

Review

State of the Art, Perspective and Obstacles of Ground-Source Heat Pump Technology in the European Building Sector: A Review

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Abstract: In the European Union, 40% of the overall final energy consumption is attributable to the buildings sector. A reason for such data may be found considering that the great majority of the building stock is more than 40 years old. According to the European Commission, an interesting potential lies in the refurbishment of the building sector, and heat pump technology has been recognized as one of the most cost-effective solutions to tackle the environmental issue of this sector. Regarding heat pump technology, ground-source heat pumps (GSHPs) have been proven to be the most efficient solution on equal boundary conditions. Despite this, in most EU states' markets, GSHPs hold only a small market share with respect to air-source heat pumps. In this paper, the state of art and possible future developments of GSHP technology have been reviewed together with a focus on the potential of such technology, most of all on the refurbishment of existing buildings, and on the obstacles to its spread. The state of art of borehole heat exchangers has been studied, focusing on the parameters characterizing the outside pipe and the pipe itself, i.e., pipe and grout materials. Moreover, an overview on the last developments involving refrigerants and secondary fluids is given. Finally, the design and control strategies of GSHPs have been reviewed.

Keywords: ground source heat pump; ground coupled heat pump; energy transition



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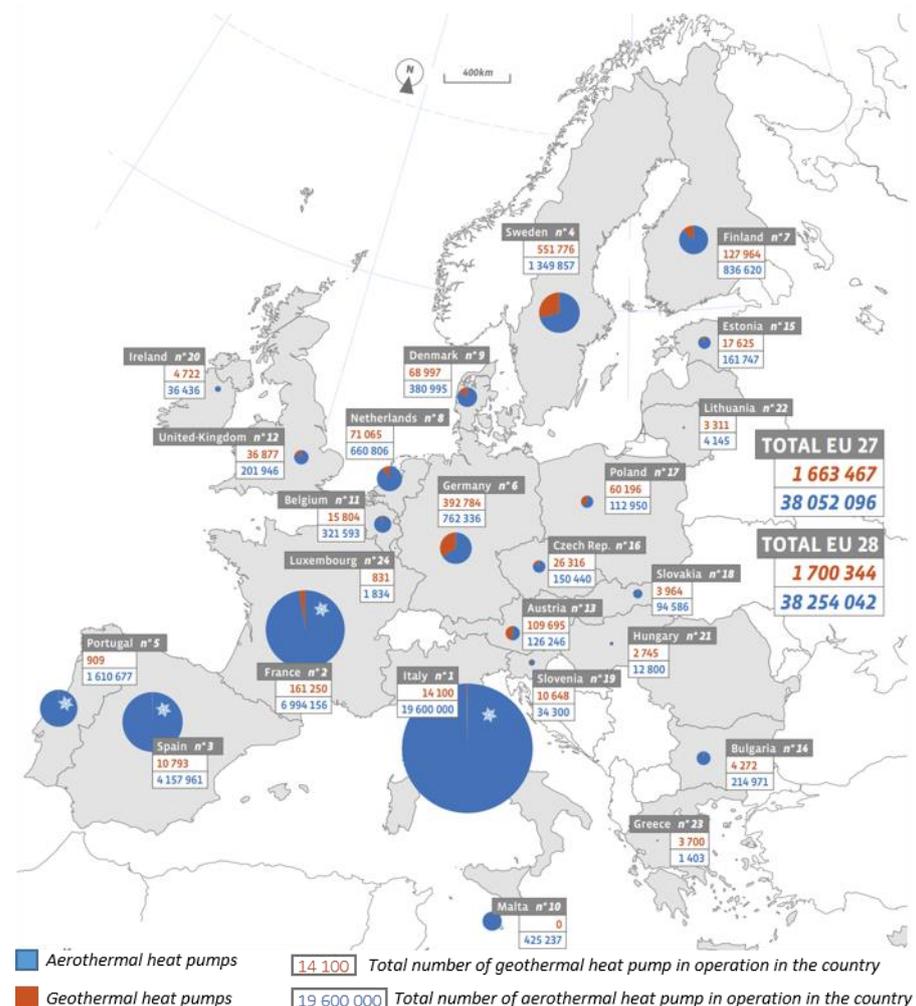
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1. Introduction

In the European Union, the building sector is responsible for 40% of the overall final energy consumption, considering both residential and commercial buildings [1]. The average specific energy consumption is 185 kWh/m² during the winter period, though a great variability can be noticed amongst EU countries: the average consumption in the Mediterranean region is 90 kWh/m² year while in the Nordic countries is 210 kWh/m². An important portion of EU buildings energy consumption, from 60% to 80%, is attributed to space heating. Such data can find an explanation considering that 64% of the EU building stock is more than 40 years old [2]. For these reasons, a significant energy saving potential lies on buildings [3]. With the purpose to enhance buildings energy performance, the European Commission released directives such as EPBD [4] and EED [5]. Such directives also identified Heating, Ventilation, and Air Conditioning (HVAC) systems as the main solutions to increase renewable energy sharing and overall building energy efficiency, considering both the retrofit of existing buildings and the construction of new ones. In this context, electric heat pumps are among the most cost-effective solutions for decarbonising thermal energy, notably in buildings, and can be used in various environments, even in colder climates. Moreover, in the last few years, the heat pump market is facing a great expansion: in UE countries, 1.6 million heat pumps were installed in 2020, 5% up with

respect to 2019, despite shortages due to COVID-19 crisis, with Italy, France and Spain as leaders in this sector [6].

Figure 1 shows the ratio between air-source (ASHPs) and ground-source heat pumps (GSHPs), which presents a great variability among EU countries. The great majority of installed heat pumps are the air-source type, most of all in the Mediterranean countries, and the ground-source heat pumps market is pushed in cold climate countries [7]. In Italy, the first country for installed heat pumps, air-source heat pumps (ASHPs) involve 97% of the market while only 3% is occupied by GSHPs. Despite a significant expansion, heat pumps cover only a small market share in the overall heating generator market. A relevant reason is the practical infeasibility of a space-heating system retrofitting without replacing radiators, which represent over 90% of the existent domestic equipment in households [8].



developments in terms of working fluids; finally, the last paragraph is dedicated to the design and the subsequent control of the system.

The papers considered in this review are articles released in recent years or widely cited in the field. Among the selected literature, 45% of the reviewed articles have been published in the past 3 years (from 2019 to the first months of 2022) and 70% relate to the past 5 years (2017–2022); only 20 articles are related to pre-2015 years (Figure 2).

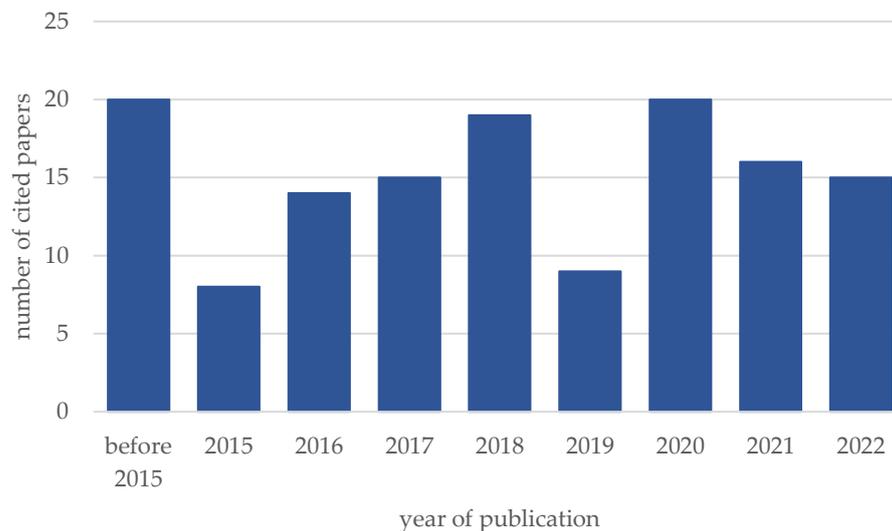


Figure 2. Year of publication of the reviewed articles.

2. Perspectives and Barriers

Heat transition is crucial for achieving EU climate targets. The European Commission has a recognized Energy Roadmap 2050 that electric heating can reach a share of 36–39% contribution to heat decarbonisation in 2050 [10] and heat pump technology seems to be the most appealing technology due to its high efficiency and profitability [11]. Moreover, heating demand is expected to decrease, while cooling demand is forecasted to increase [12] and one of the main strengths of heat pumps is their capability of generating both heating and cooling with the same device.

