However, higher fluid velocities can also increase the pressure drop, increase the pumping power required, and increase the cost of the heat exchanger.

By adjusting the pipe length and fluid velocity, it is possible to optimize the heat exchanger design to achieve the desired heat transfer rate while minimizing the cost and pressure drop.

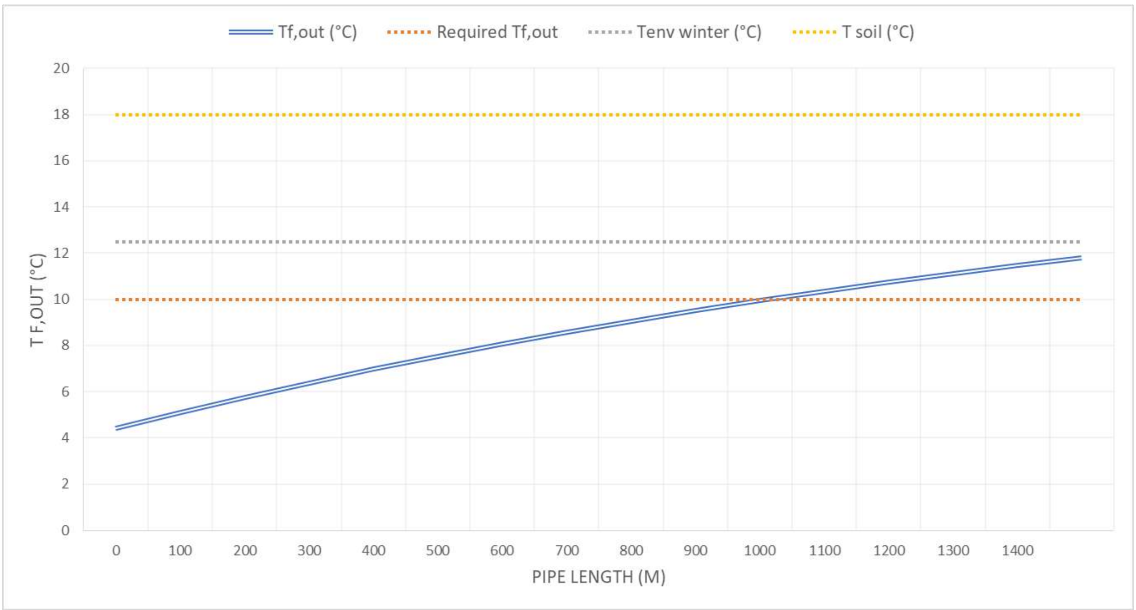



Figure 19. GHE fluid outlet temperature vs pipe length in heating conditions

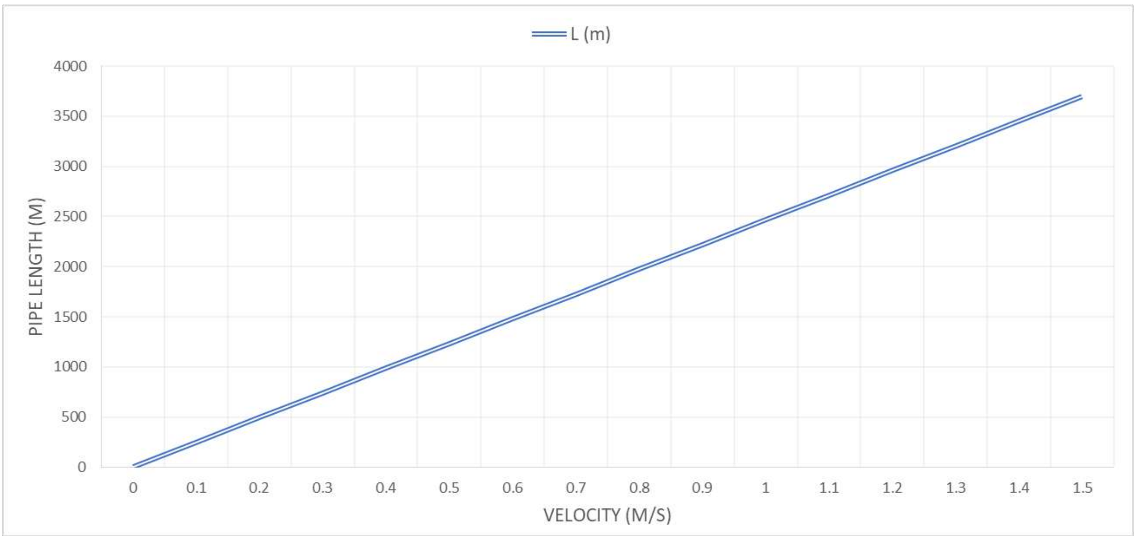



Figure 20. GHE pipe length vs fluid velocity inside the pipe in heating conditions

*Numerical Modelling. Results.*

The analytical solutions obtained in the previous sections for the steady case are corroborated through numerical simulation using the SolidWorks Flow Simulation tool.

Once the solver completes the calculations, according to the steps defined in the section *Numerical modelling*, the simulation tool provides various types of graphical and numerical results which are useful to evaluate the thermal performance of the design and make necessary changes to optimize it.

The simulation was run on the U-pipe layout evaluating a shorter pipe length (100m), for practical simulation reasons. The Figure 19 shows the thermal results obtained from simulation. The outlet temperature of the heat exchangers coincides with the values calculated by analytical methods for the same length, which supports the applied analytical methods.

