




Review

Sustainability of Shallow Geothermal Energy for Building Air-Conditioning

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Abstract: Geothermal heat pumps have a widespread diffusion as they are able to deliver relatively higher energy output than other systems for building air-conditioning. The exploitation of low-enthalpy geothermal energy, however, presents crucial sustainability issues. This review investigates the primary forms of the environmental impact of geothermal heat pumps and the strategies for their mitigation. As life-cycle analyses shows that the highest impacts arise from installation and operation stages, most optimization studies focus on system thermodynamics, aiming at maximizing the energy performance via the optimization in the design of the different components interacting with the ground and serviced building. There are environmental studies of great relevance that investigate how the climate and ground properties affect the system sustainability and map the most suitable location for geothermal exploitation. Based on this review, ground-source heat pumps are a promising technology for the decarbonization of the building sector. However, a sustainable design of such systems is more complex than conventional air-conditioning systems, and it needs a holistic and multi-disciplinary approach to include the broad environmental boundaries to fully understand the environmental consequences of their operation.

Keywords: geothermal heat pumps; sustainability; LCA; energy analysis; exergy analysis; GWP; ground heat-exchanger



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1. Introduction

In the 21st UNFCCC Conference (COP21), held from November 30 to December 12, 2015, in Paris, 197 countries ratified the Paris Climate Agreement, pointing to share a global response to the threat of climate change and eradicate poverty in the context of a sustainable development [1]. The signatory countries agreed to contain the increase in global average temperature below 2 °C above pre-industrial levels and pursue efforts to limit the temperature increase to 1.5 °C above pre-industrial levels.

The decarbonization of the building sector plays a strategic role in pursuing the climate change mitigation targets of the UNFCCC agenda. The final energy uses and related emissions of the buildings have grown by about 7.6% and 7% from 2010 to 2018, respectively [2]. Currently, the buildings account for 36% of the current global energy consumption and 39% of Green-House Gas (GHG) emissions worldwide [2], with an observed increase of 20% in the energy use of the residential spaces due to lockdown restrictions during the COVID-19 pandemic [3].

Governments and international organizations recognize the importance of an energy-efficient building sector to face climatic issues; therefore, they are presenting a new legislative framework to enhance the energy performance of buildings, reduce their consumption,

and mitigate emissions. As an example, the latest Energy Performance of Buildings Directive (EPBD) of the EU [4] requires the Member states to establish long-term roadmaps to decarbonize the building stock by 2050, paying particular attention to heating, ventilation, and air-conditioning (HVAC). This demand accounts for 80% of the total energy needs of the heating sector, the most energy and carbon-intensive sector of the European Union (50% of the whole EU's energy use [5]).

Buildings need energy from construction to demolition, and the Life-Cycle Assessment (LCA) found wide application over the last ten years in measuring the environmental impacts and energy consumption across their life [6–8]. Standard LCA (see UNI EN ISO 14044:2021 [9]) defines all the phases to be analyzed during the life of a product or service (i.e., boundaries) and provide prescriptions to collect all data about the mass and energy flows in a database, namely, life cycle inventory (LCI), and measure the environmental impact of each phase by mid-point and end-point indicators. Mid-point indicators are quantitative indices based on physical quantities such as the amount of emitted carbon dioxide (e.g., kilograms of emitted CO₂) or consumed energy (e.g., Joules), namely the carbon and energy footprint. End-point indicators are arbitrarily defined scores that measure the impacts on higher aggregation levels, such as human health or biodiversity; these are based on weighting schemes based on multiple mid-point indicators and are commonly in the form of arbitrary units (Pt) instead of physical quantities.

Sartori et al. [10] present the standard stages and approaches of LCA studies focused on buildings. Cradle-to-Grave is the most common approach, which measures the impact of a building in all stages of its life: from the extraction of raw materials, through construction, occupation (maintenance and operational energy), up to the disposal of demolition wastes. The Cradle-to-Cradle approach encompasses a more extensive life cycle, including the environmental costs and benefits of recycling demolition waste. However, for many applications, different boundaries might be defined as in the Cradle-to-Gate and Gate-to-Grave approaches, which split the analysis between the extraction of raw material phase and the building usage and construction. The former is more indicative of the design and realization of a building, hence highlighting the construction company performance; the latter focuses on the usage by the owner(s).

