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Review

Ground Source Heat Pumps in Buildings Revisited and Prospects

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Abstract: A large number of ground-source heat pump (GSHP) systems have been used in residential and commercial buildings throughout the world due to their attractive advantages of high energy and environmental performances. In particular, GSHPs constitute a proven renewable energy technology for space heating and cooling. This paper provides a detailed literature review of the primary aspects of GSHP systems. These include the technological characteristics of HPs and the main types and variations in GSHPs, along with their environmental impact. Other aspects addressed are the integration of GSHPs with other systems, as well as their optimal design and control and energy analysis. The important aspect of the system's performance is also dealt with through case studies and also the barriers hindering the further adoption of GSHPs in buildings. Two important challenges for the adoption of GSHPs is their cost and environmental efficiency. Studies have shown that GSHPs can reach a >>24% lower environmental impact than air-source HPs, while today's technology can allow for a payback period for installing a GSHP of <<5 years. Finally, based on the above review, the future challenges and prospects for the successful uptake of GSHPs is discussed. It seems that through the right steps, the wide adoption of GSHPs as an important form of 'implemented' renewable energy system can become a reality.

Keywords: ground-source heat pump; geothermal energy; heat pump; ground heat exchanger; heating and cooling of buildings

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1. Introduction

Decarbonizing the energy sectors, including transportation, heating and cooling, and electricity, is essential for the transition to a low-carbon energy future. Among such sectors, heating and cooling accounts for 50% of the total energy demand in the European Union (EU), 75% of which is contributed by fossil fuels [1]. Although fossil fuels and conventional electric heating technologies are expected to dominate the heating sector for the next few years, the market share of energy-efficient and renewable-based technologies, such as heat pumps (HPs) is expected to increase through supportive policies [2]. In mild climates, HPs can serve as primary heating/cooling systems, while in colder climates, they can serve as secondary heating systems [3]. There is a strong body of evidence in the literature that suggests that the deployment of HPs, which are considered superior to other alternatives, such as oil and natural gas boilers, solar collectors and biomass, results in savings in primary energy consumption, in increased overall efficiency and in reduced carbon emissions [4–11].

Hence, even though HPs have been popular for decades for new office and residential buildings with specific modes for domestic hot water production [10], they have gained significant importance in recent years due to their potential to reduce emissions and stakeholders' renewed interest; still, their share is only 3% of the heating in buildings [5]. However, a significant increase in HP installations is expected in the coming years, particularly in countries where the majority of heat demand is still met by fossil fuels. For example, in Europe, by 2050, it is hoped that installing high-efficiency HPs in buildings will replace natural gas space heating, saving around 60% of primary energy use and 90% of associated CO_2 emissions [12].

HPs are devices that extract heat from one place and transfer it to another, utilizing electrical or mechanical energy by means of circulating refrigerants, having an operating principle similar to refrigerators. In heating mode, HPs transfer thermal energy from outdoor to indoor, while in cooling mode, heat is transferred from warmer to cooler space [13]. HPs convert excess renewable energy to heat, thus helping to decarbonize the heating sector. The coefficient of performance (COP) can be used to compare the efficiencies of different HPs operating at the same conditions. A higher COP means that HPs consume less energy while providing more heat [14].

Among the various HP technologies, ground-source heat pumps (GSHPs) have most recently received increased interest because of their superiority in high energy performance, environmental friendliness and the ease of their integration with other energy systems [15,16]. The focus of the present study is thus on GSHPs. The reverse Carnot thermodynamic cycle serves as the foundation for GSHPs, this being a thermal installation. As illustrated in Figure 1, it is composed of an HP subsystem, a heat distribution subsystem, and a geothermal extraction subsystem [14]. Through the heat recovery device's antifreeze circulation and the HP's refrigerant circulation, the ground-source heat is extracted by the GSHP system and subsequently distributed to the interior air and water storage. The foundation of GSHPs is the fundamental fact that the earth's temperature is nearly constant at a given depth below the surface [17]. By connecting HPs, GSHP systems have become a prominent example of geothermal technology that uses the earth, groundwater, or surface water as the heat source or sink [18]. Geothermal energy is a significant renewable energy source that offers the alluring benefits of high sustainability, minimal emissions, and environmental friendliness [19]. Although installing GSHPs is more costly than installing air and water HPs (ASHPs and AWHPs), effective GSHPs can be designed by utilizing various methodologies for multi-objective optimization to optimize both thermodynamic and economic goal functions [20–23]. Hybrid ground-source heat pumps (HGSHPs), such as a cooling tower-assisted system and/or an additional heat rejecter, are typically used to address the high-cost issue [24,25].

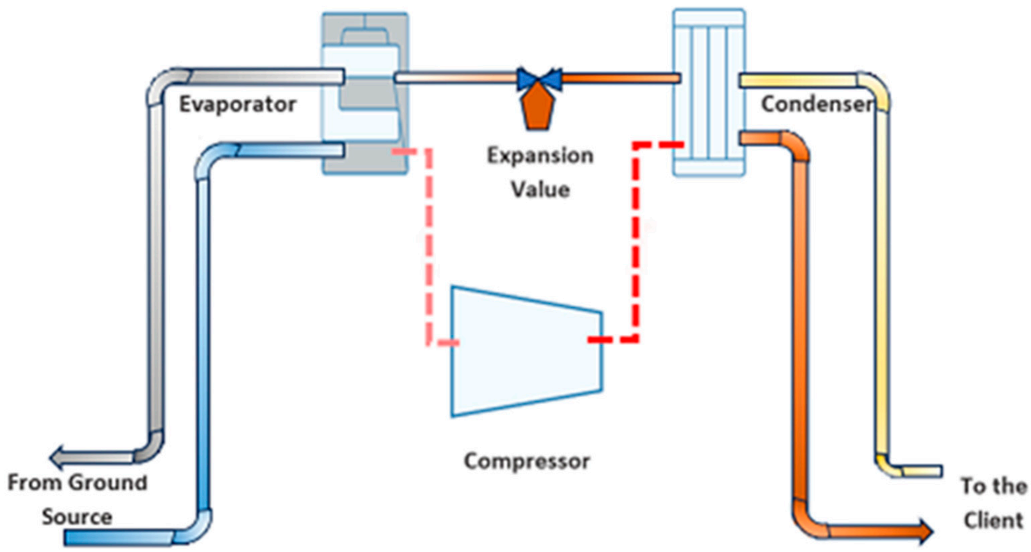

Figure 1. Schematic of a ground source heat pump system (modified from [14]).

The initial idea for employing a GSHP was stated in a successful 1912 Swiss patent by Heinrich Zoelly. Later on, Robert C. Webber, upon experimenting with a freezer, constructed the first direct exchange GSHP [26]. Therefore, over a century has passed since the beginning of GSHP applications. Following World War II, there was initial interest in GSHP technology, which persisted throughout North America and Europe into the early 1950s. In particular, the first successful commercial project was erected in the Commonwealth Building of Portland, Oregon, in 1948, and the ASME (American Society of Mechanical Engineers) declared it a National Historic Mechanical Engineering Landmark. At the same time, Professor Carl Nielsen of Ohio State University constructed the first residential open-loop GSHP version in his home in 1948 [27]. With the expansion of GSHP activities following the first global oil crisis, the next phase began in the 1970s [28]. According to estimates, the global installation of GSHPs has increased steadily over the past few years, growing by a range of 10–30% annually, with increases of 25–60% in a number of countries [29]. With knowledge from Canada, by the mid-1990s, the USA and Europe started to develop GSHPs [30,31], which led to a substantial number of installations in the 2010s, including 13,564 MWt of GSHPs in the USA by 2012 (which accounted for 29% of the world's total capacity) [32] and 1.7 million GSHPs by 2015 in Europe, with 33% of them being in Sweden. [33,34]. Also, China's installed GSHP capacity reached 631 MWt by 2005 [35,36], but by the end of 2019, China had the largest air-conditioned building area globally, measuring up to 841 million m^2, even though by 2020, it accounted for only 8.7% of all centrally heated building areas [35].

Because the earth's temperature is higher at night than it is during the day and is frequently lower than the surrounding air, the GSHP is a preferable choice for both heating and cooling applications [37]. The advantages of GSHPs include their long service life of over 25 years, their low environmental impact and durability due to their lack of greenhouse gas (GHG) emissions, their versatility in being used in a variety of building types and sizes, and their variety of ground heat exchanger (GHE) types [38,39]. However, their growth is impeded by a multitude of barriers, both technical and non-technical [4,30]. When compared to conventional cooling and heating systems, the biggest disadvantage of a GSHP is its high capital installation cost. From this viewpoint, GHEs that are horizontal and open loop are preferable to those that are vertical [37,40].

As seen in Figure 2, there are three primary types of GSHPs: ground-coupled heat pump (GCHP) systems, ground water heat pump (GWHP) systems, and surface water heat pump (SWHP) systems [18]. A GCHP connects a borehole heat exchanger (BHE) (i.e., a vertical GHE) to an HP. GWHP is frequently an open system that uses an injection well to recharge groundwater that has been pumped out of an aquifer. The water in a lake, pool or river is frequently used as a heat source or sink by the SWHP system. To address the rising ground thermal imbalance, HGSHP systems have also been created, as mentioned above, using auxiliary components, such as heat sinks or heat sources, to supply a portion of the building's cooling and heating needs [21,22].

(a) (b) (c)

Figure 2. The three types of GSHPs: (**a**) GCHP, (**b**) GWHP, (**c**) SWHP (modified from [18]).