In retrofitting an existing building or in the construction of new ones, the choice of heat generator is mainly driven by investment costs and operating costs [13], which are related to system efficiency and energy carrier price. Martinopoulos et al. [14] showed that heat pumps, and in particular ground-source heat pumps, present the lowest operating costs among the proposed heat generators. Heat pumps, in particular ground-source heat pumps, have higher investment costs with respect to gas boilers or oil boilers. Another important aspect when choosing the generator is to consider the building envelope and use, as well as the types of emission units. Since heat pump efficiency and capacity depend on the temperature difference between the cold source and the heat sink, ASHPs, whose cold source is ambient air, could be disadvantaged in cold climate countries or in the case of coupling with high temperature terminals such as radiators, which are common in existing buildings. Instead, GSHP efficiency and capacity rely on ground temperature, and consequently on a more stable cold source with a temperature level higher than ambient in winter and lower in summer, achieving a higher efficiency (up to 20%) than ASHP at the same boundary conditions [14,15]. Being almost independent on ambient air temperature, GSHPs have their greatest market share in the European Nordic region. It is worth underlining the possibility of coupling GSHPs with high temperature heating terminals without a drastic reduction on efficiency. This makes GSHP technology a feasible solution for retrofitting existing buildings involving only the heat generator and therefore making the refurbishment easier and cheaper [9,15–19]. The main barriers that actually slow down the spread of GSHP technology are investment and installation costs [20]. The installation

cost of a GSHP system depends on the system type to be installed, the collectors type and dimensioning, the heating and cooling load of the building, the soil characteristics, and the system functions (heating, cooling, domestic hot water (DHW)) [13]. For vertical closed-loop GSHPs, half of the investment cost is due to drilling the borehole [21]. In order to make GSHP technology more competitive on the market, several research projects, among which GEOCOND [22], Cheap-GSHP [23] and GEO4CIVHIC [9], were financed by UE working on the cost-effectiveness of both installation and operation and on stakeholder awareness.

3. State of the Art and Technological Developments

3.1. Theoretical Background

Heat pump technology is based on a thermodynamic reverse cycle, driven by electricity, which is able to move an amount of thermal energy from a low temperature source to a higher temperature sink. Such systems take advantage of thermodynamic properties of several fluids, named refrigerants, to perform the cycle. A heat pump basically consists of four components: an evaporator, a compressor, a condenser and an expansion device [24,25]. In the evaporator, the refrigerant, at low pressure and two-phase state, absorbs heat from the low temperature energy source in order to boil and move to the superheated vapour state. Then, its pressure is increased by an electrically driven compressor. The high pressure level is determined in order to allow the refrigerant to heat up the high temperature energy sink in the condenser. The exchanged heat to the energy sink liquefies the refrigerant, which moves to the compressed liquid state. Then, the liquid refrigerant enters an expansion device, i.e., an orifice, valve or capillary tube, which is designed to drop the pressure from the condensing level to the evaporating level. The expansion device operation is fundamental for the heat pump performance, since it sets the pressure levels in the two heat exchangers. Figure 3 shows the basic heat pump scheme, the most widespread cycle configuration for residential heat pumps; several other more complex cycles can be implemented [26]. In the case of a GSHP, the energy sink and source become respectively the user circuit and the ground-source circuit. Figure 4 shows the heat pump operation on a pressure-enthalpy diagram. The main parameter to evaluate the performance of heat pumps is the Coefficient of Performance (COP), given by the ratio between the condenser pumps power and compressor power. Such a parameter depends on several variables: amongst the most important there are refrigerant thermodynamic properties, components design and working conditions (i.e., pressure levels in the heat exchangers, mass flow rate, etc.). A corresponding parameter, EER, is used to evaluate the performance of the heat pump in cooling mode and is calculated as the ratio between the power absorbed at the evaporator and the compressor power. In order to give a basic mathematical model of heat pump, the following Equations (1)–(6) are given, assuming to set some parameters such as the superheating at the evaporator outlet ΔT_{sh} , the subcooling at the condenser outlet ΔT_{sub} and the compression isentropic efficiency η_{is} . The symbols p , T , h and s refer to pressure, temperature, enthalpy and entropy of fluid, respectively. The subscript *ev* and *cond* refer to the evaporation and the condensation. The numerical subscripts refer to the thermodynamic state of fluid during the operation (see Figures 3 and 4).

$$h_1 = f(p_{ev}, T_{ev} + \Delta T_{sh}) \quad (1)$$

$$h_3 = f(p_{cond}, T_{cond} + \Delta T_{sub}) \quad (2)$$

$$h_3 = h_4 \quad (3)$$

$$h_{2,is} = f(p_{cond}, s_1) \quad (4)$$

$$h_2 = \frac{h_{2,is} - h_1}{\eta_{is}} \quad (5)$$

$$COP = \frac{h_2 - h_3}{h_2 - h_1} \quad (6)$$

$$EER = \frac{h_1 - h_4}{h_2 - h_1} \quad (7)$$

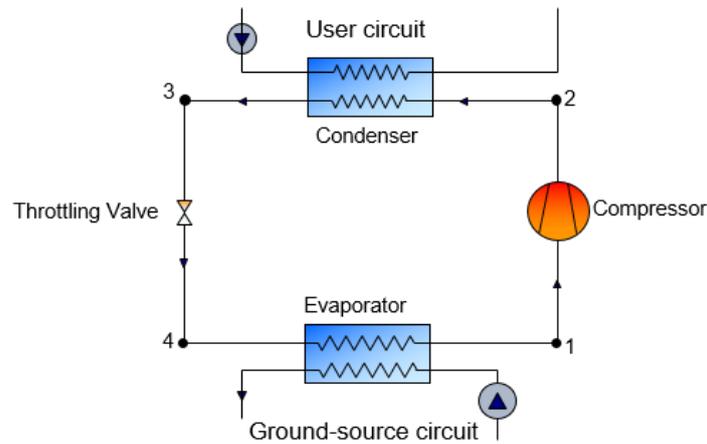


Figure 3. Basic thermodynamic cycle for heat pump.

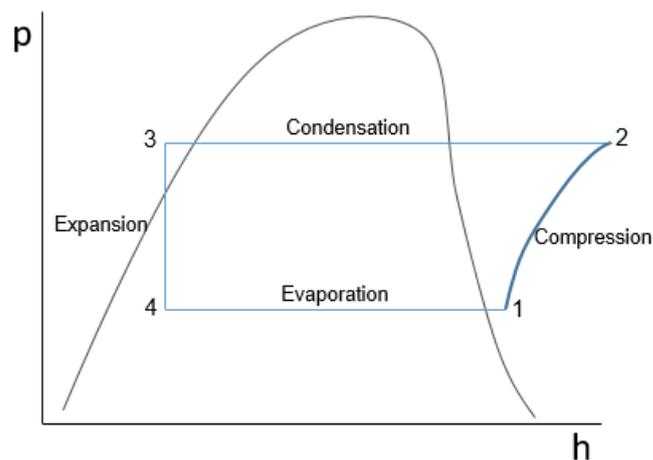


Figure 4. Pressure-enthalpy diagram for basic heat pump cycle. The black line represents the saturation curve, while the blue line represents the thermodynamic cycle. The numbers refer to Figure 3.

As already mentioned, GSHP technology has garnered increasing attention thanks to its efficiency, environmental compatibility and its potential in retrofitting buildings without replacing the existing heat terminals. A reduction of 20–40% and 30–50%, respectively for heating and cooling, of the energy demand in buildings could be potentially achieved with GSHPs, together with a CO₂ emissions reduction from 15% to 77%, considering both residential and non-residential buildings [27]. GSHPs reject (in cooling season) or extract (in heating season) heat through a heat exchanger installed in the ground, named a ground heat exchanger (GHE) onwards. Thus, the soil exploits its heat storage capacity to satisfy the energy demand of the building in the cooling and heating period. GSHPs can be primarily grouped into three subsets: surface water heat pumps (SWHP), ground-water heat pumps (GWHP) and ground-coupled heat pumps (GCHP), each one characterized by three main components, i.e., heating and cooling distribution system, the ground heat exchanger and the heat pump itself [28]. A scheme for these configurations is shown in Figure 5. Since the other GSHP systems required the availability of water as a thermal source, the present study focuses on the GCHP technology, which consists of a reversible vapour compression cycle where heat is exchanged with the ground through the GHE, a closed-loop with working fluid circulating, which can be installed either in vertical boreholes or in horizontal trenches, potentially in each type of ground. Both the vertical and the horizontal GHE

present advantages and drawbacks, and many studies have been dedicated to analyse their performance [29,30]. However, vertical GHEs are generally preferred thanks to their higher efficiency owed to the lower seasonal swing in the ground mean temperature, and the lower ground area demanded for the installation [30]. Basic geometries for the vertical GHE are the coaxial, the single or double U-tube and the helicoidal configurations. Nevertheless, several studies on this issue are ongoing, and new solutions are proposed. For instance, the use of heat pipes to reduce the energy consumption of circulation pumps and increase the overall heating performance is one of those. However, there are many limitations, such as installation issues and compatibility with conventional working fluids and pipe materials [31].