Following the above approaches, many LCA studies investigate the stages in the life of a building with the most significant impact to address the design choices toward sustainability criteria. Adalberth et al. [11] analyze four residential buildings located in Sweden with different structures, envelopes, number of apartments, and air-conditioning systems. Results show the occupation phase presenting the highest environmental impact (70 to 90%) over the whole life cycle and, in particular, the energy use of the occupation phase constitutes 85% of the total impacts based on a combination of global warming potential, acidification, eutrophication, photochemical ozone creation potentials, and human toxicity. Chang et al. [12] study urban and rural residential buildings in China, estimating the energy use in each phase of their life cycle by historical energy-intensity data. Both urban and rural buildings present the most energy needs in the occupation stage, weighing 75% and 86% over the total, respectively. Ramesh et al. [13] focuses on the energy inputs of 73 residential and office buildings, distinguishing the energy embodied by materials and technical installations, the operational energy consumed by air-conditioning and daily maintenance, and the demolition energy required by waste dismantle and disposal. In all buildings, the operational stage demands 80 to 90% of the total energy consumption, while the embodied energy weights for the remaining part (10 to 20%).

Based on the above studies, the energy needs of buildings critically depend on the occupation stage; therefore, the most effective strategies to reduce their environmental impact must aim at:

- Reducing the heating and power loads of the HVAC system and power appliances (see Section 1.1);
- Shifting the heating and power generation to renewable energy systems (see Section 1.2).

1.1. Energy Efficiency

The optimization of building envelopes represents one of the key strategies to optimize energy-saving both at the design phase and in the renovation of existing buildings. The effectiveness of the building envelope is strongly dependent upon the external condition, and Romani et al. [14] present a methodology for its optimization envelope tailored according to the climatic zones of the building location. Similarly, Asadi et al. [15] assess the effectiveness and economic benefits of the radiant barrier (i.e., heat-reflecting coatings preferentially deployed on the rooftop) under different climatic conditions in the US. Di Perna et al. [16] study the effects of five envelopes on the indoor comfort in a school building located in different climates. Results show that the wall with the higher inertia guarantees the best comfort and is less susceptible to the occupant's behavior (e.g., window opening).

However, retrofitting existing buildings can be counterproductive and inconvenient both from technical and economic points of view. Basińska et al. [17] present an energy and economic analysis of retrofitting the internal walls of a residential building with thermal insulation. They compare four alternative solutions, and none of them is economically convenient due to the extended return time of the initial investment. Sartori and Hestnes [18] reviewed the energy consumption along with the whole life of 60 literature cases, distinguishing conventional from low-energy buildings (i.e., featuring advanced energy-saving solutions), and a self-sufficient solar house that maximizes the solar energy use with active and passive technologies. Results show that the energy use of the self-sufficient house is higher than some low-energy buildings because the energy embodied in its energy-saving systems exceeds the reduction of the operational energy needs. Similar conclusions are achieved in [19]. As an alternative to technical retrofitting, the management of the room occupation with energy-saving criteria proved attractive benefits, especially in public and crowded buildings such as universities and schools. Song et al. [20] presents a timetabling algorithm to schedule the lessons of a university building complex. They prioritize the occupation of rooms with the lowest energy needs (dependent on the weather, orientation, and envelope properties), reducing the yearly energy consumption by 4%.

1.2. Energy Transition

The generation of renewable energy in buildings sees a variety of options available in the current market. Recent research trends pursue the so-called hybrid systems based on integrating different renewable energy systems in a single building. Such an approach is particularly advantageous for the design of Net-Zero Energy Buildings (NZEB, [21]), which are designed to generate an amount of energy not less than what they consume during their use phase.