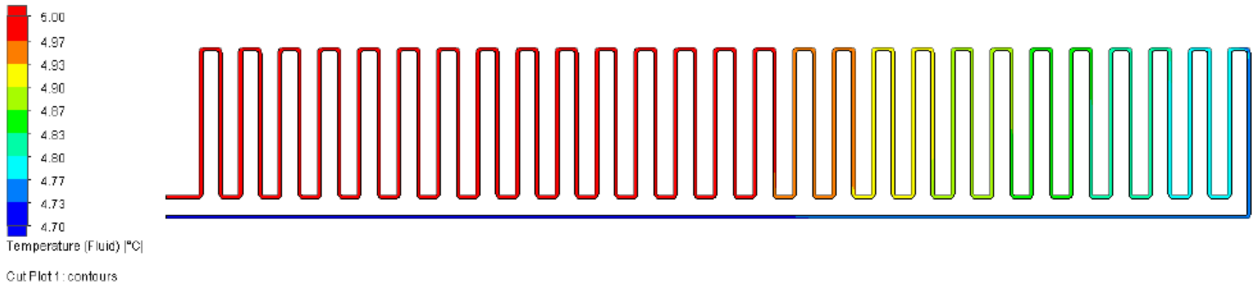


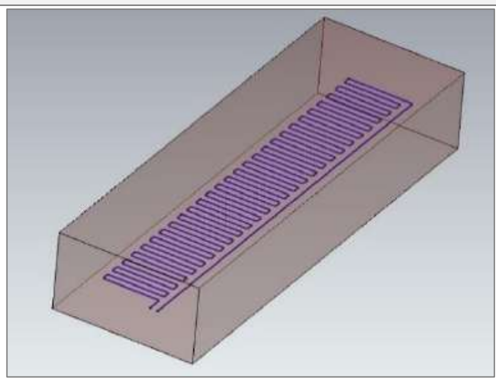

Figure 21. Thermal fluid simulation, heating mode, 100m length. Source: SolidWorks Flow Simulation

*Heat exchanger layout design*

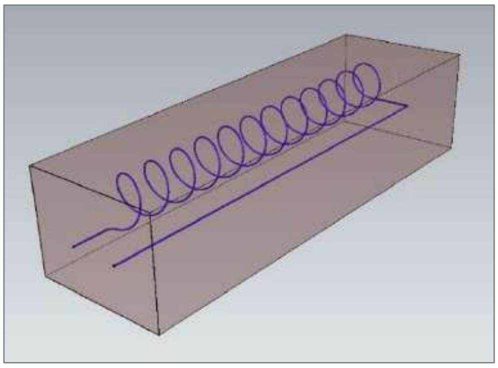
The pipe length considered for the HGHE design is the maximum value obtained from previous calculations, which corresponds to 1392 m for the cooling case. The selection of the GHE layout depends on a combination of factors, including the available space, soil conditions, climate, heating and cooling load, and budget.

For the case of analysis, two options are proposed to set the horizontal GHE in parallel trenches, see Table 17. Layout 1 proposes the setting of the piping following a U-pipe shape and the Layout 2 follows a horizontal spiral shape. This last configuration is known as "slinky coil" and offers a space reduction of around 40% compared to other configurations.

Table 17. GHE layout design. Layout options.

| Layout 1: Connection in series (U-pipe) | | | | |
|---|---|---|---|---|
| N° Trenches | $N_t$ | 5 | |  |
| Trench width | wt | 1.5 | m | |
| Separation btw trenches | $d_t$ | 1 | m | |
| U-pipe width | w | 0.2 | m | |
| U-pipe length | l | 3.2 | m | |
| N° U-pipe/trench | $N_U$ | 78 | | |
| Trench width | $W_{trench}$ | 1.5 | m | |
| Total width | W | 11.5 | m | |
| Trench length | $L_t$ | 37 | m | This layout does not fit into the available space. |
| Total occupied area | A | 423 | m$^2$ | DISCARDED OPTION |

| Layout 2: Slinky coil - Horizontal | | | |
|---|---|---|---|
| **Option 1** | | | |
| N° Trenches | $N_t$ | 5 | |
| Trenches distance | $d_t$ | 0.8 | m |
| Coil diameter | $D_c$ | 0.8 | m |
| Trench depth | z | 2 | m |
| N° coils/trench | $N_c$ | 84 | |
| Trench width | $W_{trench}$ | 0.8 | m |
| Total width | W | 7.2 | m |
| Trench length | $L_t$ | 34 | m |
| Total occupied area | A | 245 | $m^2$ |
| **Option 2** | | | |
| N° Trenches | $N_t$ | 10 | |
| Trenches distance | $d_t$ | 0.8 | m |
| Coil diameter | $D_c$ | 0.8 | m |
| Trench depth | z | 2 | m |
| N° coils/trench | $N_c$ | 42 | |
| Trench width | $W_{trench}$ | 0.8 | m |
| Total width | W | 15.2 | m |
| Trench length | $L_t$ | 17.2 | m |
| Total occupied area | A | 261.4 | $m^2$ |



The coils are superimposed on each other, as shown in the image below.

The layout selected for the case of analysis is the horizontal slinky coil. It can be set in different numbers or parallel trenches, depending on the layout of the house on the lot and the land available. Figure 22 shows the schemes of the horizontal slinky coil layout option 1 and 2 set on the lot of 500m2 and arranged next to the analyzed household building.