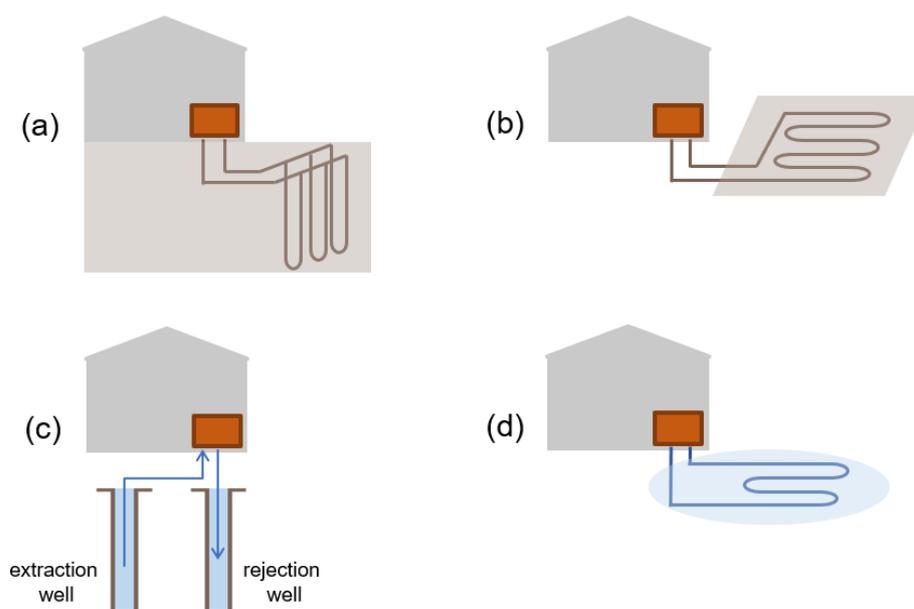


Figure 5. GSHP main typologies: (a) ground coupled heat pump with vertical GHE; (b) ground coupled heat pump with horizontal GHE; (c) ground water heat pump; (d) surface water heat pump.

Nowadays, the high initial investment cost for the equipment installation represents the main barrier for a wider diffusion of GSHPs in residential applications. To date the payback time for the investment goes from 5 to 10 years [26]. Drilling and piping costs cover a major share in the total cost of the plant, between 20% and 60% [32,33]. Although this share is highly variable, it still covers a significant percentage of the total cost; Blum et al. [21] observed a mean installation cost per unit length of a vertical BHE of 67 €/m, with 51% of the final price owing to drilling costs and the remaining 49% owing to the heat pump system. It is thus of first importance to reduce the overall cost of the GSHP. To do so, a comprehensive operation is necessary, including optimal use of materials, fluids and technologies involved, optimal design and optimal control of the system when operating.

3.2. GHE Components' Materials

According to the ASHRAE guidelines to geothermal energy [28], the thermal resistance of the ground heat exchanger (GHE), together with the thermal conductivity of the ground, must be considered as key variables when designing a GSHP. Many studies have been dedicated to decreasing the thermal resistance of the GHE, acting on its components, inside and outside the pipe. Badenes et al. [19] performed a sensitivity analysis to detect the parameters that have the highest impact on the overall performance of a GSHP system. These parameters are the thermal conductivity of the pipe and of the filling grout, together with the pipe configuration. For these three aspects, new designs have been proposed to improve the GHE's performance [19,34–37]. Although pipe configuration may have a big impact on thermal performance, and many researches have been dedicated to the

issue [19,32,38], the choice of design parameters such as the pipe arrangement is limited and bounded by economic constrains. The borehole thermal resistance R_b , i.e., the thermal resistance between the working fluid inside the pipe and the borehole wall, has been recognized as the main efficiency parameter of the GHE [19]. To date, several procedures have been proposed to model the heat transfer in the GHE, as further explained in Section 3.4. For a classical arrangement with a one U-tube, and in the hypothesis of symmetry between pipes (Figure 6), a basic definition of R_b is given, as reported in the following equations [39]:

$$R_b = \frac{R_f + R_p}{2} + R_g \quad (8)$$

$$R_f = \frac{1}{2\pi h r_1} \quad (9)$$

$$R_p = \frac{\ln\left(\frac{r_2}{r_1}\right)}{2\pi k_p} \quad (10)$$

where R_g is the conductive resistance of the grout, R_f the convective resistance of the fluid, R_p the conductive resistance of one pipe, h is the convective coefficient of the fluid, k_p is the pipe thermal conductivity and r_1 and r_2 the inner and the outer radius of the pipe.

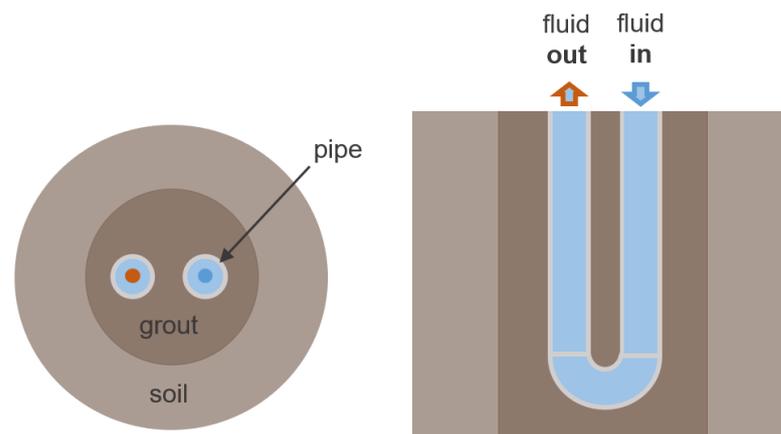


Figure 6. Example of single U-tube borehole heat exchanger.

As a consequence, the heat transfer rate per unit length of the borehole heat exchanger q_b is defined as:

$$q_b = \frac{T_f + T_b}{R_b} \quad (11)$$

$$T_f = \frac{T_{f1} + T_{f2}}{2} \quad (12)$$

where T_b is the mean borehole surface temperature and T_f is the mean fluid temperature, calculated as the mean of T_{f1} and T_{f2} , respectively supply and return fluid temperature.

Grout, secondary fluid and pipes, whose disposition is shown in Figure 6, and their effect on the GHE efficiency will be addressed in the following paragraphs.

Nowadays, the minimum R_b values achievable with present-day best solutions in terms of pipe and grout materials range from 0.06 to 0.08 K/(m·W); a reduction of this values requires a further development of ad hoc technologies, designed accordingly with the specific application and the characteristics of the ground [19].

3.2.1. Borehole Heat Exchanger Configuration

Tube configuration inside the BHE is a key parameter to improve heat transfer between the ground and the fluid circulating inside the borehole, since it can increase the available heat transfer area. A single U-tube is the basic configuration for a BHE (Figure 6).

To enhance the BHE performance, three main configurations have been proposed: multi U-tube BHE, helical BHE and coaxial BHE. The multi U-tube configuration (Figure 7a) is the simplest, consisting of two or more single U-tubes connected to the same borehole [40]. A limit for this application can be set by the larger borehole diameter to host the tubes. The 3U-tube BHE have been tested by Aydin and Sisman [41], with a thermal response test (TRT), while the heat transfer of 4U-tubes and 5U-tubes BHE has been investigated by numerical simulation resulting in no sensible improvement with respect to the 3U-tube BHE. Moreover, the helical BHE (Figure 7b) can require a larger borehole diameter. However, it allows an increase in the heat transfer area greater than the 3U-tube configuration. Such an increase may limit the use of such a configuration to energy piles. A numerical model was developed by Zarrella et al. [42] to evaluate the dependence of several designs and operation parameters, considering the heat conduction along the vertical axes of the borehole between the ground and the BHE. A 40% heat transfer increase was calculated with respect to the double U-Tube configuration. The coaxial BHE (Figure 7c) consists of an inner tube installed inside a larger coaxial outer tube, both cylindrical. The conventional coaxial BHE, made of inflexible material such as steel, results in difficulties for transportation and is an expensive procedure [40]. However, such a configuration is expected to outperform the single U-tube [43]. Oh et al. [43] studied the influence of pipe (stainless steel or HDPE) and grout thermal properties on a coaxial BHE heat exchange, highlighting the importance of high thermal conductive materials.