A GSHP's performance is influenced by several design and physical parameters [41]. Many attempts have been made to date on the mathematical modeling [42] and performance evaluation of GSHP systems, such as thermal performance simulation [43] and exergy analysis [44], which have produced basic theories and references for the suitable design and efficient control of GSHP systems. A review and discussion of the various forms, geometric features, and modeling of GHEs can be found in [45]. The choice of backfill materials, or grout, to be placed around the GHE pipes and soil is crucial since the ground's characteristics, the grout's thermal conductivity, and the hydro-geological conditions are the main factors affecting the GHE's performance [46]. The efficiency of the GHE is improved by the grout's high heat conductivity [47]. When designing a GHE, to achieve the smallest size while yet suitably providing the required heat flow for the system operation, it is imperative that the monthly peak, daily loads, and average annual loading be accurately estimated [48]. Also, for acceptable system design and operation parameters, the thermal ground recharge should be completed during the summer while satisfying the cooling requirements through the GHE, depending on the operating modes [49].

GSHPs have a large potential for energy savings and can be employed in both hot and cold climates worldwide [50–52]. In contrast to alternative solutions intended for green buildings, GSHPs have the benefit of being dependable energy sources with lower disruption rates [53]. Although there are opposing cases as well, the main conclusion from the literature emphasizes the necessity of guaranteeing high-quality HP installations as geothermal heating is not "ready-made" and must be designed for each unique circumstance [10,54,55].

Numerous innovative techniques and approaches for the best possible design and control of GSHP systems have been continuously developed because of the rapid advancement of technology and ongoing efforts to implement these systems. There has been a great deal of discussion on the optimization of GSHP systems, including how to formulate optimization problems, choose optimization objectives and techniques, identify decision factors, optimize design, and achieve optimal control [30]. Additionally, a sensitivity assessment (or analysis) is frequently useful to perform for identifying the choice variables in creating optimization challenges.

The main aim of the current paper is to provide readers with a literature review covering several aspects of GSHP application in buildings. There exist of course numerous reviews in the literature dealing with various aspects of GSHPs or HPs in general (more than 30 such reviews are cited here; see Table 1). These, however, address specific aspects of GSHPs. The current review presented herein deals collectively with the most important aspects of GSHP, given in the sections that follow. Most importantly, the challenges and prospects of the application of GSHPs in buildings are addressed. The review is extensive enough to adequately cover these aspects. The methodology followed is presented in Section 2. Then, in Section 3, the technological characteristics of HPs are presented, focusing on the main types of GSHPs and the different variations thereof, addressing their environmental impact as well. Section 4 deals with a review on the ways of integrating GSHPs with other systems through presenting relevant examples. In Section 5, the very important issue of optimal design and control and the energy analysis of GSHP systems is addressed through the various methods and models that exist in the literature. This is followed by a selection of case studies that mainly address the performance of the systems (Section 6). In Section 7, the barriers and the limitations hampering the even more widespread application of GSHP systems in buildings worldwide are presented in detail based on certain classifications. Then, based on the previous sections, Section 8 follows with a discussion on the challenges, prospects and recommendations for the successful future uptake of GSHPs. We conclude with Section 9.

Based on the themes mentioned above, the review is expected to provide answers to the following questions/hypotheses about GSHP systems in buildings:

- Today's optimization techniques allow for decreased energy consumption.
- Today's technology and design techniques allow for decreased energy consumption.
- Consequently, the payback periods (compared to ASHPs or other conventional HVAC systems) are within the acceptable limits of a few years.

- GSHPs' environmental impact in comparison to ASHPs or other conventional HVAC systems is considerably lower.
- Despite the barriers (technical and non-technical) hampering their integration, the prospects of the widespread adoption and penetration of GSHPs are high.

Table 1. Review articles on GSHP.

Reference	Theme
Gaur et al. [4]	HP technologies, environmental impact of HPs, economic aspects of HPs, mathematical modelling of HPs, barriers to HP integration
Wu et al. [14]	GSHP systems with heat pipes
Lebbihiat et al. [15]	Geothermal energy use in Algeria compared to the worldwide, utilization opportunities, barriers, and countermeasures
Yang et al. [28]	Mathematical models for various systems of vertical borehole GCHPs
Lund and Boyd [29]	Worldwide (2015) direct utilization of geothermal energy for space heating and cooling, agriculture, etc., studying geothermal HPs, capacity factors, and energy savings
Lund et al. [31]	Worldwide GSHPs for technical, environmental, and economic incentives
Wilke et al. [33]	Types of advanced thermal response tests and evaluation methods
Bayer et al. [34]	GSHP systems in Europe, installed capacity and performance, technology, greenhouse gas emissions and savings, potentials for the future
Lund and Toth [35]	Worldwide (2020) direct utilization of geothermal energy for space heating and cooling, agriculture, etc., studying geothermal HPs, capacity factors, and energy savings
Li and Lai [42]	Analytical models for heat transfer by vertical GHEs and the effect of various physical parameters
Sarbu and Sebarchievici [50]	GSHP systems for heating and cooling of buildings with regard to the HP operation principle, energy efficiency, HP types and technologies, environmental performance, and mathematical models of GHEs
Grant and Booth [56]	An analysis of 14 review types and associated methodologies such as critical reviews, meta-analyses, mixed methods reviews, etc.
Demir et al. [57]	Adsorption HP types, problems, and solutions
Luo et al. [58]	GSHP systems and the corresponding ground investigation including geological survey, ground thermo-physical properties, determination of ground thermal properties, and hydrogeological conditions
Jouhara et al. [59]	Latent thermal energy storage technologies including phase-change materials and applications
Christodoulides et al. [60]	The modeling aspects and practices of shallow geothermal energy systems including types of models, boundary conditions, short-term vs. long-term analysis, thermo-mechanical interactions, and software tools
Mohamad et al. [61]	Energy pile design, evaluation, and optimization with types, criteria, and methods
Cui et al. [62]	Types and mathematical modeling of GHEs including energy piles
Zhu et al. [63]	Applications of GSHPs integrated with thermal energy storage systems, types, and energy analysis
Marinelli et al. [64]	Life cycle thinking applied to various types of HP systems
Zhang et al. [65]	HP water heater for residential use in Japan, types of compressors and other HP water heater standards from other countries
Finnegan et al. [66]	Sustainable energy technologies, including GSHPs, used in buildings, and the embodied CO_2e through various methods and analyses
Zhai et al. [67]	Applications of GSHP systems in civil buildings and their integration with other systems

Table 1. *Cont.*

Reference	Theme
Dieng and Wang [68]	Solar adsorption technologies for ice-making and A/C and solar technologies, design and operating considerations, and energy storage
Lucia et al. [69]	GSHP systems for heating/cooling, technologies and thermodynamic approach for efficiency
Aresti et al. [70]	The design aspects of GHEs including types, geometry, materials, mathematical modeling
Fischer and Madani [71]	HPs and smart grids with regard to technologies, controls, methods
Gaigalis et al. [72]	HP implementation in Lithuania, the National Energy Strategy and EU policy regarding evaporation, compression, condensation, expansion as well as energy, integration, implementation, market characteristics, technological trends and expectations
Menegazzo et al. [73]	State of the art, perspective and barriers of GSHP technologies in the European building sector
Tsagarakis et al. [74]	Legal frameworks for shallow geothermal energy in European countries and the need for guidelines
Karytsas and Chaldezos [75]	Legislative frameworks for GSHPs and suggestions for improvement

2. Methodology

Given the purpose of this study, as stated in the preceding section, an accurate assessment of the scientific literature (well over 300 papers were included) was required, which was carried out by the authors, using a hybrid form review method. The research was carried out between 2023 and 2024. Collected information, mostly spanning the years 2000 to 2024, were supplemented with ideas/ knowledge gleaned from the authors' personal experiences, background, and current expertise.

Several databases were used, namely Google Scholar, Science Direct, Springer, Taylor and Francis, Wiley-Blackwell, and other. Numerous keywords/statements were utilized to find the articles in the primary research, in addition to "ground-source heat pump", such as "GSHP", "geothermal heat pump", and "heat pump", also in conjunction with "ground-source heat pumps", with keywords/statements such as "state of the art", "technologies", "integration with other energy sources/systems", "hybrid systems", "optimal design", "optimal control", "energy analysis", "barriers for the adoption/diffusion", "environmental impact", "technical challenges", "non-technical challenges", and so on.

The approach used to construct this manuscript's review adheres to the general characteristics of the so-called 'mixed studies review' type, as outlined by the simple analytical framework SALSA (search, appraisal, synthesis, and analysis) [56]. According to this, a 'mixed studies review' considers a variety of methodologies, with a 'literature review' being a key component. The current text contains common aspects of a 'critical review', 'literature review', and 'state-of-the-art review'. As a 'critical review' and 'literature review,' the authors' review work gives an opportunity to 'take stock' and analyze earlier literature studies as well as work on the specific issues of the development and prospects of GSHPs, including various sorts of studies and sources. Furthermore, the produced product serves as a starting point for additional examination, rather than an endpoint in itself. The examined topic is considerably broad and addresses important issues, providing insights and identifying prospective areas for future research, as is customary in a 'state-of-the-art review'.

The collection of information through the above-mentioned methods, together with constructing the framework, as introduced above (see Section 1), was then followed by reviewing all chosen aspects relating to GSHPs. Moreover, a number of relevant case studies are presented to give a quantification side to the present review.

3. Technologies and Environmental Impact

3.1. GSHP Technologies

A heat pump is a thermal installation that uses a reverse Carnot thermodynamic cycle to transport (pump) heat from a low-temperature source to a high-temperature source while consuming the drive energy [50]. The heat source may be (i) a gas or air, (ii) a liquid known as general water, or (iii) soil. The HP generates thermal energy at a higher temperature, with this energy primarily used for space heating or cooling; in cooling mode, the HP operates just like a central air conditioner. HPs can be used to power a variety of energy sources, including electrical energy (electro-compressor), mechanical energy (mechanical compression with expansion turbines), thermo-mechanical energy (steam ejector system), thermal energy (absorption cycle), and thermo-electrical energy (the Péltier effect). HPs may be classed based on (i) heat source and sink, (ii) heating and cooling distribution fluids, and (iii) thermodynamic cycle. The sizing factor (SF) of an HP is defined as the ratio of HP capacity to maximum heating demand. The SF can be maximized in terms of energy and economics, based on the source temperature and the adjustment schedule utilized [50]. Among the many categories of HP technology now available on the market, the most prevalent types are air, water, and ground source. However, additional forms of HPs now exist as a result of technological advancements and increased economic feasibility [4].