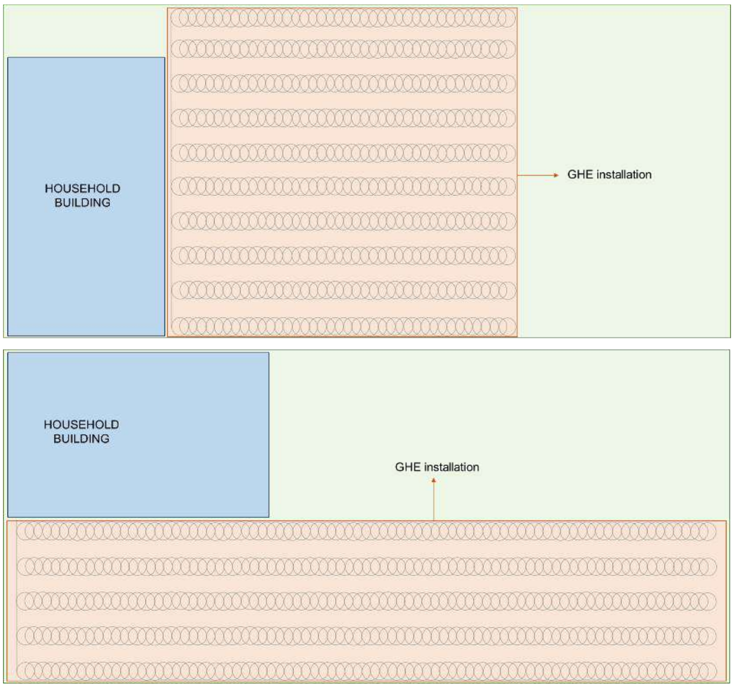



Figure 22. Slinky Coil HGHE installation possibilities

*Circulating pumping. Results.*

The pressure drop due to circulation is carried out according to the guidelines defined in the section *Circulation pumping* into the title 2.5.2 and the results are detailed in Table 18. The circulating pump selection is performed for the GHE option that contemplates five parallel trenches.

Table 18. Sizing of the circulator pump.

| Sizing of the circulating pump. | | | |
|---|---|---|---|
| Reynold number | Re | 3265 | |
| Relative roughness | e/D | 4E-4 | |
| Friction factor | f | 0.04 | |
| Length of the pipe | L | 1392 | m |
| Length per parallel trench | Lt | 278 | m |
| Equivalent length for coiled piping | Le | 167 | m |
| Fluid velocity | V | 0.4 | m/s |
| Gravity constant | g | 9.8 | $m/s^2$ |
| Head loss | $h_L$ | 3.8 | m |
| Pressure drops | p | 37 | kPa |

The Figure 23 shows the dependency between the velocity of circulation and the required pump power. As the total length that the fluid must travel increases, the power required to do so also increases. A layout with parallel piping arrangement, such as the one proposed, decreases the required circulation power.

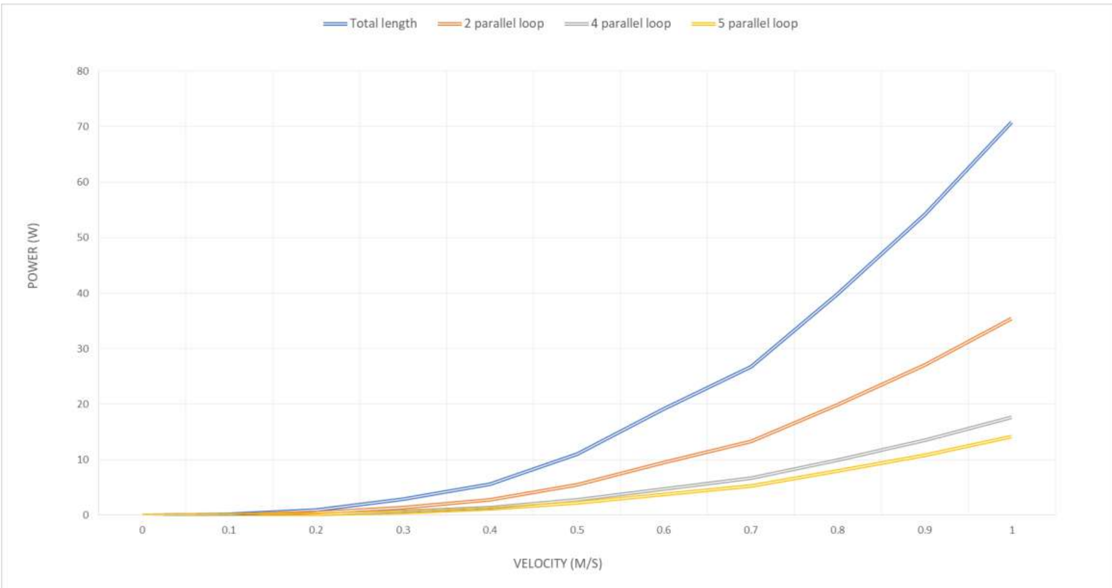



Figure 23. Pump power vs velocity and GHE length

The selection of the pump is made considering the theoretical data defined in Table 18 and comparing with the pumps available on the market to select the one that best suits the application. For this case of study, the pump selection was performed using the tool available on Grundfos website. Table 19 lists the pump details and the Figure 24 presents the corresponding performance curves.

Table 19. Selection of the circulating pump

| | |
|---|---|
| Application | Circulator pump |
| Product name | ALPHA1 20-60 N 150 |
| Manufacturer | Grundfos |
| Actual calculated flow | 1.53 m³/h |
| Resulting head of the pump | 3.934 m |
| Range of ambient temperature | 0-40 °C |
| Maximum operating pressure | 10 bar |
| Pressure rating for connection | PN10 |
| Size of connection | 11/4 in |
| Pumped liquid | Water |
| Liquid temperature range | 0-110 °C |
| Power input | 34 W |


*Source: Grundfos website [36].*

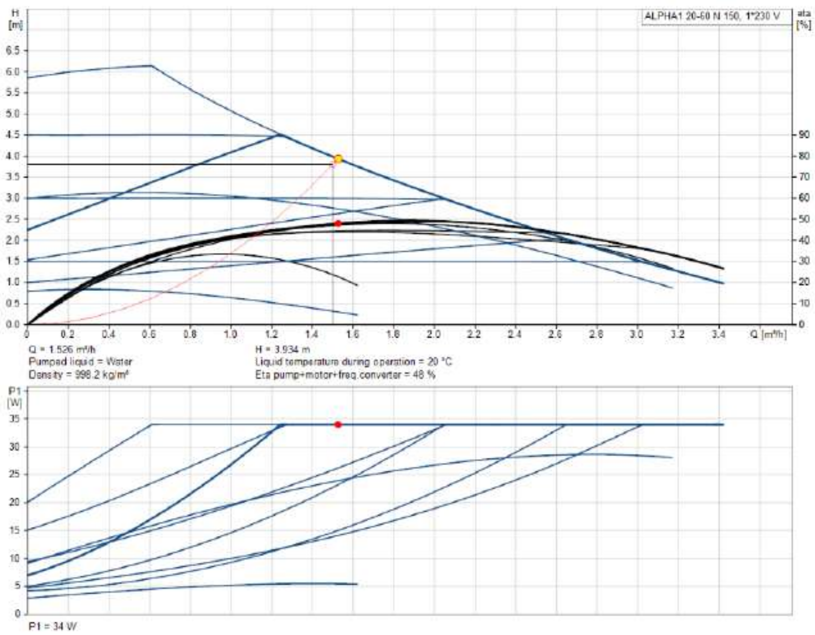



Figure 24. Performance curves of the circulator pump. Source: [36].