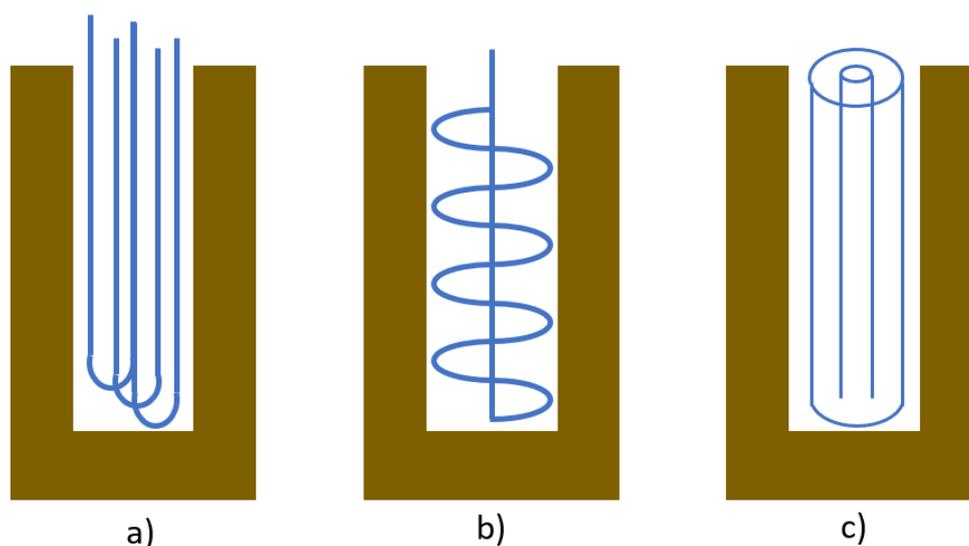


Figure 7. BHE enhanced configurations: (a) Multi U-tube, (b) Helical, (c) Coaxial.

3.2.2. Pipe Materials

According to the analysis performed by Badenes et al. [19], a significant decrease in R_b is obtained, increasing the thermal conductivity of the pipe material until a value of 4–5 W/(m·K). Above this point, R_b remains constant. Thus, this value represents the ideal target for new pipe materials, above which the technical benefit is undone by the financial unfeasibility. Nowadays, HDPE (high-density polyethylene) represents the dominant technology on the European market, thanks to its cost-effectiveness and resistance to corrosion. As an alternative, metallic pipes such as stainless steel, aluminum and copper have been considered valid alternatives for shallow GSHP application in non-corrosive soils, especially with coaxial GHEs [9,19,23,44]. Comparative analyses between metallic

pipes (mainly copper and steel) and thermoplastic polymers (e.g., PE, PA, HDPE) have demonstrated higher heat exchange rates and GHE performance for the first group of elements [38,45,46]. However, besides thermal conductivity, the choice of the selected pipe material is driven by technical requirements such as durability, cost, plumbing and flexibility, which have made HDPE the most widespread technology on the market. Although the resistance of the borehole is proven to increase until 4–5 W/(m·K) for the thermal conductivity of the pipe, the ideal value, representing the best trade-off between thermal efficiency and manufacturing cost, tends to be about 1.5–2 W/(m·K). To reach this target, thermally enhanced thermoplastic polymers, i.e., combinations of mainly PE or HDPE (whose thermal conductivity conventionally stands between 0.3–0.5 W/(m·K)) with other high thermally conductive materials, have recently been presented in many studies. In the framework of the European project GEOCOND [22], Badenes et al. [19] developed new high thermal conductive compounds, using expanded graphite as an additive to PE100, obtaining thermal conductivity values similar to those desired and mechanical properties similar to those of the original PE100. To reduce the required length of vertical GHEs, Raymond et al. [47] designed a coaxial ground heat exchanger, employing thermally enhanced HDPE with carbon nanoparticles as an additive. Through the use of nanomaterials, a thermal conductivity of 0.7 W/(m·K) has been reached; according to the authors [47], the combination of enhanced HDPE and coaxial pipe configuration leads to a reduction in the required borehole length up to 23%. Another approach is the one applied by Bassiouny et al. [48], where aluminum wires have been added to HDPE to increase its thermal conductivity up to 150%, bringing together the benefits of both metallic and plastic materials. A summary of the main conventional and innovative solutions for pipe materials is schematized in Table 1.

Table 1. Common pipe materials in GCHP systems with corresponding thermal conductivities.

Pipe Materials	
Benchmark: 1.5–2 W/(m·K) [19]	
Conventional solutions	Reference
Metallic pipes (copper: 395 W/(m·K), steel: 57 W/(m·K))	[9,19,23,44,45]
Thermoplastic polymers (PE, PA, HDPE) 0.2–0.5 W/(m·K)	[19,38,45,46]
Innovative solutions	Reference
Thermally enhanced HDPE:	[21,28,30,31]
<ul style="list-style-type: none"> • Graphite (flake or expanded): 1.1 W/(m·K) [19,22] • Graphene [19,22] • Aluminium wires: 0.625–1.25 W/(m·K) [38,48] • Nanomaterials: 0.7 W/(m·K) [47] 	
Heat pipe BHE	[40]

3.2.3. Grout Materials

When considering the outside of the pipe, thermal conductivity of the backfill material has the greatest influence on the system performance: since grout aim is to ensure the heat transfer between GHE and soil, the choice of its thermal conductivity and heat capacity is crucial for the efficiency of the GSHP [37,38]. The GHE effectiveness has been proven to be proportional to grout's thermal conductivity for all the possible configurations [49,50], and is inversely related to the length of the GHE and its cost. Specifically, a significant decrease in R_b has been detected for grouts with thermal conductivity up to 2 W/(m·K), while a less intensive decrease can be obtained with values up to 4 W/(m·K). Regarding the grout material, an optimal value has been determined, between 2.5 W/(m·K) and 3.3 W/(m·K) [19]; this value must fulfil other technical requirements, such as moisture, porosity, permeability, mechanical strength and shrinkage, chosen depending on the thermal properties of the soil, initially investigated with thermal response tests (TRT).

Thermal response test (TRT) is one of the main tests capable to give information on ground properties [51–53], which is fundamental for a proper design of borehole heat exchangers (BHE). Planning and execution of the drilling have an important influence on the overall cost of a GSHP system; thus, drilling effectiveness is a key parameter, and it is determined by the choice of equipment on drilling method [54,55]. Air method [56] is an effective and universally widespread method thanks to several aspects: economic affordability, reasonable drilling time and maintenance needs [57], borehole cleanliness and reduced environmental impact. Based on the air-technique, the Down the Hole (DTH) method shows good results in drilling hard rock [58]. Such method implements an air-activated rotary drill bit, made of alloy steel and tungsten carbide with the hammer located at the bottom of the drill string which turns to improve penetration [59]. The DTH method can benefit from a low environmental impact, and in case of drilling a nearby water source, the aquifer is not affected by chemicals from drilling mud.

Actual values for grout thermal conductivity go from 0.6 W/(m·K) to almost 2 W/(m·K), depending on whether it is a conventional grout or a spiked material [19]. The first category mainly includes bentonite grouts and cementitious grouts, traditionally used as backfilling materials thanks to their low permeability, high swelling potential and high strength. However, these materials present low thermal conductivities, from 0.65 W/(m·K) to 0.90 W/(m·K) for bentonite mixtures and from 1 W/(m·K) to 1.3 W/(m·K) for cementitious mixtures [60] respectively, which represent their main drawback. Moreover, mechanical issues such as viscosity and injection rate must be accounted for when using these materials. Lee et al. [61] observed a significant volume reduction of the backfilling material when in contact with salinity, thus causing incomplete borehole filling and a consequent decrease in the GHE performance.

Several researches have been dedicated to improving the thermal conductivity of the grout materials by using highly conductive materials as additives [62]. A summary of the most used grout materials, conventional and thermally enhanced, is provided in Table 2.

Table 2. Conventional and innovative grout materials in GCHP systems with corresponding thermal conductivities.