An air-source heat pump (ASHP) is a device that raises low-grade airborne heat to a high-grade state suitable for use in home heating and other applications. The HP generates more heat than it consumes when it comes to power. Air-to-water HP (AWHP) or air-to-air HP (AAHP) are the two types of ASHPs. Wet central heating systems are utilized by AWHPs to distribute heat, while AAHPs create heated air that is blown around by fans. Analogous processes exist in the case of cooling. Applications for ASHPs include hot water supply and home space heating and cooling. When used in conjunction with a floor heating system, ASHPs may offer thermal comfort at a lower cost of operation than cast iron or bi-metal radiators. However, when integrated for the purpose of heating and cooling an interior space, they may require more sophisticated control mechanisms in order to satisfy the thermal comfort needs of occupants [76,77]. Utilizing thermal energy from low-grade heat sources (such as waste heat), sorption heat pumps (SHPs) produce heat. SHPs include absorption and adsorption HPs, which are also referred to as heat-driven HPs. The thermodynamic cycle is what separates these two kinds of HPs from one another. The SHP system's capacity to use waste heat in industrial settings is one of its main advantages [57].

A GSHP operates using the same refrigeration cycle as a traditional ASHP [58,78]. Its four main components are the expansion valve, compressor, condenser, and evaporator. As shown in Figure 1, using the heat rejected from the condenser or the heat received by the evaporator, a conventional heat exchanger can be used to directly heat or cool the conditioned room. Among the many HVAC (heating, ventilation, and air-conditioning) systems in which GSHPs have been employed are underfloor heating systems and conventional HPs. Similar to an ASHP, it can provide heating and cooling by employing a directional control valve to alter the working fluid's flow direction through the different refrigeration cycle components. For instance, the terms 'condenser' and 'evaporator' refer to the indoor and outdoor heat exchangers in the context of heating. The primary difference between a GSHP and an ASHP is that the former uses the earth instead of air for heating and cooling [79]. It performs better and is more stable since the ground's temperature is almost always the same, which is not the case for air. It is feasible to more accurately choose the cycle's pressures and temperatures to run under optimal conditions and provide the highest COP. While both ASHPs and GSHPs generally emit fewer GHGs than direct electric heating, GSHPs perform better than ASHPs and maintain a relatively constant performance year round in contrast to ASHPs, whose performance is very location-specific [80–85]. Generally, a route towards sustainable development is offered by HPs. A ground connection subsystem, an HP subsystem, and a heat distribution subsystem are the three main parts of a GSHP system [50]. It should be noted that the phrases 'ground-source HP system', 'earth energy system', and 'geothermal HP system' are used interchangeably in the literature. The three primary categories of GSHPs are described below.

(i) Ground-coupled heat pump (GCHP): A GCHP is a closed-loop GSHP. A ground heat exchanger (GHE) transfers heat between the earth and HP. Vertical, horizontal, and coiled GHEs are the three fundamental types that can be used in a GCHP. The type of GHE significantly influences the system's cost and performance. Horizontal GHEs are classified into at least three types, single pipe, multiple pipe, and spiral, and are installed in dug trenches around 1–2 m below ground level. To save the required ground area, multiple pipes (two, four, or six) placed in a single trench can reduce the amount of required ground area. Vertical configurations may include many boreholes, each containing GHEs through which the heat exchange fluid (refrigerant/antifreeze fluid) is circulated. Typical U-tubes have a nominal diameter of 20–40 mm, and each borehole is usually 20–200 m deep and has a diameter of 100–200 mm. The drilling annulus is typically backfilled with a specific substance (grout) designed to avoid groundwater pollution. According to Figure 3, GCHPs can be of the direct expansion type, with the evaporator and condenser installed immediately in the ground, with the GHE, which is commonly made of copper tubes, receiving the refrigerant directly. The majority of GCHPs, however, use a secondary loop between the ground and the HP, with the GHE, which is this time commonly built of HDPE (high-density polyethylene) pipes, used to circulate water or antifreeze fluid. Because only one heat exchanger is needed, a direct exchange GCHP often outperforms the secondary loop GCHP. However, the use of direct exchange GCHPs is limited to small units due to the pressure drop effect, which may significantly impair its performance in applications where big GHEs are required [59,86]. A variant of the above is using energy piles (or other types of so-called energy geo-structures) in the GSHP system to save drilling cost [60–62,87].

(ii) Groundwater heat pump (GWHP): Geothermal energy systems employ open loops to take subsurface water (e.g., from a well), use it, and then inject it back into the earth. A GWHP mainly makes use of open ground loop systems to introduce or remove heat from the well [88]. Among GSHPs, GWHPs perform the best and have the lowest initial cost. However, to operate, they require a substantial amount of groundwater and must follow certain environmental regulations, and they are prone to water pollution, most notably from thermal short circuits, which are a basic drawback of open loops and are mostly found in standing column wells, where water is produced and injected into the same well. The rejection well and the extraction well are kept apart in a two-well arrangement. The performance of the GWHP may be further enhanced by injecting the water at a distance from the extraction well to encourage increased groundwater flow. Open-loop geothermal systems (OLGSs) can reduce the impact of thermal short circuits without requiring two wells. OLGs use a packer to divide the injection and production portions, with perforated pipes allowing adequate working fluid circulation [89–92].

(iii) Surface-water heat pump (SWHP): An SWHP is a different sort of water source heat pump that depends on different types of water sources such lakes, ponds, rivers, and oceans. SWHPs, unlike GWHPs, come as open- or closed-loop systems [93,94]. Closed-loop GCHPs and closed-loop SWHPs function similarly. The main difference is that instead of using water as a heat source or sink, the GCHP employs the ground. In the open-loop configuration, water is forced from the water supply to the HP and then returned far from the extraction point. The closed-loop SWHP uses a heat exchanger to facilitate heat transfer between the groundwater and the HP. The closed-loop system has lower operating expenses since it requires less pumping power than an open loop. Closed-loop SWHPs commonly use coiled GHEs.

Other varieties of HPs, including multi-temperature, thermoelectric, and magnetic regeneration-integrated heat storage models, are used in the refrigeration sector (although research on these models is still under progress) [95–97]. Direct expansion GSHPs, a variation on the ordinary GSHP, have the potential to perform better since they circulate refrigerant through a network of buried copper pipes [98,99]. Also, with the exception of their limited selection range and inability to cool, GSHPs with heat pipes (HPGSHPs) offer significantly better heating performance than conventional GSHP systems. They can achieve nearly constant temperature distribution inside the heat pipe, maximizing the temperature difference between the evaporation section of the GSHP and the heat source [14].

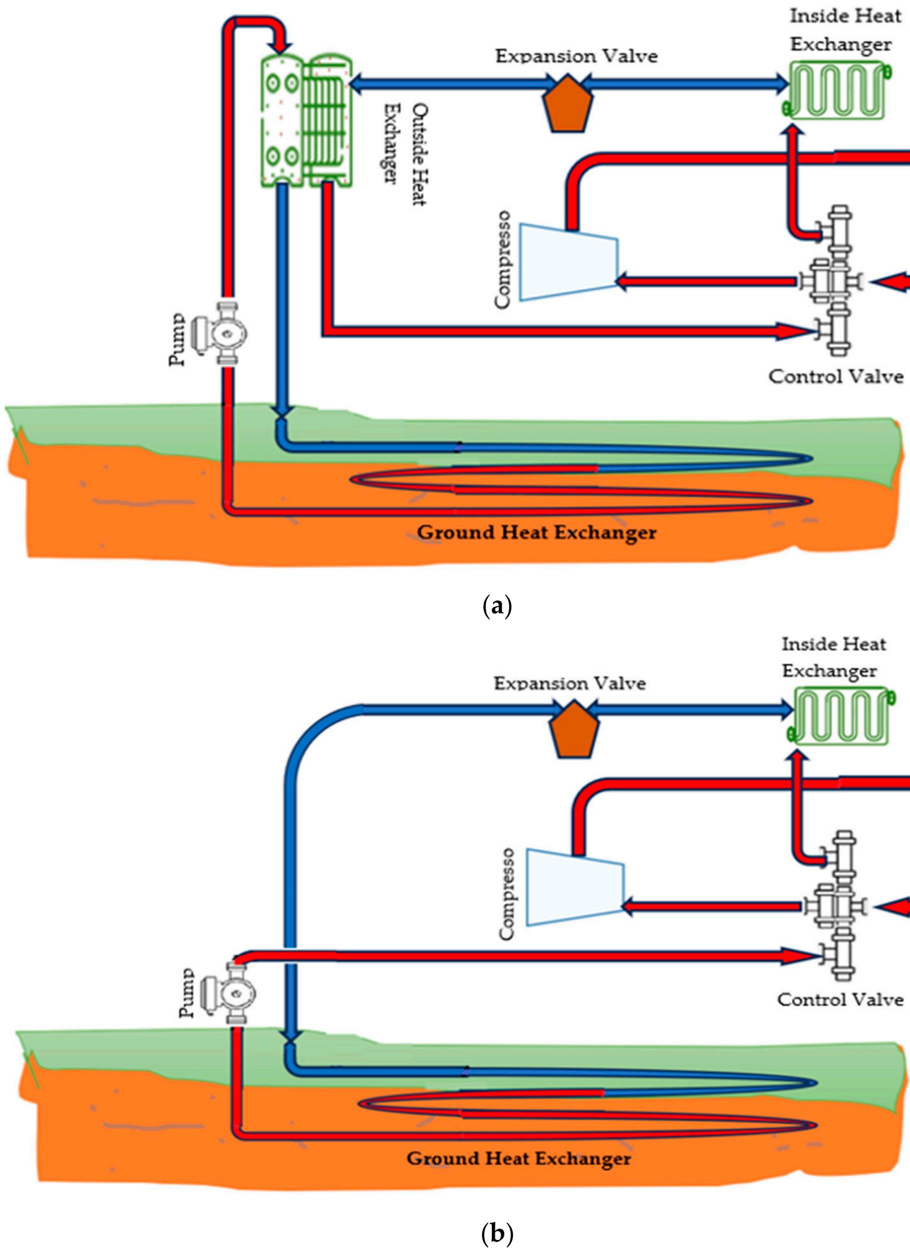

Figure 3. Schematic of types of GCHPs: (**a**) secondary loop, (**b**) direct loop (modified from [37]).