## 3.4 System COP

To estimate the system coefficient of performance, must be considered the total power demand respect to the thermal load to supply. The Table 20 resumes the obtained values.

Table 20. System COP

| System COP | | | |
|---|---|---|---|
| Parameters | Heating | Cooling | |
| Thermal load | 11.54 | 11.1 | kw |
| Heat pump compressor | 2.46 | 2.49 | kw |
| GHE circulator pump | 0.04 | 0.04 | kw |
| Total power demand | 2.49 | 2.53 | kw |
| COP | 4.6 | 4.4 | |

### 3.5 Energy demand

The energy demand is calculated for each one of the air conditionings and DHW supply options defined in section 2.6. This will make it possible to buy the options and evaluate the energy efficiency of each one to supply the same thermal demand. Table 21 defines the annual energy demand calculated to keep the thermal comfort and supply the DHW for the household of analysis and the Table 22 presents the annual energy use required for each thermal installation option.

Table 21. Annual energy demand

| Annual energy demand (kWh/year) | |
|---|---|
| Heating | 22558 |
| Cooling | 8081 |
| DHW | 3010 |

Table 22. Comparison of energy demand for each alternative option

| Thermal installations | Option 1 | Option 2 | Option 3 | Option 4 |
|---|---|---|---|---|
| Equipment | | | | |
| Heating | Gas heater- RFH | Gas heater- RFH | Electric heater- RFH | GSHP-RFH |
| Cooling | Split AC | Split AC | Split AC | GSHP-RFC |
| DHW | Gas Thermotank | Gas Thermotank | Electric Thermotank | GSHP-Accumulator |
| Energy sources | | | | |
| Energy source 1 | Natural gas | LPG | Grid electricity | Geothermal |
| Energy source 2 | Grid electricity | Grid electricity | - | Grid electricity |
| Energy use (kWh/year) | | | | |
| Heating | 29682 | 29682 | 23745 | 4872 |
| Cooling | 2694 | 2694 | 2694 | 1839 |
| DHW | 3960 | 3960 | 3168 | 1583 |
| Total energy use (kWh/year) | 36335 | 36335 | 29607 | 8294 |

Figure 25 shows the total expected annual energy consumption for the three proposed comparative options. The option based on gas and electricity represents the highest energy consumption, followed by the fully electric installation. The thermal installation based on the GSHP assumes an annual electricity consumption of 8294 kWh, which means an energy saving of more than 70% compared to the other options.

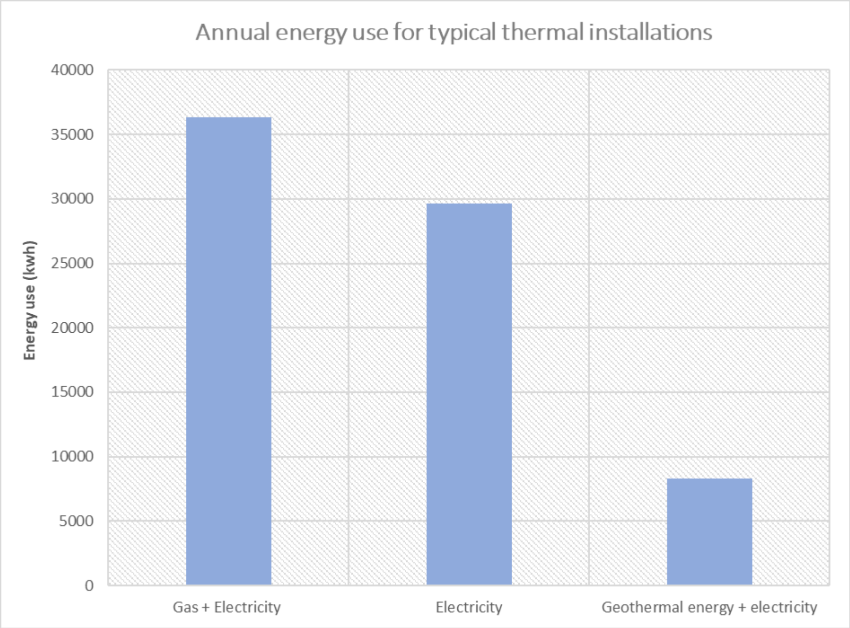



Figure 25. Annual energy use for typical thermal installations systems

### 3.6 Greenhouse gas emissions

The GHG emissions estimation for each thermal installation alternative is done considering the activity data defined in the previous section in kWh/year for each energy source (3.5) and the fugitive emissions are determined for the same refrigerant and load. This activity data is then affected by a proper emission factor that indicates the emissions generated per unit of activity as mass of equivalent carbon dioxide [kg CO2eq/unit]. The Table 23 below indicates the activity data and the emission factor taken for each case.