Grout materials Benchmark: 2.5–3.3 W/(m·K) [19]	
Conventional solutions Bentonite, Cement: 0.65–0.9, 0.8–1.3 W/(m·K))	Reference [19,21,28,30,43]
Innovative solutions Thermally enhanced grout:	Reference
<ul style="list-style-type: none"> • Sand: 1–2.91 W/(m·K) • Graphite: 2.73–2.91 W/(m·K) (flake or expanded) • Aluminium shaving: 3.27–3.75 W/(m·K) 	[19,50,62–65] [19,50,63,64,66] [49]
CLSMs: 1.11–2.35 W/(m·K) PCMs: 0.2–1.52 W/(m·K)	[60,63,67–70]
<ul style="list-style-type: none"> • Composite materials • MPCM • SSPCMs • nanoPCMs 	[71–73] [74–76] [77,78] [79–82]

Graphite represents, together with sand [63], the most used additive to increase the thermal conductivity of the grout material, either in flake or expanded form. The choice of graphite is mainly driven by its carbon content, which improves its thermal performance, and its insolubility in water, preventing any risk of contamination. In a study by Lee et al. [64], the thermal performance of seven bentonite-based grouts has been tested,

adding either silica sand or graphite. Results assessed graphite as more efficient than sand, with a conductivity of about $3 \text{ W}/(\text{m}\cdot\text{K})$ at a concentration of 30% wt, while a thermal conductivity of only $1 \text{ W}/(\text{m}\cdot\text{K})$ has been reached with the same amount of sand without graphite. However, the analysis highlighted that a higher amount of additive in the mixture corresponded to an increase in the grout viscosity. In this regard, with the aim to maintain the graphite content under 10% wt, Delaleux et al. [66] obtained thermally enhanced grout, with thermal conductivity up to $5 \text{ W}/(\text{m}\cdot\text{K})$ through insertion of Compressed Expanded Natural Graphite CENG particles at a reduced graphite content (i.e., 5% wt), leading to a reduction of 33% for the required BHE and of 30% for the overall GHE cost.

Many other additives have been analysed which guarantee an improvement in the grout thermal conductivity up to 100% compared to conventional materials [50,77]. For instance, Liu et al. [83] investigated the thermophysical properties of quartz sand-bentonite-carbon fiber mixtures and their potential as a backfilling material. The analysis resulted in an optimal mixture, with thermal conductivity $1.98 \text{ W}/(\text{m}\cdot\text{K})$, corresponding to a percentage of bentonite about 10–12% wt. The study also assessed the role of moisture content and the degree of saturation in grout performance, which increases as the two parameters increase.

Although a significant improvement in the GHE performance could be obtained through the use of additives, an excessive increase in the thermal conductivity of the grout may lead to thermal interference between pipes, defined as “the influence of each tube on the amount of heat transfer to the surrounding soil” [84], and thus a reduction in the system efficiency. In this regard, new proposals have been made that prevent thermal interference between two pipes. In particular, novel grout materials are controlled low-strength materials (CLSM) and Phase change materials (PCM).

Controlled low-strength materials (CLSM): these materials are mixtures composed, usually, of fine aggregates (e.g., natural sand, coal ash), cement, fly ash and water. These materials have historically been used as filling materials for structural fills, and only recently they have been considered as possible alternatives to conventional thermal grouts for geothermal systems, thanks to their low compressive strength, high thermal conductivity, good flowability, low shrinkage and low cost [85]. However, a major problem for CLSM is their low mechanical strength, which makes it necessary to add supporting materials to the mixture [50]. Do et al. [67] presented an experimental program on various mixtures of CLSMs, characterized by thermal conductivities from $1.11 \text{ W}/(\text{m}\cdot\text{K})$ to $1.46 \text{ W}/(\text{m}\cdot\text{K})$, which confirm them as a good replacement to conventional grouts, with higher heat exchange rates and prospects for economic saving of up to 29% of total construction cost. Several studies have addressed the development of thermal and mechanical characteristics of CLSMs [68–70]. In a study performed by Kim et al. [60], the use of a thermally enhanced controlled low-strength material with steel-making slag in a GSHP has been investigated. The study demonstrated a potential construction cost reduction of up to 40% when compared with conventional grouts and a maximum thermal conductivity of $2.35 \text{ W}/(\text{m}\cdot\text{K})$, demonstrating the potential of this technology in the geothermic field.

Phase change materials (PCM): the other novelty in grout materials is represented by PCMs, latent storage materials, capable of storing and releasing heat by solid to liquid phase changing. Thanks to their thermal capacity, PCMs can smooth the effect of peak loads, reducing, as a consequence, the total volume and cost of installation of the GSHP system, especially in intermittent operation systems. Moreover, PCMs operate at almost constant temperature, improving the stability of the system. The operating temperature must, of course, be chosen according to the system's operating conditions. Aljabr et al. [74] provide design recommendations for a vertical GHE using PCMs: according to the study, the optimal melting temperature of the PCM should be the intermediate value between undisturbed ground temperature and the peak design temperature of the secondary fluid entering the heat pump. This temperature corresponds to the point at which all the PCM mass changes phase at the time of peak load. Regarding the thermal interference between pipes, the thermal affects radius of PCMs is much smaller compared with the one of conventional grouts and thus the borehole spacing can be decreased. According to a study

by Yang et al. [65], conducted with two different PCMs, for cooling and heating period respectively, a mean reduction of the thermal interference radius of 13% with respect to that of soil backfill can be reached. Qi et al. [86] compared three different PCMs as backfill materials with conventional soil, and the results reported a reduction of the thermal affects radius of 15.14% for RT27, 34.13% for capric and lauric acid mixture and 21.63% for enhanced acid. The reduced thermally affected range directly affects the land occupation, which especially benefits installations in urban areas, with a required space reduction from 18% for ordinary PCMs to 29% for thermally enhanced PCMs [77].

Thanks to their qualities (e.g., high storage capacity, stability and temperature uniformity) the use of PCMs in boreholes may reduce their length up to 9% [38], making it the best choice for grout at present [50]. However, despite their many advantages, PCMs are characterized by low thermal conductivities, around $0.2 \text{ W}/(\text{m}\cdot\text{K})$ for paraffin waxes and $0.5 \text{ W}/(\text{m}\cdot\text{K})$ for inorganic salts [86]. These values result in a poor heat exchange with the surrounding soil and a decrease in the GHE efficiency and in the COP of the heat pump; thus, the use of thermally enhanced PCMs is needed.

Aljabr et al. [74] performed a parametric analysis of the thermal properties of micro-encapsulated phase change materials (MPCM) blended with grout, while Chen et al. [77] investigated the effects of the use of PCMs as grout on GHE and heat pump efficiency, comparing MPCM and shape-stabilized phase change materials (SSPCM), where a supporting material is added to increase stability and prevent leakages, which represent the second major problem of plain PCMs. Another possibility is to improve the thermophysical properties of PCMs by incorporating nanoparticles, usually metals, metal oxides and carbon-based particles (e.g., graphene) [79]. In this respect, Daneshazarian et al. [79] simulated the effect of 14 selected nanoPCMs on the operation of a TES-GSHP system over a period of 5 years. The addition of nanoPCMs resulted in an increase of 11% and 8.7% for heating and cooling COP respectively, compared to the no PCM scenario (average COP over the 5 years period of 3.34 for heating and 5.30 for cooling).

Composite materials [71–73], MPCM [74–76], SSPCMs [77,78] and nanoPCMs [79–82] thus represent the future of PCM as grout in GSHPs, increasing the thermal conductivity of conventional PCMs: in fact, only if thermal conductivity is sufficiently high, about that of conventional grout [77], is the efficiency and operational stability of the GSHP improved. On the other hand, only a significant improvement justifies the current high cost of this technology, which otherwise nullifies the reduction of the overall cost obtained, reducing the required BHE length. From a mere economic point of view, nowadays PCMs are not sufficiently competitive, and thermally enhanced grout materials often turn out to be more cost-effective [74].

Badenes et al. [19] suggest a target for grout's thermal conductivity between $2.5 \text{ W}/(\text{m}\cdot\text{K})$ and $3 \text{ W}/(\text{m}\cdot\text{K})$, and reported that an increase in the thermal conductivity of the pipe in combination with the one of the filling grout can lead to a reduction in the total length to be drilled up to 22%, for the same pipe configuration.

The implementation of these technologies should contribute to making the GSHPs a more widespread and accessible option for HVAC in residential buildings.

3.3. Working Fluids

3.3.1. Refrigerant Fluids

Working fluid selection is a crucial point in the design of heat pumps, since the environmental impact of the system strongly depends on this choice. The environmental impact of a heat pump system, as well as of an air conditioning system, is given by the sum of direct and indirect emissions. Direct emissions are related to the refrigerant flowing into the atmosphere, usually caused by accidental leakages, and they are computed through the Global Warming Potential (GWP) of the fluid [87]. Such an index compares the refrigerant impact as a greenhouse gas with the one of carbon dioxide as reference fluid. It is used by national and international regulations to define the related restrictions on usage and on market share of refrigerants. Indirect emissions are defined as the carbon dioxide emissions

related to the energy consumptions necessary for heat pumps operations: therefore, they depend on the system performance and the type of energy mix for electricity production.