Because of the long-term transient heat transfer in GHEs, it is known that GCHP systems can achieve improved energy performance in certain locations where building heating and cooling loads are well balanced year round. Nonetheless, the majority of buildings in regions with either a warm or cold environment have unbalanced loads, with cooling or heating loads predominating. The hybrid GCHP (HGCHP) system is a solution that lowers the initial cost of the GCHP system while simultaneously improving system performance. It consists of an additional heat rejecter or heat absorber [63].

Furthermore, solar-assisted GSHPs (SGSHPs) are dependable and efficient systems that can handle low temperature heat demands, such as those for hot water and space heating in homes. With the right control technique, they can even prove to be the most economical heat supply option [100–102]. Moreover, the so-called hybrid gas-source HP system combines GSHPs, which may operate economically with the right control techniques, with conventional heating or cooling systems like gas boilers, electric heaters or cooling towers [103,104]. More on this can be found in Section 4.

The literature generally agrees that the type of application and weather conditions play a major role in selecting the best HP technology [4]. For instance, ASHPs are preferable in warm climates, whereas GSHPs are ideally suited for areas with harsh winter weather. If using waste heat is the goal, sorption (adsorption or absorption) HPs should be considered first. As long as there is consistent solar radiation in the vicinity, HPs using solar technology have greater COPs.

Regarding GSHPs, numerous approaches have been put forth to enhance their thermo-economic performance, including optimizing the subsurface heat transfer efficiency of GHEs [95], optimizing parametrically the use of high-temperature-conductive grouting materials [96], experimenting with various U-pipe configurations [97], arranging GHEs in relation to groundwater flow [103], and managing GHE operations [104].

3.2. GSHPs Environmental Issues

One of the problems in developing sustainable energy is minimizing the negative effects on the environment and human health. Simultaneously, the sustainable energy system may be seen as a dependable, economical, and eco-friendly system that efficiently utilizes existing energy resources and networks, while also experiencing increases in energy access, security, affordability, and efficiency in energy utilization [105]. Accordingly, GSHPs have been widely realized as thermal energy solutions based on renewable energy resources that can help reduce energy consumption and mitigate CO_2 emissions [106]. These technologies include features that include energy savings, economic benefits, and environmental protection [35,107].

As already mentioned, GSHPs are regarded as among the most promising options for decarbonizing the heating and cooling sectors, often with a very short payback period (<3 years), after replacing coal-fired boilers and electric resistive space heating [108–111] or (<5 years) upon choosing GSHPs instead of ASHPs [112]. It is worthwhile to investigate the social aspects of GSHPs that have previously been disregarded [64]. HPs are a cause of noise pollution, and their removal may be necessary to prevent disturbances in the neighborhood [113,114]. Often, thermal efficiency, fluctuating subsurface temperatures, and higher drilling and installation expenses are just a few of the challenges that must be managed [115]. Also, studies in the literature include quantifying the frequency and types of applications with incidents like drilling through multiple aquifers, leaving hazardous heat transfer fluids unchecked, and not sealing boreholes to prevent surface water infiltration. They also include increased perturbation of the groundwater temperature fields and hydrochemical and geo-microbiology impacts on the groundwater ecosystem, particularly in the event of a leak, which compromise groundwater as a source of drinking water [116–119].

Depending on the refrigerant type, GSHPs (but also HPs in general) may be regarded as a source of emissions and pollution due to the potential leakage of the refrigerant [64]. Refrigerants, or hydro-fluorocarbons (HFCs), have a higher global warming potential (GWP) than CO_2. The Kigali amendment to the Montreal Protocol, which went into effect in January 2019, attempts to gradually phase out the use of HFCs, which are frequently used in the air-conditioning (A/C) and refrigeration sector [120]. Although natural refrigerants, like ammonia, produce carbon capture and have a low GWP (see also, life cycle assessment—LCA), their use is limited due to their flammability [64,65]. Several studies on the relationship between the performance of HPs and different low GWP refrigerants have been conducted; the results indicate that the choice of refrigerant type is contingent upon the application and cost [121–124]. When it comes to technical methods for reaching the Kigali amendment target at low outside temperatures, propane appears to be the most formidable opponent [125,126]. Of course, refrigerant selection for GSHPs should take into account multiple considerations, including fire hazard, health and environmental concerns, the impact on microbiological activity, and groundwater quality [127–129]. It is possible to quantify the environmental impact of HPs using either embodied energy or embodied carbon emissions [4].

According to a thorough analysis of the literature, there might be large national variations in the embodied carbon of HPs. These emissions are related to sustainable energy technologies [66]. Through comparison by an LCA, the many HP technologies and other conventional heating and cooling technologies can be evaluated in terms of their environmental impact, ideally all at the same place. Remember that embedded emissions are dependent on a number of factors, including the mix of electricity used, the cost of transportation and fuel, the materials used, and more. According to the LCA of GSHPs, the main environmental impact appears to be the supplied energy and related air pollutants, followed by the manufacturing of the HP and HP refrigerant. [130]. Another LCA has demonstrated that an ASHP underfloor heating combination may be accomplished within 10 years of achieving the necessary energy savings over time to offset the environmental impact of HP production, whereas other heat emitters may take up to 45% longer [109]. Also, LCAs have shown that when it comes to the environment, gas-based absorption HPs are a better option than electric HPs and gas-fired boilers [131] under UK conditions; however, gas boilers and ASHPs are the next most impactful appliances after GSHPs (both GCHPs and WSHPs) [132]. Other LCAs studies conducted in a number of European countries have demonstrated that ASHPs have a greater environmental impact, as much as 24% according to the location and GHE configuration, than different GHE setups and GSHP systems [84,85].

4. Integration of GSHPs with Other Systems

The efficiency of GSHPs to integrate central heating and cooling systems with other traditional HVAC systems can enhance the way in which heat is transferred to and from the earth. When combined GSHPs are correctly controlled, system performance can be improved to a level greater than when each system operates independently [30]. The main types of GSHP integration with other systems are summarized below.

(i) GSHPs integrated with air-conditioning systems: In moderate-weather areas, GSHPs show promise for A/C applications. They are considered green HVAC systems as they have higher energy efficiency for A/C systems than traditional ones; this is because the underground medium provides higher temperature levels for heating and lower levels for the cooling applications. Specific examples and successful case studies concerning such systems include studies on the efficiency of a GSHP system with heat exchangers and friction piles for the A/C of buildings for residential and also office applications [133]; the energy consumption of a GSHP integrated into an A/C system for public buildings, where the energy requirement was remarkably low compared to that for traditional cooling and heating systems [134]; the simulation of the hourly operation of HGCHPs (see Section 3) for residential buildings in Hong Kong, where the COP was considerably higher than that for conventional ASHPs [135]; an assessment of the efficiency and consumption of the electrical energy of various A/C systems, GSHPs, GSHPs combined with AWHP, or GSHPs combined with a TES (thermal energy storage) device, for cooling buildings around the Mediterranean coast [136]; an investigation into the performance of an A/C system driven by GSHPs at a fixed relative humidity and temperature for a building in Shanghai, China [67]; and testing the performance of a split-type GSHP system for heating rural households in North China [137].

(ii) GSHPs integrated with solar systems: Heating alone with GSHP throughout the winter may not be effective in frigid climates. As a result, as was indicated in Section 3, solar energy can be used to achieve seasonal TES for GSHPs when they are not producing heat. Through the usage of GHEs, solar energy captured in the spring, fall, and summer can be stored in the soil and combined with heat from solar collectors to provide warmth throughout the winter [138,139]. Specific examples concerning such systems include studies on the following: simulations by TRNSYS18 software (Thermal Energy Systems Specialists

LLC) of the system performance of a PV/T (photo-voltaic/thermal) combined with a GSHP, where the generated electricity of the PV panel increased and its maximum temperature decreased compared with cases without cooling systems, while the consumed electric energy by HPs also decreased and its COP increased [140]; a numerical simulation of a PV-GHE system under the arid climate of northwestern China, where the production of annual electricity increased compared to traditional PV panels [141]; experiments for the energy performance of various working modes of an SGSHP system in Shijiazhuang, China [142]; the thermal performance of an SGSHP for heating under cold weather in Turkey, where it was found experimentally that the COP of the HP increased compared to a regular GSHP, while the solar collectors' efficiency increased compared to a regular solar system [143]; a numerical simulation of SGSHPs for heating, where, due to soil temperature increasing with time, it was found advantageous to operate the system for a long period of time [144]; and the proposition of a PV/T-GSHP system to face the shortage of electricity at high consumption for heating buildings in Jordan [145].

(iii) GSHPs integrated with ice storage: The demands of heating and cooling loads in cooling-dominated regions cannot be met by GSHPs used alone. For cooling reasons, ice storage systems can be used in conjunction with other methods under certain operating conditions [68]. Ice storage is a useful technique that produces and stores cooling thermal energy inside an insulated tank for energy storage at night and then extracts that energy for cooling during peak hours. Specific examples and successful case studies concerning such systems include studies on the combination between vertical GHEs, GCHP, and soil cold storage [146]; a ground ice TES combined with a reversible HP for A/C during the heating and cooling seasons [147]; cooling storage inside both the soil and GSHPs [148]; and the operating modes of a GSHP combined with ice storage for a large building in Beijing, China [149].