Table 23. Parameters of the GHG emissions calculation

| ACTIVITY DATA by thermal installation alternative | | | |
|---|---|---|---|
| Thermal installation alternative | Fugitive emissions (kg/year) | Gas consumption (kwh/year) | Electricity use (kwh/year) |
| Option 1 | 0.03 | 33642 | 2694 |
| Option 2 | 0.03 | 33642 | 2694 |
| Option 3 | 0.03 | 0 | 29607 |
| Option 4 | 0.03 | 0 | 8294 |
| EMISSION FACTOR (EF) by activity unit | | | |
| Activity unit | Emission Factor (kg CO2eq) | EF Source | |
| Fugitive emissions R410A (kg) | 2087.5 | GWP IPCC AR4 [37] | |
| Natural gas (kwh) | 0.19 | UK DEFRA (2021) [38] | |
| LPG (kwh) | 0.23 | UK DEFRA (2021) [38] | |
| Grid electricity (kwh) | 0.46 | Sec. de Energía de la Nación (2021) [39] | |

Table 24 details the total emissions as tonnes of CO2 equivalent expected for each thermal installation alternative and the carbon intensity of each technology. The carbon intensity reflects the climate impact of each technology considering the same energy demand.

Figure 26 shows the climate impact associated to each thermal installation options.

Table 24. Total emissions by HVAC alternative

| Carbon emissions by scope | Carbon emissions by HVAC alternative | | | |
|---|---|---|---|---|
| | Option 1 | Option 2 | Option 3 | Option 4 |
| SCOPE 1 | | | | |
| Stationary combustion | 6.22 | 7.70 | 0.00 | 0.00 |
| Fugitive emissions | 0.05 | 0.05 | 0.05 | 0.05 |
| SCOPE 2 | | | | |
| Grid electricity | 1.24 | 1.24 | 13.59 | 3.81 |
| TOTAL EMISSIONS (tn CO2eq/ year) | 7.51 | 8.99 | 13.64 | 3.86 |
| CARBON INTENSITY (kg CO2eq/kwh) | 0.22 | 0.26 | 0.39 | 0.11 |

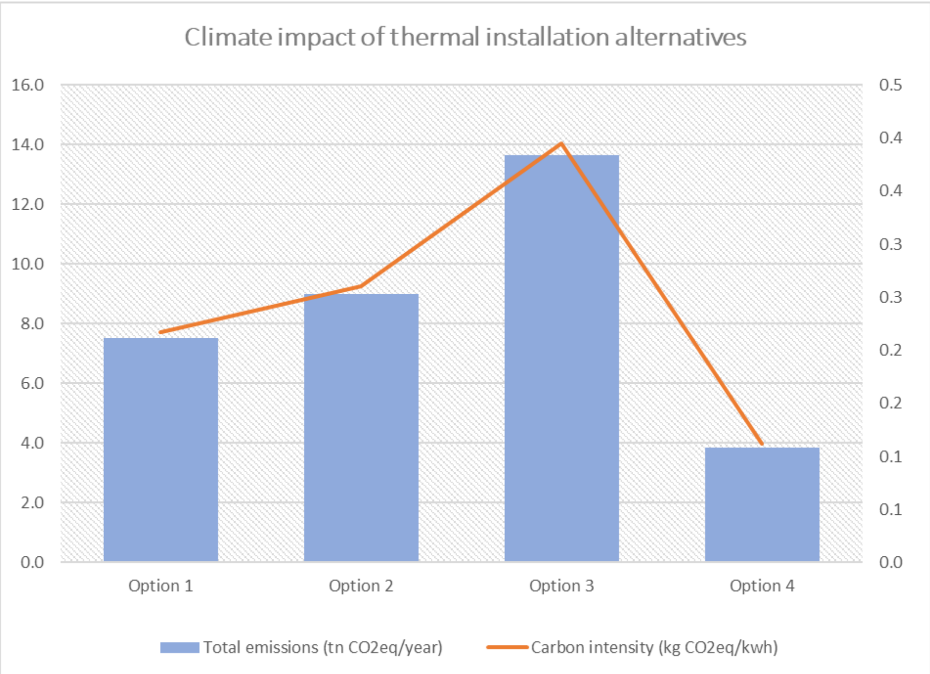



Figure 26. Climate impact of HVAC alternatives

The GSHP facility offers the less intensive technology to provide heating, cooling and DHW for the residential building of analysis. The greater climate impact is derived from an electricity-based facility. This is mainly because of the dependence of the carbon intensity of the electricity grid. If the provision of electrical energy were 100% from renewable sources, the carbon intensity would be much lower. The gas-based alternatives have a better performance, but the inherent emissions linked to the fossil fuels combustion increase the climate impact.

### 3.7 Economic evaluation

An economic analysis is carried out comparing the thermal installations mentioned in the previous sections. Firstly, the total investment cost for the GSHP installation is estimated. This estimation is based on local market values and does not include the cost of the internal energy distribution system. The Table 25 details the cost of each item contemplated in the estimation.

Table 25. Investment cost of a thermal installation based on a GSHP (Option 4).

| Item N° | Detail | Cost/unit (USD inc. VAT) | Unit | Quantity | Total cost (USD inc. VAT) |
|---|---|---|---|---|---|
| 1 | Equipment | | | | |
| 1.1 | Heat Pump | $ 10558 | Gl. | 1 | $ 10558 |
| 1.2 | Hot water accumulator | $ 3760 | Gl. | 1 | $ 3760 |
| 1.3 | Installation | $ 1056 | Gl. | 1 | $ 1056 |
| 2 | GHE | | | | |
| 2.1 | Piping HDPE D 40mm | $ 11 | m | 1715 | $ 1575 |
| 2.2 | Manifold + accessories | $ 194 | Gl. | 1 | $ 157 |
| 2.3 | Trench construction | $ 263 | day | 2 | $ 526 |
| 2.4 | Circulation pump | $ 652 | un. | 2 | $ 1303 |
| 2.2 | Installation | $ 246 | day | 2 | $ 493 |
| | TOTAL INVESTMENT COST in USD (inc. VAT) | | | | $ 15667 |

Although this work focuses on the design of a horizontal GHE, for a comparison matter was made the estimation of the investment cost associated with a vertical GHE to meet the same thermal load demand. The investment cost is around 35.106 USD, which the double of the one for the horizontal system.

For the case of gas-based equipment, the same equipment is considered for the case of Natural Gas and LPG. It is assumed that the house has a connection to the natural gas network, otherwise, the connection cost must be included in the investment cost. Currently it is estimated in approximately 3.319 USD the cost of connecting a house to the natural gas network.