Hydrofluorocarbons (HFCs) have dominated the refrigerant market in the last twenty years. HFCs are characterised by a relatively high GWP and are subjected to restrictions imposed by EU Regulation 517/2014 [88]. Consequently, HFC price will continue to increase, urging the industry to find economically and environmentally sustainable low GWP alternatives [89]. The introduced regulation system imposed several limitations on the available F-gases share on the market, with distinctions related to the final use of a refrigerating system. The main purpose of the European Commission is, indeed, to gradually phase high-GWP fluids down. For instance, since 2015, a working fluid with a GWP value lower than 150 is required for a domestic refrigerator to be sold. In the domestic refrigeration, air conditioning and heat pump sector, a GWP lower than 150 is requested to refrigerants considered for long term usage [88].

Nowadays, R410A is the most used refrigerant in heat pumps and air conditioning sector due to excellent performance and near-zero temperature glide [90], but its GWP is equal to 2088. Then, R410A needs to be substituted. Several criteria have to be met to assert that a proposed fluid can be an interesting substitute for R410A, such as suitable thermodynamic properties, chemical stability in the system, low flammability and toxicity and low environmental impact [91]. However, if the substitution of a high-GWP refrigerant with a low-GWP fluid leads to performance worsening, the total environmental impact of the system may not be actually reduced [92]. Mota-Babiloni et al. [93] analysed different HFC/HFO mixtures, showing good results for R447A and DR-5 as alternative refrigerants for R410A. Thu et al. [90] studied a blend of R32, R1234yf and CO₂ as a low-GWP drop-in alternative for R410A in domestic heat pumps. Yang et al. [94] analysed R447A, R447B, R452B, R454B, R459A and R466A as possible substitutes for R410A, and the last one was promising. Heredia-Aricapa et al. [95] studied several substitutes for R410A, among them R446A, R447B, R452B, ARM-71A, R463A, R466A, R457A and ARM-20B, highlighting the COP reduction introduced by the last two ones, which present the lowest GWP values. In Table 3, the proposed R410A alternatives are resumed, together with their GWP indices. The authors want to clarify that the literature review is not comprehensive about working fluids.

Table 3. R410A proposed substitutes.

Refrigerant	Composition	GWP	Reference
R410A	R32/R125 (50/50)	2088	
R32		675	[90,96,97]
R446A	R32/R600/R1234ze(E) (29/3/68)	470	[95]
R447A	R32/R125/R1234ze(E) (68/3.5/28.5)	583	[93,94]
R447B	R32/R125/R1234ze(E) (68/8/24)	710	[94,95]
R452B	R32/R125/R1234yf (67/7/26)	677	[94,97]
R454B	R32/R1234yf (68.9/31.1)	466	[94,96,97]
R457A	R32/R1234yf/R152a (18/70/12)	139	[95]
R459A	R32/R1234yf/R1234ze(E) (68/26/6)	460	[94]
R463A	CO ₂ /R32/R125/R1234yf/R134a (6/36/30/1414)	1377	[95]
R466A	R32/R125/R131I (49/11.5/39.5)	733	[95]
ARM-20B	R32/R1234yf/R152a (35/55/10)	251	[95]
ARM-71A	R32/R1234yf/R1234ze(E) (68/26/6)	460	[95]
DR-5	R32/R1234yf (72.5/27.5)	490	[93]
ND	R32*R1234yf*CO ₂ 22/72/6	151	[90]

Several recent studies present low GWP refrigerants for ground-source heat applications. Emmi et al. [98] proposed a high temperature GSHP working with CO₂ and R1234ze(E) as refrigerants in a cascade arrangement. Bobbo et al. [96] shows the benefit in terms of COP of R454B as R410A alternatives, but, at the same time, the volumetric heating effect reduction applied to GSHPs. Wu et al. [99] analysed the possibility to use natural refrigerants, such as CO₂, ammonia, water, propane and isobutane as working fluid in GSHPs applications.

3.3.2. Fluid Flowing in the GHEs

When dealing with BHE design, the average temperature difference between secondary fluid circulating through the pipes and the undisturbed ground temperature is a key parameter to determine the BHE total length. Equally important is the choice of the secondary fluid. Several properties, such as good heat transfer properties, low viscosity, environmental safety, low cost and long life, are requested of a fluid to be feasible for GSHP application [100]. Water is known to be a good solution, but its application is limited by its freezing point. In cold climate countries, such as, for instance, Central and Northern Europe, the outdoor air temperature often falls below 0 °C in winter, and thus anti-freeze mixtures are often necessary. Otherwise, the BHE total length needs to be increased in order to reduce the temperature difference between the secondary fluid and the soil, increasing the installation costs as a consequence. Working with anti-freeze mixtures allows us to attain minimum temperatures lower than 0 °C, thus reducing the BHE length and still obtaining better performance than ASPHs, since the air temperature is lower than the minimum temperature reached by the secondary fluid. Glycols are commonly used in Europe as additives to water (20–30% usually) [100] and most of those used are ethylene glycol and propylene glycol. Other anti-freeze solutions, like alcohols (ethanol and methanol) or salts (calcium chloride, sodium chloride, potassium carbonate, etc.), are less used because of their toxicity or corrosive properties [101]. On the other hand, the addition of an anti-freeze solution may worsen the heat transfer properties and, when reaching low temperatures, the increased viscosity leads to a high energy consumption by the circulation pumps [100]. Bartolini et al. [101] compared the application of ethylene glycol, propylene glycol and calcium chloride with the use of water as a secondary fluid from an environmental and economic point of view. Emmi et al. [102] compared the performance of water and water/glycol in GSHPs in several scenarios, accounting for the type of thermal load (balanced, heating dominant or cooling dominant), the borehole field configuration and the choice between a dry expansion evaporator or a flooded one, showing that the addition of anti-freeze fluids, in mild climates, is more suitable for grid-shaped borehole fields and heating-dominant thermal load, while using pure water as a secondary fluid is suggested for all the other cases, reducing the overall operating costs.

As a further option, CO₂ in supercritical conditions has been considered to improve the heat transfer characteristics of the BHE, especially at high temperatures and rapid pressure change applications, such as hot dry rock geothermal exploitation. In their review on the latest advances on ground heat exchangers, Liang et al. [103] provided a brief excursus on the application of carbon dioxide as working fluid in GHEs, whose better performance compared to water is strictly related to the conditions of inlet temperature and inlet velocity to guarantee the supercritical state of CO₂. For the inlet pressure, an optimal value of 28 MPa is suggested.

Nevertheless, conventional heat transfer fluids, such as the abovementioned water and glycols, but also gas options such as CO₂ and air-ground heat exchangers (AGHE) [103], present a low thermal conductivity. This limit is overcome by the use of more recent technologies: Micro Phase Change Materials slurries (MPCMS) and Nanofluids.

Micro Phase Change Materials slurries (MPCMS): these materials are latent functional heat transfer fluids obtained by the dispersion of MPCMs in a conventional carrier fluid to get a slurry able to store and release energy with a minimum temperature difference. The presence of dispersed microcapsules of PCM with a diameter ranging between

0.1 and 1000 μm provides a high surface-to-volume ratio and enhanced turbulence, which leads to higher specific heat capacity and thermal energy storage potential. Recent studies have introduced the application of MPCMS for thermal energy storage purposes and as working fluid in GSHP systems: Pathak et al. [104] reviewed the available methods for the preparation of MPCMS and the techniques of characterization, displaying the potential fields of application for MPCMS. Kong et al. [105] experimented with the use of methyl stearate MPCM slurries in GSHP systems to assess their performance and durability as a secondary fluid in a coil heat exchanger. The results demonstrated an increase in the COP and in the heat load-to-pumping power ratio up to 5% and 34% respectively compared to water, thanks to the higher heat capacity of PCMs. Pu et al. [106] combined MPCMS and a three-shaped GHE to enhance the thermal performance of the GSHP system compared with traditional tube configuration with pure water flowing. The authors found out an improvement in thermal performance thanks to MPCMS, regardless of the tube shape. However, a high concentration of MPCM particles resulted in an increasing viscosity of slurry and thus in increasing pressure losses; in this respect the authors identified an optimum value for MPCMS concentration, corresponding to the 12% volume fraction.

Nanofluids: these fluids consist of nanometric solid particles (1–100 nm diameter) of chemically stable metals or metal oxides dispersed in a carrier medium, e.g., water, ethylene glycol, oils and polymer solutions.