Solar energy is the most abundant and widespread renewable source, and it can be easily converted into final-use forms using standard and tested technologies, such as [22]:

- Photo-voltaic (PV) panels, integrated into vertical walls or roof, to generate electricity for self-consumption. According to their size, the panels cover part or the whole annual electricity need.
- Solar-thermal electric systems, using the heat from solar radiation for electricity generation.
- Solar-thermal heating systems, as on-site thermal collectors, to produce hot water by the solar radiation.

Co-generation systems in buildings consist of small-to-medium scale systems for combined heat and power generation (CHP), namely, micro-CHP; these systems include an internal combustion engine coupled to a generator that recovers the waste heat to produce electricity [23]. The heat-generation may use conventional fossil fuels [24], biogas [25], biomass [26,27], and hydrogen [28]. As popular technologies for electricity generation, see the Stirling engines [29], and Organic Rankine Cycles (ORC) [30]. An upgrade of the micro-CHP systems is the tri-generation (combined cooling, heat, and power) that also produces the cold water necessary for space cooling [31].

1.3. Ground-Source Heat Pumps

Heat Pumps (HPs) for building air-conditioning are having a wide diffusion worldwide. For instance, the statistics from the European Heat Pump Association (EHPA) report an uninterrupted growth of the HP installations in the European Market from 2012, leading to a total installed capacity of 10.6 million units in 2017; at this rate, the European HP market will double by 2024 [32,33]. The popularity of HPs depends on their energetic and environmental benefits [32]:

- HPs consume electricity to extract heat from a low-temperature source and produce higher-temperature thermal energy. According to the nature of the colder source, the generated heat is about 2–4 times greater than the consumed electricity, and therefore, most of the output energy is renewable.
- HPs produce thermal energy with high efficiency. Nowak [32] compare the energy demanded to produce a thermal energy unit by HPs and traditional fossil fuels systems; their results show the HPs more efficient than conventional heating systems up to four times; similar benefits also emerge in terms of CO₂ emissions per produced kWh that can be three times lower than fossil-fueled heating systems.

Ground-source heat pumps (GSHPs) use solar energy stored in the first layers of the ground, which is available as a low-temperature energy source all year long. Torio et al. [34] indicate the GSHPs as particularly convenient in terms of energy and exergy efficiency among the available renewable energy systems for building air-conditioning. Furthermore, the feasibility of such systems does not depend on the nature of the geothermal source at the site. Since the low operative temperatures involved in its thermodynamic cycle (5–30 °C [35]), a GSHP system exploits the shallow layer of the ground, and it could theoretically be installed worldwide (the maximum layer depth involved in the heat exchange generally ranges between 20 and 200 m [36]). We remind further technical details on the Heat-Pump (HP) thermodynamics in Section 3. Market statistics highlight the benefits presented above: the installed capacity of geothermal heat pumps increased from 2000 to 2009 by 6.28 times [37], and the latest report by Lund and Toth [38] indicate the worldwide yearly exploitation of geothermal energy by heat pumps increased by three times from 2010 to 2020.

Our review summarizes the studies of current scientific literature investigating the environmental benefits and issues of GSHP systems for HVAC, analyzing their role in the decarbonization of the building sector and aiming at presenting a comprehensive view on their sustainability (Figure 1). In Section 2, we report the main results and remarks from the application of the LCA technique to different case studies. Section 3 discusses the main operative conditions and working principles which affect the sustainability of a GSHP system from a thermodynamic point of view. Finally, Section 4 investigates the environmental impact of a GSHP system as related to the climate, terrain, and other exogenous variables characterizing the installation site.