Table 26. Comparative investment costs with alternative thermal installations

| Option 1/Option 2 | | |
|---|---|---|
| Thermal installation | Equipment | Cost (USD inc. VAT) |
| Heating | Gas heater | $ 738 |
| Cooling | Split AC | $ 2.941 |
| DHW | Gas heater | $ 738 |
| Option A- TOTAL INVESTMENT COST | | $ 4.416 |
| Option 3 | | |
| Thermal installation | Equipment | Cost (USD inc. VAT) |
| Heating | Electric heater | $ 452 |
| Cooling | Split AC | $ 2.942 |
| DHW | Electric heater | $452 |
| Option B- TOTAL INVESTMENT COST | | $3.846 |

The operating costs of each thermal installation depends primarily on the cost of the energy source to which each thermal technology is associated. For this analysis, the same scenario proposed in section 3.5 and 3.6 is analyzed, in which the GSHP-based installation is compared to an alternative that works based on natural gas and electricity, another LPG and electricity and another that is provided by 100% grid electricity. In the case of the thermal installation based on a GSHP, it is assumed that the external work will be carried out on grid electricity.

Table 27. Comparative operative costs with alternative thermal installations

| ALTERNATIVE THERMAL INSTALLATIONS | | Option 1 | Option 2 | Option 3 | Option 4 |
|---|---|---|---|---|---|
| HEATING | Technology | Gas heater- RFH | Gas heater- RFH | Electric heater- RFH | GSHP- RFH |
| | Energy source | Natural Gas | LPG | Electricity | Electricity |
| | Annual use (kwh) | 29682 | 29682 | 23745 | 4872 |
| | Total cost (inc. VAT)[1] | $ 219 | $ 3472 | $3102 | $637 |
| DHW | Technology | Gas Thermotank | Gas Thermotank | Electric Thermotank | GSHP- Accumulator |
| | Energy source | Natural Gas | LPG | Electricity | Electricity |
| | Annual use (kwh) | 3960 | 3960 | 3168 | 1583 |
| | Total cost (inc. VAT)[1] | $ 29 | $463 | $ 414 | $207 |
| COOLING | Technology | Split AC | Split AC | Split AC | GSHP- RFC |
| | Energy source | Electricity | Electricity | Electricity | Electricity |
| | Annual use (kwh) | 2694 | 2694 | 2694 | 1839 |
| | Total cost (inc. VAT)[1] | $ 352 | $ 352 | $ 352 | $240 |
| TOTAL OPERATIVE COST (inc. VAT) | | $ 600 | $ 4288 | $ 3868 | $ 1084 |

[1] *Electricity price: 0.13 USD/kwh, inc. VAT. Source: EPEC, April 2023 [40].*
*Natural gas price: 0.01 USD/kwh, inc. VAT. Source: ECOGAS, April 2023 [41].*
*LPG price: 0.12 USD/kwh, inc. VAT. Source: distributors from local market, April 2023.*

The Figure 27 shows the estimated investment and operative costs for the GSHP-based thermal installation compared to the alternative options.

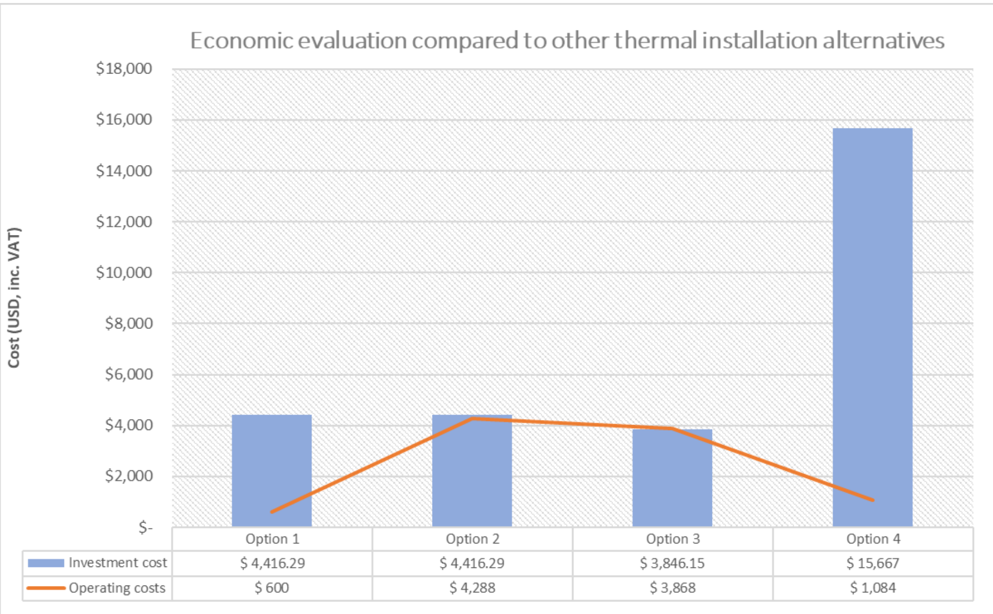



Figure 27. Economic evaluation compared to other thermal installations alternatives.

The Table 28 details the results obtained for the comparative economic evaluation considering a 10-year period of analysis.

Table 28. Economic evaluation considering the payback period.

| | Option 1 | Option 2 | Option 3 |
|---|---|---|---|
| Differential investment[1] | $ 11251 | $ 11251 | $ 11821 |
| Annual Saving[2] | $ 0 | $ 3204 | $ 2784 |
| Payback period (years) | NA | 3.5 | 4.2 |
| NPV[3] | (-) | $ 11081 | $ 7738 |
| ROI | (-) | 38% | 27% |

*[1] Considering the investment of the GSHP thermal installation as a reference investment.*
*[2] Comparing to the cost of the GSHP thermal installation.*
*[3] Considering a discount rate of 8%.*

## 4. SUMMARY RESULTS

Vertical ground heat exchangers were not considered in this work, because despite the small land surface required and high system efficiency, important initial costs for practical depths of 50 to 100 m discourage the potential users. Horizontal ground heat exchangers require large available land, therefore are viable in urban developments located in the outskirts of the city. This requires cheaper installations and is a mature and simple technology 30-60% less carbon intensive than gas or electric similar options. The appropriate selection of the equipment depends on parameters such as the thermal properties of the soil and the household thermal load demand.