(iv) GSHPs integrated with cooling towers: The released heat to the ground during the operation of GSHP systems, for refrigeration and for cooling buildings, is accumulated around the GHEs; this causes performance degradation and increases the costs of system operation during the summer season. Cooling towers (CTs), or other auxiliary or additional heat rejecters, can be employed to disperse condensation heat in order to address this crucial problem [150]. Specific examples concerning such HGSHP (see Section 3) systems include studies on the control and design of the system under different climatic circumstances [151]; the control and design of the system using an additional heat rejecter as a cooling pond [41]; the control and design of the system using an additional source of heat such as thermal solar collectors [152]; modeling and analyzing the heat transfer of the components of the fundamental system [153]; and the optimization in relation to thermal and economic analysis [23].

Application: Three categories of geothermal energy, namely high, intermediate, and low-temperature resources, are used in GSHP applications [154,155]. High-temperature resources, defined as those that have a temperature above 150 °C, are primarily utilized in areas with strong geothermal gradients that are located between 1500 and 3000 m below the earth's surface. They are typically used to produce electricity and occasionally consist of dry steam or a combination of steam and water. The water-based intermediate-temperature resources, which fall between 90 and 150 °C, are primarily used in areas 2000 m below the earth's surface and in sedimentary basins with a high geothermal gradient between 3000 and 4000 m. They are appropriate for producing electricity through binary cycles. The low-temperature resources in the range of 30–90 °C are primarily used in areas with a normal geothermal gradient at depths of 1500–2500 m or at <1000 m in areas with a high geothermal gradient. They are employed directly for heating processes in A/C systems as well as in a variety of industrial applications. GSHPs function at temperatures below 32 °C, and their applications also operate at low temperatures [156].

5. Optimal Design and Control and Energy Analysis

In general, the initial investment costs of GSHP systems are higher than other types of HVAC technologies, gas furnaces, and district heating systems due to the necessary installation of GHEs. Hence, the appropriate design and control optimization of GSHP systems is critical to maximizing their performance and minimizing the payback period.

Several thermodynamic and economic objectives can be used as objective functions in the design optimization of GSHP systems. The performance of such systems is frequently assessed using thermodynamic objectives, which were created in accordance with the first or second law of thermodynamics. While the COP is a commonly used thermodynamic objective, system irreversibility, as expressed in terms of entropy creation or exergy destruction, is frequently employed to identify the locations where inefficiencies occur [49,157]. Other thermodynamic objectives employed are the entropy generation number, system performance factor, relative performance loss, and energy extraction/dissipation rate [30]. Since the initial cost does not need to be considered, the economic objectives used in the control optimization of GSHP systems are rather straightforward. The optimization objectives are primarily the overall energy usage and the operating cost [30]. Economic objectives seek to reduce the GSHP system's overall cost or energy consumption in order to generate profits for end-users and investors. In recent years, the objective functions in GSHP design have frequently included total cost [158], life cycle cost (LCC) [159], and total annual cost [160]. Exergy-based economic analyses, including thermo-economics and exergo-economics, have been applied to the study and optimization of GSHP systems, taking into account both thermodynamic and economic objectives [23,161].

Two categories of optimization techniques exist in the analysis of GSHP systems, namely (i) design optimization and (ii) control optimization [30].

5.1. Design

There are various ways to formulate design optimization problems. One approach is to use rule-of-thumb design approaches, which are quite straightforward and simple to apply. For example, one can determine the total length of BHEs and the maximum amount of heat that can be extracted per unit length of BHEs [69,162]. These are not suitable for best capturing the interactions between GHEs and other parts of GSHP systems [30].

Compared to the rule-of-thumb methods, model-based methods can represent the real GSHP system to be designed in a better manner and offer a more reliable solution. This requires a good understanding of system dynamics and behaviors, with a set of performance data needed for both model training and model parameter identification. In model-based methods, some optimization problems are solved by an optimization algorithm. For multi-objective optimization design problems, there mainly exist two different approaches, namely Pareto-based methods and decomposition-based methods [163].

Building HVAC systems can be controlled in two ways: locally and supervisory (or optimally) [164]. Proportional–integral–derivative controllers are some of the most extensively utilized local control methods. Supervisory control employs two primary approaches: model-based control and data-driven control, both of which have been widely employed to establish optimal control strategies for building energy systems, GSHP systems included.

The model-based technique makes use of performance models to calculate the system's energy consumption or operating costs under specific working conditions. An optimization tool then finds the best course of action among various trials within the specified searching domain [165]. With the data-driven technique, the controller computes the optimal solution straight from the raw data, negating the need for a physical model. Extensive performance data, which can be produced from large-scale computer models or big performance tests, are frequently needed for the data-driven method. Examples of the data-driven method include reinforcement learning control and performance map-based control [30].

In addition to the above, several model-free techniques, like fuzzy logic control and extremum seeking control, which employ specific algorithms, have been modified to create control schemes for GSHP systems [166,167]. Whether these techniques are more effective than model-based control methods is difficult to say.

In general, optimization approaches are often necessary to solve optimization problems, particularly those pertaining to the optimal design and operation of GSHP systems that are highly nonlinear, dynamic, and constrained by a number of restrictions. Nelder–Mead [168], response surface [169], dynamic programming [170], evolutionary algorithms [171], and genetic algorithms [172] are a few examples of these techniques.

The primary parameters that influence the thermodynamic and economic performance of GSHP systems, as shown in Table 2, are the most usual primary decision variables for GSHP optimization problems. They can be broadly divided into five categories, which are as follows: (i) soil properties, (ii) climate and piping system parameters, (iii) GHE parameters, (iv) HP parameters, and (v) supplementary heat/cold source parameters. In order to reduce the operating costs of GSHP systems and the thermal imbalance of the GHEs, control optimization seeks to identify the ideal number of HPs, water pumps, fluid flow-rates, and temperature settings [30].

Table 2. Factors affecting GSHP performance [30].

Factors	Primary Decision Variables
Soil Properties	• Density • Diffusivity • Groundwater motion • Grout material properties • Moisture • Temperature • Thermal conductivity
Climate and piping system	• Distribution pipe network's condition • Humidity and temperature of surrounding air • Indoors temperature settings • Quantity, size, and type of water pumps
Ground heat exchanger (GHE)	• Borehole number, depth, diameter, half-shank spacing, and resistance • Diameter, heat conductivity, and type of U-tubes • Flow rate • Horizontal HE loop pitch, number of pipes, pipe length, and trench length • Temperature of inlet fluid
Heat pump (HP) unit	• Number and type of HPs • Efficiency of compressor • Flow rates and pressure of condenser/evaporator • Temperatures of condenser/evaporator inlet fluid
Supplementary heat/cold source	• Capacity and type • Method of connection/distribution • Rate of fluid flow • Temperature of inlet fluid • Type of working fluid

Sensitivity assessments are frequently used to identify the key variables influencing system performance and optimization objectives. This might lead to dimension reduction in order to determine the primary design parameters that have a substantial influence on the performance of the GSHP system, whereas less significant parameters are frequently regarded constants and are not optimized in the optimization problem. There are three types of regularly utilized methods, namely screening methods, local methods, and global methods [70]. Local techniques focus on the effects of the inputs on a specific point or base case, whereas global methods focus on the effects of the inputs across the entire input space [173]. Local techniques are simpler and require less processing, but they are less reliable than global methods. Regarding global methods, regression methods, variance-based methods, screening-based methods, and meta-modeling methods are some of the most popular ones [174].

Different methods have been used to determine the key variables for the performance evaluation and optimal design of GSHP systems, such as the effect of varying the design variable on the total cost of a GSHP system [160]; the primary influencing parameters of a GSHP system with integrated PV/T collectors [159]; the most dominant design parameters of BHEs in terms of energy generation number [175]; the relative influence of various design parameters on GHE performance indicators [176]; the factors that most affect the power consumption of a GSHP system [177]; the influential simulation parameters on the performance [164]; the influence of borehole length on energy performance and environmental influence [178]; the main facilitating parameters [179]; and the influence of ground thermal conductivity, groundwater, and electricity price [180]. It must be noted that the primary design variables for a given system may vary depending on the objectives. Therefore, to ensure that the intended optimization outcomes may be obtained, it is crucial to choose the right objective functions, method, number of parameters of interest, and range for each parameter [30].

Research on the optimal design of GSHP systems largely started in the mid-1990s, with the development and expansion of mathematical models of GSHPs to enable system design, thus providing useful tools and fundamental theories for the performance evaluation of GSHP systems as well as foundations for design optimization strategies. Ever since, a number of design optimization strategies for GSHP systems have been developed, both for single-objective and multi-objective optimization (SOO and MOO) [30]. Both SOO and MOO strategies can deliver higher performance for GSHP systems than rule-of-thumb methods and strategies that do not take into account system-/subsystem-level interactions and characteristics when formulating the optimization issue.

Examples of SOO include the entropy generation minimization method and the Taguchi method for the design of vertical GHEs [181,182], two-criteria optimization for determining the minimum depth and diameter of horizontal GHEs [183], and the Taguchi method and utility concept for optimizing the design parameters of an SGSHP system [184]. Regarding thermodynamic objectives, these have been used in the optimal design of GSHP systems in relation to heat transfer rate per unit borehole length [185], entropy generation [186], exergy analysis [187], energetic potential of the borehole thermal energy storage [188], heat flux [189,190], and the COP [150,191,192]. Regarding economic objectives, these have been used for the optimal design of GSHP systems in relation to the system's LCC [41], total annual cost [159], total investment and operational cost [169], total initial cost [160], total present value cost [193], and system annual heating cost [194]. The above studies, and many more indicate that SOO strategies are generally effective for identifying the 'globally' optimal solutions of the optimization problems because of taking the system-/subsystem-level interactions and characteristics into account [30]. Such approaches though primarily focus on maximizing or minimizing a single objective only, at the expense of the system's performance in terms of other objectives.