The reviewed literature highlighted a higher heat transfer coefficients in nanofluids compared with the pure carrier medium, due to the higher thermal conductivity of the nanoparticles together with their size and shape, which provides a larger surface area and a better dispersion in the base fluid [103]. However, a key issue has been highlighted regarding the use of nanofluids, i.e., the increase in viscosity at higher nanoparticles concentration ratios. An increase in the volumetric concentration ratio involves an increase in thermal conductivity, accompanied, on the other hand, by an increase in viscosity, which leads to higher pressure losses and thus higher required pumping power, and to a linear decrease in volumetric heat capacity, with negative effects on the heat transfer coefficient. In the context of the European Project Cheap-GSHPs, Bobbo et al. [107] characterized the stability and thermal conductivity of two Al_2O_3 nanoparticles dispersed in water in four different concentrations (3%, 5%, 30% and 40% wt). The results demonstrated a significant increase in dynamic viscosity, which narrowed the focus to one nanofluid, W440 (3% wt). At lower concentrations, the authors found out that for the thermal conductivity enhancement to be significant, a temperature of 40–50 °C is required, thus excluding the mixture as a working fluid in GHEs. Kapicioglu et al. [108] studied the effect of Al_2O_3 /ethylene glycol-water nanofluid (0.1% and 0.2% wt) in GHE within a GSHP system in real environmental conditions, which determined an increase in the COP of 2.5% in U-type GHE and 3% spiral GHE with a concentration of 0.1%. Overall, both the studies by Bobbo et al. [107] and Kapicioglu et al. [108] confirmed a higher performance in the application of nanofluids for lower nanoparticle volume fractions. Jamshidi et al. [109] investigated the effect of different volume fractions of Al_2O_3 in Al_2O_3 / water nanofluid to flow inside a finned conical helical GHE, resulting in an increase in the heat flux on the surface of the tube of 18% for 0.5% volume fraction. The authors underlined the effect of the nanoparticle diameter, whose reduction increases the available surface area and the Brownian motion of the nanoparticles, thus improving the heat transfer rate. Diglio et al. [110] analysed the performance of various nanofluids to replace a conventional ethylene glycol-water mixture. According to the study, Ag-based nanofluids are characterized by the highest convective heat transfer coefficient, followed by Cu-based nanofluids, Al_2O_3 , SiO_2 , and CuO. On the other hand, Ag-based nanofluids and Cu-based nanofluids presented the highest pressure drops among all of the possibilities. On the whole, Cu-based nanofluids resulted in the highest reduction of the borehole thermal resistance R_b (up to 3.8%), thanks to a lower volumetric heat capacity reduction compared with the other nanofluids. The effect of nanofluids on the overall cost of the GHE represents another issue to be considered: Diglio et al. [110] assessed the cost of Cu-based nanofluid around 10 €/m (tube length), which corresponds to 12% of

total cost of the BHE, a significant percentage of the investment. Although an objective improvement is obtained in the literature by using nanofluids as heat transfer fluids in geothermal applications, the increase in the energy efficiency of GHEs does not exceed 5% [111]; Du et al. [111] identified the reason of this limit in the structure of traditional GHEs. To optimize the GHE geometry, the authors tested the use of CuO/water nanofluid as a heat transfer fluid in a dedicated experimental system, obtaining an increase in the heat load-to-pumping power ratio of 20.2%, contributing to a wider use of this technology for GHE applications.

3.4. Design and Control Optimization

The advantages of the use of the above technologies may be undone in the absence of design and control optimization procedures, key steps to guarantee high efficiency of the GSHP and avoid oversizing or downsizing of the system, together with a poor management of the system when operating. Appropriate design and control optimization are thus essential to enhance the cost-effectiveness of this technology, in terms of both installation and operating costs [112].

The main issues of any optimization procedure are: (i) definition of one or more objectives; (ii) identification of the problem variables to be optimized and the technological constraints to the procedure; (iii) formulation of the optimization problem; (iv) selection of the optimization method [110].

To date, several procedures are available in the open literature to reduce the energy consumption of GSHP systems by optimizing design and control strategies, usually validated on the basis of simulations or simplified applications [113].

Accurate design represents the first means of reducing energy consumption in HVAC systems. The challenge of optimal design lies in optimally determining the configuration of the plant and the heat transfer mechanisms, involving boreholes and the transient response of the system. As regards design optimization, when defining the objective functions, a main distinction can be made between thermodynamic objectives, focused on the performance of the GSHP (e.g., COP and total energy consumption), and economic objectives (e.g., operating and total costs), focused on reducing the overall costs of the system. As a consequence, depending on the primary objective, the problem variables to be optimized are identified, together with the relative constraints to be respected. For this purpose, sensitivity analysis is often used to determine those variables that have a higher influence on the selected output, as previously seen in Badenes et al. [19].

Nowadays, several works have been presented aimed to design and optimize GSHP configurations: Ma et al. [113] recently discussed and reviewed recent advances and development in the design optimization of the GSHP system, distinguishing between single-objective optimization (SOO), where a single objective function is assessed, and multi-objective optimization (MOO), where more objective functions subject to various optimization constraints are minimized or maximized simultaneously. Once the objectives and the variables are determined, the optimization method is chosen, strictly depending on the modelling approach used to design the GSHP. In fact, a first distinction in optimization methods can be made between simplified models such as the ASHRAE approach [28], a rules-of-thumb method which does not require computer code, and detailed calculations based on precise mathematical models [114,115].

The many methodologies for GSHP modelling have been widely applied and reviewed in detail and they can be roughly categorized in thermal response factor-based models (either numerical, analytical or hybrid models) [112,116–118], numerical thermal models [119–124], artificial neural network models (ANN) [125–128], and state-space models [129,130]. Based on the provided model, different design-optimization methods may be applied: in a study by Atam et al. [129], an exhaustive overview on recent advances in optimal design of GSHPs is provided. According to the authors, the easiest optimization approaches, based on rules-of-thumbs and charts, such as the famous ASHRAE method [28], are supposed to remain the dominant optimal design methods in the next future, thanks

to their ease of implementation and the absence of a mathematical model. However, rule/chart-based methods are widely recognized as being incapable of capturing the complex interactions between the GHE and the other components of the system, such as the evaluation of the penalty temperature T_p , a key parameter of the ASHRAE procedure, representing the interaction between borefield and ground after a certain operating time. Capozza et al. [30] assessed the role and the calculation of T_p in the ASHRAE method, which resulted in an underestimation of the length of the BHE of more than 10%. The simplicity of rule/chart-based methods is thus a double-edged sword, since it leads to an improper, or at least, non-exhaustive insight of the phenomenon.

For this purpose, mathematical model-based methods have a higher chance to solve the optimal designing issue [131]: numerical, analytical and computational heat transfer approaches are the macro-categories, including all the recent advances in this field. Nevertheless, most of the proposed solutions have been formulated considering just one borehole and may result in being inefficient when applied to an entire and complex system; moreover, to properly evaluate the validity of an optimal design method, the procedure should be compared with others on the basis of a common benchmark; this latter point remains nowadays mainly unexplored.

Optimal design alone may not provide an optimal solution for the GSHP system, since it should always be followed by control optimization, i.e., by optimising the operation time of the GSHP, considering the thermal inertia of the building. Since systems are typically sized based on the peak load, control systems are necessary to optimise the use of the stored heat in the ground and thus to reduce the operating costs [113]. However, optimal control depends on the aim of the control itself, i.e., the objective of the optimization process, which could be either the GSHP efficiency, cost saving or maximizing comfort of the inhabitants; from this perspective operating variables such as temperatures, flow rates and heat pumps speeds must be optimized in a range of operating constrains. Moreover, as for design optimization, the control method is strictly related to the approach used to model the heat transfer mechanisms in the GHE, which should properly consider both short- and long-term dynamic effects involving the soil, the boreholes and the thermal interaction between them; thus, some control procedures can be applied only to specific GSHP models. For this purpose, the choice of a co-design appears to be optimal, since it allows one to choose an integrated method for both optimal design and control at one time [129]. Compared with design optimization, a limited number of optimal control strategies has been presented in the literature [113]. A first distinction can be made between local control, i.e., control optimization performed at component level, and supervisory control, i.e., control optimization performed at system level taking into account the interaction between components [132]. Local control strategies may be basically identified with traditional/rule-based controls, also defined as Expert Rule Systems (ERS); this method mainly consists in a set of rules and operating schedules acting on a variable, typically a temperature set-point, to simulate the human decision-making process. Of course, control rules can be made more complex to increase the system performance by optimizing the set-point itself, the schedules' range and shape, and the parameter used for control. As happens for optimal design rule/chart-based methods, ERS are widely used thanks to their ease of implementation and the fact that a mathematical model of the underlying system is not needed, which is advantageous in case of complex borefields; however, ERS are unable to predict future states of the system and are fatally characterized by a lack of flexibility, which makes the optimization minimal, given the low number of scenarios considered [132].