**Study case parameters**

- Location: Córdoba, Argentina.
- Typical house, middle-income family, 4 people, 500 $m^2$ lot of land, house with 136 $m^2$ of covered area.
- 100% energy demand for air conditioning and domestic hot water
- Horizontal geothermal heat exchanger for water flow coupled with a heat pump, internal energy distribution system by radiant floor and domestic hot water supply through accumulator tank.

**Design results**

*Horizontal ground heat exchanger*

- 1392m length of High-Density Polyethylene piping of 40 mm nominal diameter.
- Layout: horizontal slinky coil arranged in 5 parallel trenches.
- Space required: 7.2m x 34m.
- Water circulation flow rate of 1.5 m3/h with head loss of 3.8 m.
- Water recirculating pump with power demand of 35 W.

*Heat pump*

- Refrigerant selected R410A
- Heating: 11.5 kW, COP = 6.5
- Cooling: 11.1 kW, COP = 5.5
- Overall system COP: ≈ 4.6 for heating and ≈ 4.4 for cooling. These values are 3-4 times higher than those with exclusive use of gas and electricity.

**Economic evaluation**

- Payback period: less than 5 years.
- Net Present Value: USD 11081 for LPG-electricity based option and USD 7738 for fully electrical installation.
- Return on Investment: 38% for LPG option and 27% for fully electrical one.
- From an economic point of view, currently, in Argentina, it is not convenient to replace a thermal installation that works with natural gas.

**Climate impact**

- Carbon intensity: 0.11 kg CO2e/kWh. This value is 49% lower than the NG-electricity-based option, 57% lower than the LPG-electricity-based option and 72% lower than the fully electrical option. This last one considers the current national electricity mix.

# 5. CONCLUSIONS

Shallow geothermal heat was studied as a renewable heat source to attend the thermal load demand for household at Córdoba city, Argentina.

The coupling of shallow geothermal reservoirs with efficient heat pumps, arises as an efficient technology for air conditioning and water heating needs. This option was studied, considering local climate characteristics, energy demand of a typical residential house and regional technical and economic feasibilities.

The current price of natural gas in Argentina is competitive with respect to other energy sources. Therefore, installing a heat pump with a horizontal ground heat exchanger is a good option for homes without access to natural gas networks.

Heat pumps with vertical heat exchangers require higher initial investment, therefore it could be not rentable for residential thermal demands, but a good solution for industrial thermal demand.

In global and regional scenarios, with different variation of the energy prices, each case should be considered separately.

Advantages of using shallow geothermal heat pumps are economic savings, guaranty of renewable energy supply and fight against climate change.

In Córdoba, Argentina, the local market around shallow geothermal heat pumps is incipient and it needs to be encouraged.

# 6. SUGGESTED FUTURE WORK

This master thesis concludes a series of guidelines which it is suggested to continue in future works.

- Feasibility of developing urban development projects supplied by thermal installations based on ground source heat pumps and claiming the emissions reduction, by displacement of more carbon intensive energy sources, in carbon markets. These carbon credits could work as a financing opportunity for the implementation of the project.
- Evaluate the implementation of hybrid systems by complementing the GSHP-based installation with auxiliary equipment to obtain the highest energy efficiency.
- Design of a GSHP-based thermal installation that works with renewable energy as the primary energy source, such as photovoltaic panels.

## 7. REFERENCES


[1] Heat Pump Centre (HPC). IEA Technology Collaboration Program on Heat Pumping Technologies. Retrieved from: https://heatpumpingtechnologies.org/about/heat-pump-centre/

[2] Letcher TM (2013). Future energy: improved, sustainable and clean options for our planet. Elsevier Science

[3] Consumos en el hogar (n.d.). Eficiencia Energética. Ministerio de Economía de Argentina. Retrieved from: https://www.argentina.gob.ar/energia/uso-responsable/mayores-consumos-hogar

[4] Informe anual 2022 – Mercado Eléctrico Mayorista (2022). Compañía Administradora del Mercado Mayorista Eléctrico Sociedad Anónima (CAMMESA). Retrieved from: https://cammesaweb.cammesa.com/informe-anual/

[5] Informe anual 2021 – Mercado Eléctrico Mayorista (2021). Compañía Administradora del Mercado Mayorista Eléctrico Sociedad Anónima (CAMMESA). Retrieved from: https://microfe.cammesa.com/static-content/CammesaWeb/download-manager-files/Informe%20Anual/2022/Inf%20Anual%202021.pdf

[6] Legislation (n.d.). Energías renovables. Secretaría de Biocombustibles y Energías Renovables. Ministerio de Servicios Públicos de la Provincia de Córdoba. Retrieved from: https://ministeriodeserviciospublicos.cba.gov.ar/biocombustiblesyenergiasrenovables/legislacion/ .

[7] ¿Cuáles son los mayores consumos en nuestro hogar? Ministerio de Energía de la Nación. Retrieved from: https://www.argentina.gob.ar/energia/uso-responsable/mayores-consumos-hogar

[8] Encuesta Nacional de Gastos de los Hogares (2022). Instituto Nacional de Estadísticas y Censos (INDEC). Ministerio de Economía de Argentina. ISBN 978-950-896-629-2.

[9] García Gil A., Garrido Schneider E.A., Mejías Moreno M., Santamarta Cerezal J.C. (n.d.). Shallow Geothermal Energy: Theory and Application. Springer Hidrogeology. Switzerland

[10] Carro Pérez M.E, Pleitavino M., Mansilla B., Toledo R., Aratano S., Bruni R. (2020). Evaluación de la distribución de temperaturas en un perfil somero de suelo loéssico. Córdoba, Argentina. ISSN 2314-1433.