Examples of MOO include methods and objectives as follows: the response surface method [170]; mixed-integer nonlinear programming with evolutionary and generalized-reduced-gradient algorithms [195]; the global sensitivity assessment method or Kriging response surface model with a multi-objective genetic algorithm [196]; the Taguchi method and utility [197]; genetic-algorithm-based optimization analysis [176]; the multi-objective particle swarm optimization (PSO) algorithm [198]; the exergy destruction rate and the total cost of the system [199]; total irreversibility and the total product cost [200]; the total annual cost of the system, the system COP, heat transfer efficiency, and heat exchanger efficiency [168]; and the entropy generation rate, integrated evaluation factor, GHE length, and GHE thermal resistance [23]. The above studies, and many more, illustrate that

MOO strategies can generally result in more reasonable solutions than the baseline design strategies and SOO strategies because of the consideration of multiple objectives [30]. However, the objectives used in MOO strategies must be carefully determined, while the formulation of the optimization problems must consider computational efficiency as well as the criteria for determining the 'globally' optimal solution.

5.2. Control

Less work has been conducted on the control optimization of GSHP systems. Examples of the limited number of control strategies for optimizing the performance of GHEs are dynamic programming techniques with control algorithms to minimize the terminal cost for borehole thermal storage systems, numerical models, and linear programming [171,201]. The aforementioned studies focused on finding the maximum performance of a certain individual component, with no consideration of any interaction with other components.

Over the last decade, a number of control strategies for GSHP systems have been developed, with the goal of improving their overall performance by taking into consideration the interactions between different components, both for stand-alone GSHP and HGSHP systems. Most control strategies use extensive optimization algorithms that contain specific optimization objectives, optimization variables, optimization methods, and approaches to handle the highly nonlinear and dynamic control problems of GSHP systems' optimization [30]. In general, such control systems can be more energy- and cost-effective than conventional strategies.

Examples of the control optimization of stand-alone GSHP systems include the Taguchi method and utility concept to determine the operating variables for enhancing its overall COP [179]; numerical simulations for comparing the performance of on/off controlled systems with inverter-driven variable capacity systems [202]; the degree–minute method for the control of the supply of water temperature from/to buildings for an on/off controlled system [203]; a regulation strategy with proportional–integral actions for the control of the compressor frequency and the water flow rates [204]; mixed-integer quadratic programming with an MPC (model predictive control) strategy [205]; a performance map-based strategy and the exhaustive search method for the determination of the optimal control settings [206]; a radial basis function neural network for the estimation and forecast of the performance of the GSHP system [207]; an adaptive PSO to identify optimal control settings [208]; an ANN (artificial neural network)-based predictive controller to predict the weather and power consumption [209]; TRNSYS simulations to evaluate the optimization of the chilled water return temperature and the control bandwidth of the water temperature [210]; and performance map-based control strategies to reduce the system's power consumption and increase the system's performance significantly [211]. When comparing optimal control systems to conventional control strategies, energy performance is typically enhanced. One should keep in mind that simulation findings may not accurately reflect how control techniques operate in real-world settings [30]. For example, if the operating conditions differ significantly from the data used to build the performance maps, the application of performance map-based control techniques may lead to inefficient operation. The incorporation of additional heat and/or cold sources complicates and increases the nonlinearity of the optimization problem for the optimal control of HGSHP systems. However, there exist successful optimization attempts for such systems in the literature, like the study of three control strategies [212]; performance evaluation [213]; the comparison of six control strategies [150]; the comparison of four control strategies [214]; the study of the operating performance [215]; the application of a convex approach [216]; the discretization of the control problem [217]; the utilization of three control strategies [218]; the utilization of extremum seeking control [219]; the application of a fuzzy logic controller [220]; the study of the system's performance [221]; the determination of optimal load rates [222]; the identification of optimal control settings [223]; the application of a rule-based control strategy [224]; the determination of the on/off status of the system [225]; and the application of an ANN-based control strategy [226]. All the above studies make use of either simulations or experiments for validation purposes.

Although, optimal control leads to energy savings compared to using simple rule-of-thumb-based control strategies, in general, the reliability and long-term control performance of the above strategies in practical applications should be further tested.

5.3. Energy Analysis

An essential aspect of understanding and optimizing the performance of GSHPs lies in conducting comprehensive energy and exergy analyses. There exist many such studies in the literature that in general deal with the efficiency or COP for stand-alone or hybrid GSHP systems [227–230]. In terms of energy efficiency, the operation of an HP can be characterized by (i) the COP, (ii) the seasonal coefficient of performance ($COP_{seasonal}$ or SPF), and (iii) the energy efficiency ratio (EER). The COP is known as SPF if the total energy used and usable energy for a season (year) are added together [50]. COP values vary according to both the source temperature and the temperature at the consumer. Factors affecting the life cycle efficiency of an HP include (i) the local method of electricity generation, (ii) climate, (iii) the type of HP (e.g., ground- vs. air-source), (iv) the refrigerant used, (v) the size of the HP, (vi) thermostat controls, and (vii) the quality of work during installation.

Other more specific examples include studies on how the depth of GHEs and the configuration of the system influences the efficiency for space heating [231–233]; the peak of the system efficiency for cooling and heating or for water heating [234,235]; comparing the loss of exergy in heating and cooling modes for space heating and cooling [236]; a comparison of the efficiency of various GSHPs for building cooling and heating; a comparison of the efficiency between GSHPs and other systems for building heating [237–240]; how temperature increment influences the efficiency for space heating; comparing the efficiency in heating and cooling modes [241–244]; comparing the rate of exergy destruction of each component of the system for space conditioning and cooling [245,246]; how the dead state temperature influences the efficiency of each component of the system for drying food [247]; how applying a proper control strategy leads to better efficiency for building heating and cooling [248]; how the working fluid can influence efficiency [249]; how the summer versus winter mode influences the irreversibility rate for domestic hot water production [250]; which components of the system have the maximum and lowest efficiency for domestic use and water heating [251]; computing the efficiency of components [252,253]; how additional components influence irreversibility [254]; how the time of operation influences the efficiency for building cooling and heating [255,256]; and how using a nanofluid influences efficiency [257].

The purpose of thermal analysis is to ascertain the temperature of the heat carrier fluid (refrigerant) that is circulated in the GHE tube and the HP under specific operating conditions. This determination has implications for the GSHP system's energy efficiency. Given the complexity of the problem and its long-time scale, it is typical to analyze the heat transfer process in two distinct regions [28]. That is, one must treat heat conduction as a transient process in the solid/rock or soil outside the borehole separately from the region inside the borehole, which includes the grout, U-tube pipes, and the circulating fluid inside the pipes. On the borehole wall, the analyses of the two spatial regions are connected. The heat transfer models for the two distinct regions are as follows.

(i) Heat conduction outside the borehole: A variety of simulation models for the heat transfer outside the borehole exist in the literature; the majority of these models are based on analytical or numerical techniques, which comprise Kelvin's line source, also known as the infinite line source [258,259], the cylindrical source model [260–262], and Eskilson's model as well as the finite line source model [262–265].

(ii) Heat transfer inside the borehole: The configuration of the borehole's flow channels and the thermal resistance inside the borehole, mostly influenced by the thermal characteristics of the grouting materials, have a big effect on the GHE's performance. The primary goal of such analysis is to determine the circulating fluid's entering and exiting temperatures in relation to the temperature of the borehole wall, its heat flow, and its thermal resistance. Existing models include one-dimensional models [174,266], two-dimensional models [262], and quasi-three-dimensional models [267].

6. Case Studies

Numerous case studies with GSHP systems have been presented in the literature. Such examples include the following:

- A large building, part of the TESS library of the TRNSYS program, in Atlanta, GA, USA, where TRNSYS simulations were performed to obtain the heating and cooling loads and the system performance for four different scenarios involving HPs and GHEs, with regard to annual energy consumption, life cycle cost, and CO_2 emissions. High-efficiency HPs had the lowest annual CO_2 emissions with 21,100 Kg, while low-efficiency chillers with a gas boiler had the highest with 30,000 kg [268].
- A family house in the city of Freistadt, Austria, where using CO_2 as the working fluid for the heat pipe, of a heat pipe–GSHP system, yielded the highest performance figures and the greatest operating reliability (see the COP and SPF), with an SPF of 4.1–4.8 [269].
- A Belgian hospital with one of the first and largest systems in Belgium, which included aquifer thermal energy storage, where, following a 3-year monitoring plan, the system was proved to be favorable with respect to high efficiency and small payback period compared to conventional systems. The result was an annual cost reduction of EUR 54,000 in comparison to the reference installation, yielding a payback time of 8.4 years (with subsidies not included) [270].
- An archive building in Shanghai, China, where the performance of a constant temperature and humidity A/C was studied and proved to be significantly more efficient compared to an ASHP, with corresponding average COPs of 5.2 and 2.9 [271].
- A field test in existing buildings in Germany was performed, showing significantly higher performance upon comparison with ASHPs and condensing boilers; the corresponding SPFs were 2.9, 2.3, and 0.96 [272].
- The Department of Earth Science, the University of Oxford, UK, where an actual hybrid system served as a validating example for a probabilistic model for the economic feasibility of a full-size system that was compared to four alternative HVAC systems, yielding positive results depending on the gas and electricity prices [273].
- An office building in Nuremberg, Germany, where the heating and cooling performance was analyzed based on the accumulated data obtained through a data logging system over a 4-year period, yielding high efficiency both for heating and cooling, with a winter COP of 3.9 and a summer EER of 8.0 [242].
- A construction at the Incheon International Airport site in South Korea, where an experimental and numerical study on the evaluation of TRT (thermal response test) results for an energy pile and a spiral-coil-type GHE led to the evaluation of the ground thermal conductivity, with a common value of around 2.18 W m^{-1} K^{-1} [274].
- Ten buildings in Southern Ontario, Canada, where optimally-sized hybrid systems and non-hybridized systems as well were found to significantly reduce CO_2 emissions compared to conventional systems by as much as 3.6% [275].
- A then new school building in Belgium, where the performance of a borehole thermal energy storage (BTES) system was favorably compared to several low-temperature heating methods. With the annual thermal imbalance decreasing from the initial 91% to 23% after 15 years, the COP increased from 4.5 to 4.8 [276].
- Fifty cases selected from different areas in Jiangsu, China, which included office, residence, and other building types, where the water temperatures, energy efficiency, energy consumption, and thermodynamic perfectibility were comparatively analyzed statistically. With the ground side temperature differences being about 3.07 °C in both the winter and summer, the winter COP was 4.6 and the summer EER was 3.4 [277].