Regarding supervisory control, Atam et al. [130] provided a comprehensive review on the state of the art and challenges of optimal control, using the conventional classification of model-based, data driven and model-free approaches; while Ma et al. [113] operated a further distinction between control optimization of stand-alone GSHP systems and of hybrid GSHP systems. Noye et al. [132] reviewed the challenges and strategies of control optimization and highlighted the potential of Artificial Intelligence for parameter optimization, system modelling and control optimization.

Model-based methods are widely applied for control purpose and it requires explicit knowledge about the system, on the basis of which detailed performance models are developed and used to guide control operations. On the other hand, data-driven methods require real performance data, that should be of a higher quality and be as extensive as possible, since the consequent method only relies on the selected dataset. Lastly, model-free approaches do not require a proper control model, but they only need of a correlation between control inputs and outputs; from a performance point of view, they are located between rule-based controls and model-based methods. From the reviewed literature the model-based approach appears to be the preferable one, guaranteeing significant cost savings [130]. Although the use of an accurate control model could be too difficult to apply for complex borefields, the use of adaptive models allows the control to continuously vary based on the values assumed by the model's parameters, thus following the performance degradation of the GSHP system [113]. Xia et al. [133] developed a model-based optimal control strategy in order to minimize the total energy consumption of a GSHP system by varying the speed of the variable speed pumps in the ground loop system. In the study, the use of a hybrid optimization technique, integrating a performance map-based near-optimal strategy and the exhaustive search method, resulted in an energy saving of up to 8% for heating and 9% for cooling, compared with ERS solutions.

Xia et al. [134] presented a model-based optimal control strategy based on simplified adaptive models for a GSHP-PVT system, and the optimal control strategy resulted in an energy saving of 7.8% and 7.1% for cooling and heating respectively, when compared with an ERS system.

Among the model-based controls, Model Predictive Controls (MPC), widely used for HVAC systems, have attracted a lot of interest for GSHP applications thanks to the possibility to optimize more parameters simultaneously and to predict the system's future states based on boundary conditions. MPC, in fact, uses mathematical adaptive models based on the physics of the system to adapt the control operations and to predict future scenarios. Despite the high computational effort, MPC can provide significant results: Weeratunge et al. [135] presented an MPC approach to control the operation of a Solar Assisted Ground Source Heat Pump (SAGHP) system, optimized using a mixed integer linear programming; by considering the variations of the price of the electricity inside the MPC, a reduction of operating cost of 7.8% has been obtained.

Table 4 provides a schematic of the main GSHP design and control optimization methods found in the literature.

As already highlighted for design optimization, an objective evaluation of a control strategy should be supported by the comparison with other methods on the basis of a common benchmark, where control studies are instead usually built on specific cases and optimization objectives. For instance, comfort of the occupants should always be maintained as key point in the development of design and control strategies, while in many of the reviewed researches this aspect is likely to be given up in favor of other priorities such energy performance and cost-effectiveness.

In conclusion, as a general rule, the control strategies have to be considered when dealing with unbalanced thermal energy cases, i.e., when there is a dominant heating case or a dominant cooling case, when usually the drift of temperatures have to be avoided in the ground in order to keep the seasonal COP and EER stable over time. This is usually linked to the issue of combining the GSHP systems with other sources, as shown before, i.e., solar thermal collectors, PV, PVT, air to water heat pumps. This latest case is particular promising, especially in medium/large heating and cooling plants or in any case when the space available in the surrounding area is not sufficient to host the whole GHE field. As shown in recent researches [136], the dual source heat pumps, also named hybrid solutions, can lead to better performance compared to an undersized GSHP with an undersized GHE field.

In general, the so-called multi-source systems present energy storage systems, which are usually able to store energy for some hours or up to few days. In multi-source systems,

the ground can play a role in storing energy seasonally both in the heating period and in the cooling period.

Table 4. Classification of GSHP design and control methods.

Modelling		
Model		Reference
Thermal response factor-based models		[112,116,117]
Numerical thermal models		[119–124]
Artificial neural network models		[113–128]
State space models		[129,130]
Optimal design		
Model		Reference
Numerical methods		[129,131]
Analytical methods		[129,131]
Computational heat transfer approaches		[129,131]
Rule/chart-based methods		[28,30]
Optimal control [113,130–135]		
	Model-based	
		Data-driven
Model-free	<ul style="list-style-type: none"> Linear/dynamic programming Mathematical optimization Metaheuristic Model Predictive Controls Extremum seeking control 	<ul style="list-style-type: none"> Predictive ERS Metaheuristic
<ul style="list-style-type: none"> Conventional ERS Fuzzy logic Statistical optimization 		
Co-design		

4. Conclusions

A great potential emerges for GSHPs due to their high efficiency level. In particular, for the building sector, a reduction of 20–40% and 30–50% of the energy demand could be potentially achieved, for heating and cooling respectively. At the same time, such potential is still mostly unexpressed due to economic issues regarding drilling and installation costs. Other obstacles are the low awareness of the main stakeholder and the invasiveness of the drilling, the latter covering a major share in the total cost of the plant, between 20% and 60%. In order to exploit GSHP potential, several EU research projects are ongoing with the aim to make this technology cheaper and more cost-effective by working on more cost-effective heat pumps and more efficient borehole heat exchangers, with reduced length. Current research on borehole heat exchangers focuses mainly on more compact and easier to install heat exchangers, more efficient materials and more compact drilling machines to reduce the invasiveness of installation. In this paper, the state of the art and future developments on GSHP technology have been reviewed, providing an overview on last advances regarding (i) pipe materials, (ii) grout materials, (iii) refrigerants and secondary fluids, (iv) optimal design and control strategies. From the reviewed literature promising developments emerge:

- (i) As far as pipe materials are concerned, an optimal value of 1.5–2 W/(m·K) has been defined for thermal conductivity of pipes in GHEs; for this purpose thermally enhanced HDPE is expected to remain the dominant technology, thanks to the possibility to combine the good mechanical properties of conventional HDPE with the high thermal conductivity of additives, especially graphite and aluminum wires. Newer solutions, such as the use of nanomaterials and heat pipe BHEs still require further improvements, although they have demonstrated interesting potential.

- (ii) A new benchmark of 2.5–3.3 W/(m·K) has been defined for thermal conductivity of grout materials, which has been proven to be proportional to GHE effectiveness and is inversely related to the length of the GHE and its cost. To reach this optimal value, graphite thermally enhanced grouts remain the best option, both in terms of know-how and numerical results, achieving thermal conductivities up to 5 W/(m·K) and a reduction of 33% for the required BHE and of 30% for the overall GHE cost. Between new proposals, CLSMs and PCMs have shown good potential, the latter able to reduce thermal interference between pipes, which severely affects conventional thermally spiked grouts. However, the low thermal conductivity of PCMs has necessitated the introduction of thermally enhanced PCMs, whose performances, in terms of thermal conductivity, are still not comparable to those of CLSMs and conventional spiked grouts.
- (iii) Micro Phase Change Materials slurries (MPCMS) represent the best substitute to conventional heat transfer fluids at present, providing an increase in the COP and in the heat load-to-pumping power ratio compared to water up to 5% and 34% respectively, thanks to the higher heat capacity of PCMs. On the other hand, at the moment, nanofluids are still a non-competitive technology, due to their high cost, which corresponds to up 12% of total cost of the BHE, and their slight increase in the energy efficiency of GHEs, which does not exceed 5%.
- (iv) Finally, great attention has to be paid to proper design and proper control of the GSHP plant, in order to guarantee low operational costs and limit investment cost. Although rules-of-thumb and chart approaches are supposed to remain the dominant optimal design methods in the next future, mathematical model-based methods have a higher chance of solving the optimal designing issue. Moreover, from the control side, the model-based approach appears to be the preferable one, guaranteeing significant cost savings. In particular, the use of adaptive models such as MPCs have shown great potential for GSHP applications, thanks to the possibility to adapt control operations and predict future scenarios, providing a reduction of operating cost up to 8%. However, to be properly evaluated, optimal design and control methods should be compared with other procedures on the basis of common benchmarks; this point, which remains nowadays mainly unexplored, and the reduction of computational effort and model complexity, should be the focus of research in the future.

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