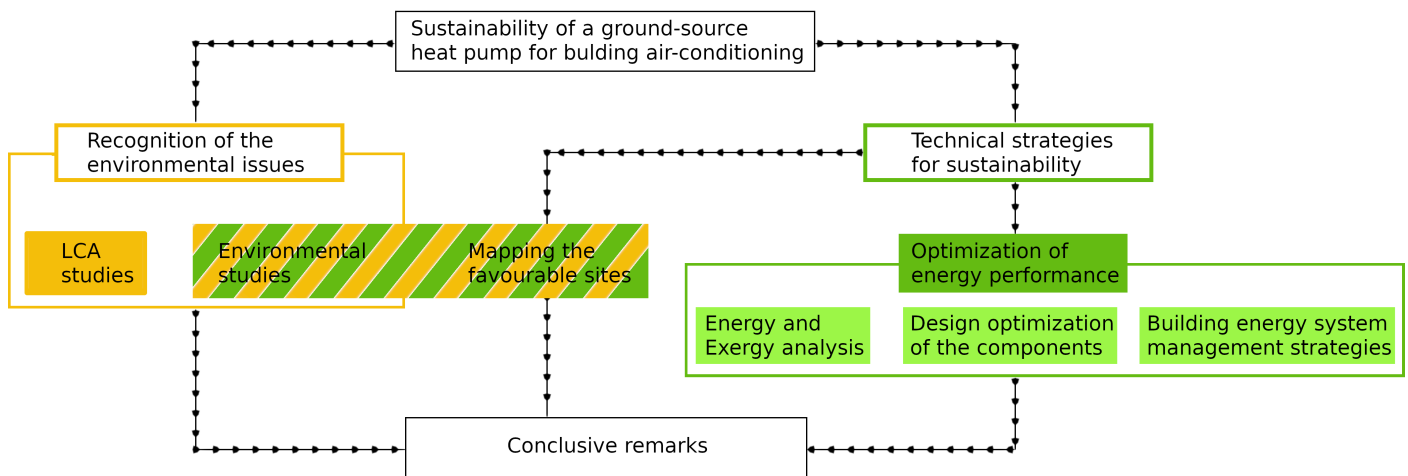


Figure 1. The overall structure of this review: environmental issues of geothermal heat pumps (yellow) and proposed solutions to enhance their sustainability (green).

2. Life-Cycle Impact Assessment of Shallow Geothermal Energy

In its classic applications, geothermal energy exploitation is not one of the best performing technologies in environmental terms among all the renewables, showing the highest impact values in several environmental indicators compared to the other technologies [39]. However, many environmental impact studies available in the literature indicate the low enthalpy, namely, the shallow geothermal energy exploited by GSHP as key renewable sources for sustainable heating and cooling applications.

Saner et al. [40] reviewed LCA publications aimed at analyzing the net energy consumption and GHG emissions or savings associated with geothermal heat pumps and also at examining environmental burdens and benefits related to their applications by employing a state-of-the-art LCA. Their study showed a considerably variable range of savings (from 30% to 80%) when compared to existing heating or cooling systems (for example, chiller, gas or oil boiler, wood combustion, air conditioner, and air source heat pump), with average savings in GHG emissions exceeding 50%. Saner et al. [40] concluded that CO₂ emissions from primary energy consumption for heat pump operations are most crucial for GSHP systems and that CO₂ emissions can be considered as a good proxy for environmental assessment of GSHP systems, even if other noteworthy categories, such as fossil energy depletion and particulate matter formation, appear relevant to define their environmental burdens.

Results showing a strong dependence of CO₂ savings related to GSHP systems on the supplied energy for the heat pumps and the efficiency of installation also emerge in a study by Blum et al. [41]. In the considered reference scenario, they estimated CO₂ emissions per kWh of heating demand in 149 gCO₂/kWh using the German electricity mix and 65 gCO₂/kWh using the regional electricity mix, which results in CO₂ savings of 35% and 72%, compared to conventional heating systems, respectively.

Similarly, Bayer et al. [42] investigated the potential of GSHP application in the residential sector to save GHG emissions when replacing alternative space heating technologies, based on a specific calculation methodology focused on the operation phase and using life cycle emission factors. They concluded that GSHPs seem to be attractive when the primary energy for the electricity used by the heat pump is renewable, nuclear, and hydropower and that higher GHG savings derive from the carbon-intense substituted heating carriers, estimating GSHPs savings that reach up to 61 tons of CO₂ per Tj of heating energy.