- A cellular tower shelter in Varna, New York, US, where the performance of an experimental hybrid system was assessed yielding a high COP and high savings compared to ASHP systems. With a COP of 4.8, the GSHP-based system can lead to 30% savings on lifetime electricity use compared to ASHPs [278].
- An office in Istanbul, Turkey, where the inlet and outlet temperatures of the fluid, the soil temperature, the burial depth of the pipes, and the distance between the pipes were analyzed for optimality through numerical simulations for a 10-year period. Inlet temperatures of 2 °C (or much lower) are observed and are shown to be much lower than the desired ones for a GSHP operation. Desired burial depths are shown to be higher than 2 or 3 m, while effects of the ground surface can be seen earlier for depths of <1 m. Regarding the distance between pipes, it was shown that distances of over 2 m have no significant effect on soil temperature [279].
- A hotel in Antalya, Turkey, where energy and exergy analyses were performed for the potential energy efficiency improvement in this system, along with a comparative thermo-economic analysis that showed its superiority over fuel oil 4 and LPG boiler systems. The COP was found to be 2.88, significantly higher than the respective 0.80, 0.92, and 0.90 for fuel oil 4, LPG, and natural gas [280].
- A university-oriental hospital in southeastern Korea, where prediction models were used for real-time performance monitoring to detect system malfunctions and as a baseline for measuring and verifying potential future energy conservation measures. Based on the CVRMSE (coefficient of variation of the root mean squared error), the prediction accuracies of the ANN and MLR (multiple linear regression) were 1.75% and 3.56%, respectively [281].
- A four-story building in Stockholm, Sweden, where long-term measured system performance data showed how the various system components affected the performance (see the SPF), with COPs affected by the amount of heating and cooling provided rather than by the entering fluid temperature to the HPs. Evaluated SPFs varied from 2.7 to 3.7 for heating and 27 for cooling [282].
- A school building in Korea, where the cooling performance of a water-to-refrigerant-type system was evaluated, exhibiting considerably higher COP values, while an almost constant subterranean temperature throughout the year indicated that the system could also efficiently operate as a heating system in winter. The system COP was found to be 5.9 (65% partial load conditions), considerably higher than the corresponding 3.4 of an analogous ASHP [181].
- A commercial building in Japan, where the capacity ratio and the efficiency of the system were determined in relation to the values of the design parameters, showing the influence of the peak load, the building site conditions, and the configuration of the GHEs. The capacity ratio increases as the length and number of GHEs increases and decreases with the peak load intensity, and it is heavily influenced by the changes in the HPs' COP. It was concluded that capacity ratios in urban areas (for the site conditions studied) of over 12.4–23.3% could be the norm [283].
- A hotel building and office building in Beijing, China, where the energy, environmental, economic, and flexibility performance of the solar-assisted system was analyzed in relation to multiple variables including the PV coverage ratio, ambient temperature, solar beam irradiance, and electricity price. Compared to a pure GSHP system, the hybrid system's respective energy savings are up to 33%, with 9% annual cost savings and a 23% emission reduction [284].
- A large building beneath a university library in Shijiazhuang, China, where the economic and environmental efficiency of a solar-assisted system and a regular system were assessed, both showing significant reductions in CO_2 emissions compared to conventional heating, while increasing the GHE spacing reduced the economic efficiency of the solar-assisted system. The CO_2, SO_2, and flue gas emissions are reduced by 4641, 37.58, and 18.9 tons, respectively. For a GHE spacing of 3 m and 4 m, the respective payback periods are 18 and 34 years [285].

- A hospital in Norway, where the performance of a hybrid system consisting of borehole thermal energy storage, an auxiliary heater, radiators, and ventilation coils was performed in relation to important operational parameters on the overall performance. For a heat recovery of 50% and condensation temperature of 40 °C, increasing the HP capacity does not affect the system's performance [286].
- Hospital buildings in northern Sweden, where analytical and artificial neural network models were used to accurately represent a hybrid system's long-term behavior with respect to cost and CO_2 emissions' reduction. A stable long-term operation can be achieved while reducing these aspects. The annual operation cost and the annual CO_2 emissions savings can be of the order of EUR 64,000 and 92 tons, respectively [287].
- The Beijing Daxing Airport system (the largest in the world, consisting of 10,497 GHEs), where a new performance indicator was used to access the effectiveness of operational strategies on alleviating thermal anomalies with regard to cooling and heating. It was found that after a 50-year operation, the thermally affected zone could extend to 27.2 m NS and 32.6 m EW. In all other directions, the distance of adjacent BHE arrays could remain at least 4.6 m [288].
- A reconstructed hotel building in Zibo, China, where the feasibility of a system with energy storage, coupled with an ASHP, was studied through the minimization of the system operation cost, showing considerable cost and CO_2 emission reduction compared with the regular system. The annual operation cost and the CO_2 emission can be lower by 42% and 7%, respectively, compared to a traditional GSHP system [289].
- A large educational building in Espoo, Finland, where the performance, life cycle cost, and CO_2 emissions of a hybrid system combined with district heating and an air-cooled chiller were examined using 25-year model simulations, showing that varying strategies can greatly increase the performance. The 25-year total CO_2 emissions could decrease by 3% upon adjusting the cooling water temperature and the indoor heating and cooling set-points. Reducing the HP heating power and/or increasing the borehole depth, the total CO_2 emissions could decrease by 6% [290].

7. Barriers for the Adoption of GSHPs

Regarding GSHPs' ability to reduce GHG emissions and their overall role in promoting the sustainable growth of the heating and cooling industries, opinions are almost unanimous [71,291]. HPs have large market potential, which has various positive socioeconomic effects [72]. However, numerous obstacles, including technological, economic, regulatory, policy, and public acceptance concerns, stand in the way of the broad adoption of GSHP technology [73]. Policies and regulations, financial and economic, technical, environmental, and social are the typical categories used to categorize barriers and the difficulties encountered in overcoming them [37].

(i) Policy and regulation: GSHP systems deal with a number of legal and regulatory challenges, such as the absence of national standards, various incentives and subsidies, net metering, connectivity, and building codes [37]. For GSHP systems, there are no national standards or regulations, a fact that makes it challenging for building owners to compare the benefits and drawbacks of different systems and for the industry to have a standardized set of guidelines to adhere to [74,292]. For example, a cross-national analysis conducted in the EU has revealed a deficiency in legislative and regulatory frameworks impeding technical advancements. Building owners may find it challenging to obtain these resources and develop long-term plans because the kinds and amounts of financial incentives and subsidies for GSHP systems vary by location and are subject to change [54,293,294]. Throughout the EU, obtaining authorization to install GWHPs is challenging [75,114]. There are laws or guidelines governing the design and installation of HPs in many European nations [295–298], but the implementation of HPs may occasionally be hampered by the regulatory framework [297]. Building owners have challenges when trying to sell excess energy back to the grid due to the absence of clear regulations in some countries and regions, governing the use of net metering for GSHP systems. Some countries and regions lack explicit laws that deal with connecting GSHP systems to the grid. Thus, building owners may find it puzzling to connect their systems to the grid and benefit fully from GSHP systems as a result. Installing GSHP systems that comply with local norms and laws can be difficult for building owners because there may be great differences between jurisdictions [37].

(ii) Financial: The implementation of GSHP systems is linked to several complicated financial and economic problems, such as high initial expenditures, ongoing maintenance costs, government grants and incentives, and a protracted payback period. Building owners may find GSHP systems financially unappealing due to the high upfront costs, particularly for drilling or excavating the ground for installing the ground loop, and the need for frequent maintenance and servicing, which can add up over the system's lifetime [299–301]. Also, since it may be that GSHP systems cannot be funded through traditional means and because financial subsidies and incentives for such systems differ from country to country, obtaining finance for such systems may be challenging. As a result, because there are so many factors that affect the payback period of GSHP systems in addition to physical (such as ground temperature), technical (such as efficiency), and other (such as electricity rate) issues, the payback period can be hard to determine [302–305].