[11] Energía Geotérmica. Estado del Arte de la Tecnología de generación de energía eléctrica a partir de la geotermia (2019). Subsecretaria de Energías Renovables y Eficiencia Energética.

[12] Geotermia en Argentina: estado, áreas de interés, potencial (2021). Servicio Geológico Minero (SEGEMAR). Instituto de Geología y Recursos Minerales. Secretaría de Minería. Ministerio de Desarrollo Productivo de Argentina.

[13] Sticco, M., Lemos M.L., Barredo, S.P. (2018). Aplicación de la energía geotérmica de muy baja entalpía para climatización, un caso de estudio en la localidad de Olivos, provincia de Buenos Aires. Retrieved from: http://dx.doi.org/10.13140/RG.2.2.25612.77448

[14] Peiretti, A. (2017). Geotermia de baja entalpia en suelos loessicos: caso de estudio. Práctica supervisada. Universidad Nacional de Córdoba.

[15] Narsilio G., Francisca F., Herrrero H., Bidarmaghz A. (2015). Geothermal Energy in Loess: A Detailed Numerical Case Study for Cordoba. Fundamentals to Applications in Geotechnics.

[16] Carro Pérez M.E., Peiretti A., Francisca F.M. (2018). Energía geotérmica de baja entalpía en suelos loéssicos: cálculo y diseño para caso de estudio. Córdoba, Argentina. ISSN 2314-1433.

[17] Energy Technology Perspectives (2023). International Energy Agency (IEA). Retrieved from: https://www.iea.org/

[18] Instituto Argentino de Normalización y Certificación (IRAM) (2012). Clasificación bioambiental de la República Argentina (11603:2012).

[19] Climate data (n.d.). Servicio Meteorológico Nacional de Argentina. Retrieved From: https://www.smn.gob.ar/

[20] Domestic Ground Source Heat Pumps: Design and installation of closed-loop systems (2007). Energy Saving Trust. CE82.

[21] Instituto Argentino de Normalización y Certificación (IRAM) (2001). Aislamiento térmico de edificios (11604:2001).

[22] Instituto Argentino de Normalización y Certificación (IRAM) (1996). Acondicionamiento térmico de edificios, condiciones de habitabilidad en edificios (11605:1996).

[23] Instituto Argentino de Normalización y Certificación (IRAM) (2012). Aislamiento térmico de edificios, métodos de cálculo (11601:2002).

[24] Instituto Argentino de Normalización y Certificación (IRAM) (2007). Acondicionamiento térmico de edificios. Verificación de sus condiciones higrotérmicas. Ahorro de energía en refrigeración. Parte 2: Edificios para viviendas (11659-2:2007).

[25] Sayago J.M., Collantes M.M., Karlson A., Sanabria J. (2001). Genesis and distribution of the Late Pleistocene and Holocene loess of Argentina: a regional approximation. Quaternary International, Vol. 76/77, pp. 247-257.

[26] Teruggi, M., 1957. The nature and origin of Argentine loess. *Journal of Sedimentary Petrology* 27: 322-332

[27] Sukhija A., Sharma A. (2020). Design studies on horizontal and vertical configuration of ground earth heat exchanger. Journal of Thermal Engineering. Yildiz Technical University. Istanbul, Turkey.

[28] Said S.A.M., Habib M.A., Mokheimer E.M.A., Al-Shayea N., Sharqawi M (2009). Horizontal Ground Heat Exchanger Design for Ground-Coupled Heat Pumps. King Fahd University of Petroleum & Minerals. Dhahran Saudi Arabia.

[29] What they didn't teach you in engineering school about heat transfer (n.d). SOLIDWORKS White Paper. Retrieved from: https://www.solidworks.com/sw/docs/Flow_Heat_Transfer_Whitepaper.pdf

[30] Etiquetado en Eficiencia Energética. Ministerio de Energía de la Nación. Retrieved from: https://www.argentina.gob.ar/economia/energia/eficiencia-energetica/etiquetado-en-eficiencia-energetica

[31] The Greenhouse Gas Protocol (n.d.). A corporate accounting and reporting standard. World Resources Institute.

[32] R410 thermodynamic properties. Freon Refrigerants. Retrieved from: https://www.freon.com/

[33] Heat Pumps Technical datasheets. EcoForest. Retrieved from: https://ecoforest.com/wp-content/uploads/2021/08/DS_Ecoforest_heat_pumps_ES_v2022_01.pdf

[34] TIGRE products brochure. Retrieved from: https://tigrecombr-prod.s3.amazonaws.com/tigre.com.bo/files/catalogos-tecnicos/2019-09/Polietileno.pdf

[35] Geothermal Heat Pump: Design Manual (2002). Application Guide (AG 31-008). McQuay International.

[36] Product selection. Grundfos. Retrieved from: https://product-selection.grundfos.com/

[37] Direct Global Warming Potentials. Intergovernmental Panel on Climate Change (IPCC). Fourth Assessment Report. Retrieved from: https://archive.ipcc.ch/publications_and_data/ar4/wg1/en/ch2s2-10-2.html

[38] Greenhouse gas reporting: conversion factors 2021. Government of the United Kingdom. Retrieved from: https://www.gov.uk/government/publications/greenhouse-gas-reporting-conversion-factors-2021

[39] Cálculo del factor de emisión de CO2 de la red argentina de energía eléctrica. Secretaría de Energía de la Nación. Retrieved From: https://datos.gob.ar/el/dataset/energia-calculo-factor-emision-co2-red-argentina-energia-electrica

[40] Empresa Provincial de Energía de Córdoba (EPEC). Retrieved from: https://www.epec.com.ar/

[41] ECOGAS. Gas distributor. Retrieved from: https://www.ecogas.com.ar/

## 8. LIST OF FIGURES



## 9. LIST OF TABLES