(iii) Technical: The GSHP systems face several technical challenges: design and implementation, scaling, maintenance, integration, and so forth. One of the most important technical issues is the design and installation of the GHE, which transfers heat to and from the earth. This can be a costly and challenging process, particularly if the ground is difficult to access or the soil is not suitable for the installation. In general, it can be difficult to appropriately size GSHP systems because the system's size must correspond to the building's heating and cooling requirements and take into account the amount of open space surrounding the structure [114,306–308]. In addition, it may be a challenging process to integrate GSHPs with other building systems, like A/C, ventilation, and insulation, particularly in older structures. The restricted availability of groundwater and the high maintenance costs associated with fouling corrosion in pipes and equipment limit the wide adoption of GWHPs. Regarding SWHPs, the main drawback of the system is that the weather, particularly in the winter, has a greater influence on the temperature of the surface water [50]. Finally, it can be difficult to optimize the performance of GSHPs because of the several factors that affect it, such as ground temperature, GHE effectiveness, and size and design [309]. Another barrier, given that the heating industry is heavily electrified, could be that the electrical network's capacity may be limited. This is because electrical distribution grids are typically designed to withstand lower electrical loads [310]. For example, the implementation of HPs could potentially increase peak electricity demand (14% in the UK) [311] and could even lead to overloading and voltage stability issues [312]. The large-scale deployment of HP technologies could necessitate further spending, such as strengthening the electrical grid, redesigning homes, and changing boilers; otherwise, predicted drops in the heating sector's carbon intensity might not materialize [313–315]. Additional challenges include a shortage of information on the effectiveness and cost efficiency of GSHP systems, which makes it challenging for decision makers to evaluate the potential benefits of these systems. In addition, the GSHP industry lacks skilled workers, which makes it difficult for building owners to find qualified experts to plan, implement, and service GSHP systems [37].

(iv) Environmental and social: GSHP installations raise a variety of social and environmental issues. There may be ecological repercussions from GHE installation, including soil erosion, the devastation of natural habitats, and contaminated underground water supplies [37]. Adopting HP technology also faces substantial obstacles related to public acceptance and awareness. These are the result of unfounded fear, false impressions, misinformation, and/or prior bad experiences with HPs' reliability or an inadequacy in HP technology. Even in developed nations, there is frequently a lack of public awareness regarding the financial and environmental advantages of HPs [316,317]. Because of the noise they can produce and the aesthetic unpleasantness of the installation, GSHPs may encounter resistance from the surrounding community. For example, HPs may contribute to noise pollution, raising public concerns and reducing public acceptance. To prevent noise-related annoyances in a community, noise baffles are frequently used to control their noise levels [113,114]. Even though HPs have more positive environmental effects than negative ones, some research indicates otherwise. For instance, comparing gas boilers and HPs in a power system that primarily relies on fossil fuels indicates that gas boilers may be less harmful to public health than HPs [131]. On the other hand, an LCA has indicated that HPs deplete fewer fossil resources and have greater environmental impacts than gas boilers while emitting less CO_2 and particulate matter [132]. Numerous research has looked into the environmental effects of HP deployment, particularly those connected to water pollution and ground subsidence, which have an impact on the dispersion of HPs [5,318,319]. Water resources may be impacted by GSHPs that use water-source HPs (GWHP and SWHP), particularly in areas where water resources are scarce [320,321]. Also, working fluid leakage from GSHPs might occur from deformation or rupture during operation; therefore, the working fluid needs to meet environmental regulations [322]. Finally, even though GSHP systems are thought of as low-carbon technologies, the production and distribution of electricity still has an impact on the environment [323].

8. Prospects and Recommendations

Regarding sustainability, GSHPs could help achieve a number of the sixteen sustainable development objectives that the UN has established. However, a recent bibliometric review of the relevant literature indicates that "Affordable and Clean Energy" is the primary objective [37]. Thus, it is strongly advised to look at how GSHPs directly affect each goal. This would be incredibly beneficial because it might encourage people to rely more on these systems rather than traditional methods; increase awareness of the serious problems that GSHPs face, which could aid in the discovery of new solutions; increase subsidies and incentives, which are necessary but lacking in these systems; and provide new ideas for lowering the capital cost of GSHPs, which is one of their main problems, like the use of novel pipe grout materials as well as improved storage materials (see for example PCM (phase-change materials) [324,325]).

There are undoubtedly still a lot of obstacles/barriers to overcome in the effort to boost the use of GSHPs, which revolve around two primary ideas: lowering system costs and utilizing technology to enhance thermal performance [18]. For instance, by using better design, the primary problem of the high initial cost can be resolved by cutting the resistance and length of the borehole. Additionally, combining it with another system to absorb the excess heat and using it for other purposes can help overcome the issue of diminished system performance over time caused by the imbalance of heat rejected to the ground [326]. Several more challenges are expected to be further addressed, such as investigating the application of copper pipe as a GHE and various composite materials and working fluids; introducing coupled heat transfer models for a GSHP's GHE and HP in order to properly analyze its dynamic system performance; using an ANN to forecast temperature response in several applications; additional in-depth numerical models, such as approaches based on energy economy; parametric optimization concerning grouting materials, GHE configuration, and geological conditions; taking advantage of groundwater flow and the GHE layout; operation management in conjunction with GHE's sporadic operation to reduce subsurface thermal accumulation; the application of HGSHP systems to address issues with buildings' uneven seasonal thermal load; pursuing and enhancing legislative changes as well as financial incentives; and creating pertinent and useful handbooks, technical codes, and reference materials for thermal response testing, GSHP design, and application.

In particular, more advancements in the area of GSHP system optimization [326], might be beneficial, including acts such as enhancing the model-based approach's reliability by utilizing adaptive models; utilizing a large amount of data (many operational data sets are easily accessible due to the growth of the Internet of Things) for the data-driven method to calculate 'globally' optimal solutions; increasing attention to control optimization; giving greater focus on MOO tactics, which are typically more effective than SOO; selecting more precisely the variable ranges utilized in sensitivity assessments; using an experimental validation of the techniques rather than simulation-based validation; creating novel tools and techniques to lower GHE installation costs; creating reliable fault detection and diagnosis techniques to quickly find and identify possible problems and operating concerns in order to enhance long-term operating performance; creating and implementing inexpensive sensors for GSHP systems to enable the collection of high-quality data; developing data-driven controllers; developing strong MPC methods that can deliver reliable forecasts and optimal control performance; and conducting more research on the suitability, reliability, and efficacy of the optimal control strategies in real-world scenarios including lengthy operations.

Regarding technical, social, and environmental concerns, it is crucial, for instance, that HPs are not promoted in structures for which they are inappropriate, such as homes with low energy efficiency [327]. Also, more investigations and studies into novel approaches to lower the ratio of peak to average demand may be required in order to fully understand the relationship between HP penetration levels and peak power demand [310]. GWHPs can be made less susceptible to thermal short circuits by employing two wells or one well with two screens [37]. The difficulty in widely implementing HPs on the demand side of the electrical grid is similar to the continuous difficulty in widely implementing renewable energy, particularly wind, on the supply side of the grid [328]. Also, technical advancements may be leveraged to reduce the risk, as HPs are a source of noise pollution that would require abatement measures to avoid neighborhood disruption [4]. The application of existing GSHPs in already improved (of reduced heat demand) buildings may require the development and market release of new high-temperature HPs for the major task of replacing conventional heating systems. Finally, the participation of stakeholders in GSHPs may guarantee that the systems are designed, put into place, and maintained to satisfy stakeholder and community demands [329].

Regarding space heating, including district heating, between 2015 and 2020, the global number of GSHPs increased by 68.0% in installed capacity and 83.8% in annual energy use for space heating. In 2020, the installed capacity was 12,768 MWt and the annual energy use was 162,979 TJ/year [35].

9. Conclusions

This paper has provided a study of most of the main aspects of GSHPs, an evolving renewable energy technology, which can be used to heat and cool buildings, having the potential to significantly reduce CO_2 emissions. Over the last few decades, their enticing features of high efficiency and environmental friendliness have led to the widespread implementation of GSHP systems in many buildings worldwide.

Based on an extensive literature review, HPs—in general—and GSHPs—in particular—are categorized according to the main technologies that exist on the market. The main types of GSHPs, namely GCHPs, GWHPs, and SWHPs, all have their pros and cons, but due to practical reasons, the GCHPs are by far the most commonly used technology. Combining GSHPs with traditional heating systems, such gas boilers, is frequently a very effective and cost-effective option.

The efficiency of GSHPs, which integrate central heating and cooling systems with other typical HVAC systems, can improve heat transfer to and from the soil. When combined GSHPs are correctly controlled, system performance can be improved to a level that exceeds levels when each system runs alone. Examples of integrated GSHPs have been presented in conjunction with A/C, solar, ice storage, and cooling tower systems.

The kind of GSHP that must be installed depends on the application and the area (geographical and political). To this end GSHP optimization models may offer insights for better design and operation. Design optimization studies have been presented in terms of single-objective optimization (SOO) and multi-objective optimization (MOO) for both stand-alone and hybrid GSHP systems. Energy analysis in relation to factors affecting the life cycle efficiency and the performance (e.g., COP) of GSHPs have also been addressed, followed by indicative case studies examining the performance, environmental, and economic issues of GSHPs.

A crucial issue for GSHP uptake is that they confront a number of obstacles to their widespread use. In addition to the expected technical barriers, these also include the equally important policy and regulation barriers, financial barriers, environmental barriers, and, more generally, social barriers. These have been adequately addressed.

Following the results from existing case studies in the literature, one can indicate the following:

- Today's optimization and design techniques as well as technology allow GSHP system to consume decreased energy.
- Today's technology and design techniques allow for short payback periods (for the installation of GSHPs) in the range of <<5 years (or even <2 years for hybrid systems).
- The decreased environmental impact of GSHPs in comparison to ASHPs and other conventional HVAC systems could reach figures of >>25%.
- The COP of GSHPs can easily reach values of >5, significantly higher than the ASHP's COP and well above conventional HVAC's COPs.
- Today's optimization methods for the control strategy of GSHP systems can result in significant energy conservation measures (>>4% savings).

Finally, the reviewed aspects above have led to identifying the challenges that GSHP systems may face in their wider adoption, and through resulting recommendations, the prospects points to the future extensive use this renewable energy technology. This conclusion is backed by the fact that between 2015 and 2020, the number of GSHPs for space heating increased by 68.0% in installed capacity and 83.8% in annual energy use.

All the above point to the satisfying conclusion that the questions/hypotheses posed in the framework of the current study are fully or partly satisfied, although there is still work to be conducted in the direction of technology and societal approval.

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