Greening and Azapagic [43] compared domestic heat pumps—i.e., GSHP but also Air- (ASHP) and Water- (WSHP) Source Heat Pump—with gas boilers in the UK using life cycle assessment. Their findings show that, currently, heat pumps do not seem to offer

significant environmental benefits over condensing gas boilers for the UK conditions since they present a higher impact for most of the considered categories. An exception is for the Global-Warming Potential (GWP), with the ASHP pumps saving around 6% of the impact, while GSHP and WSHP, which perform much better, have an average of 36%. Greening and Azapagic [43] results also show that the environmental sustainability of heat pumps improves with a more extensive penetration of renewable energies in the electricity mix. In particular, they estimated that an increase in renewables national share to 80% allows reducing the GWP of heat pumps by 50% (and the other environmental impacts on average by 42%, even if most of them remain higher than those from gas boilers for all types of the pump). Other sustainability assessments of geothermal heating and cooling systems focused on specific case studies are available in the literature.

In particular, Rodríguez et al. [44] developed an LCA study over a GSHP installation in a nursery school in Spain, comparing it with the fuel boiler system previously installed. Their study shows a saving of CO₂ emissions associated with the GSHP equal to 54.3%, which reach up to 95.8% if the electric power consumed by the GSHP comes from renewable sources. More in detail, they found that the GSHP system has a more significant impact than the boiler system in the installation phase due to fuel consumed by the drilling machines and the construction of geothermal probes.

Hong et al. [45] performed a sensitivity analysis on the impact factors of GSHP systems, using a dormitory building in a university in South Korea (Seoul) as a case study. Authors carried out the sensitivity analysis in terms of energy generation and environmental impact and, regarding the latter, they used the LCA to evaluate the material manufacturing, use, and maintenance stages in terms of Resource Depletion Potential. Results show the borehole length as the most influential impact factor in environmental terms, i.e., the factor that influences the environmental impact of the GSHP the most compared to the other ones.

Bonamente and Aquino [46] used LCA to evaluate the environmental impact of an innovative GSHP system installed in a commercial building in central Italy, analyzing three different scenarios in terms of system configurations and operative modes. They calculated a CF indicator ranging from 0.156 kgCO₂eq/kWh_{th} in the “baseline scenario” to 0.187 kgCO₂eq/kWh_{th} in the “storage scenario” and assessed the land occupation/transformation within their impact assessment. Land occupation slightly varied in the different scenarios (from $1.08 \cdot 10^{-2}$ to $1.33 \cdot 10^{-2}$ m²a/kWh_{th} for Agricultural Land and from $1.32 \cdot 10^{-3}$ to $1.51 \cdot 10^{-3}$ m²a/kWh_{th} for Urban Land) and the same applies for land transformation, that varied from $2.50 \cdot 10^{-5}$ to $2.84 \cdot 10^{-5}$ m²a/kWh_{th}.

Reddy et al. [47] presented a comparative sustainability assessment—using LCA to evaluate the environmental impacts—of geothermal and conventional systems used in three different buildings in the United States and concluded that from the environmental, economic, and social point of view, the geothermal system is more sustainable than the conventional one. Furthermore, regarding the environmental impact, the geothermal system showed a better performance in all the ten impact categories considered, with a reduction in climate change impact in the order of 80 to 90%.

Marinelli et al. [48] evaluated the environmental life cycle performance of a dual-source heat pump prototype that uses both air and ground as external heat sources, showing results according to the above. They found that when the electricity used is renewables-based, the overall environmental impact of the system can be reduced by about 50%, also highlighting that the studied system is more environmentally friendly than conventional solutions in particular conditions.

Pratiwi and Trutnevte [49] calculated the life cycle impacts of different (six, hypothetical) heating and cooling configurations from shallow to medium-depth geothermal wells with connected, decentralized heat pumps and district heating and cooling in Switzerland (State of Geneva), comparing them with other heating and cooling sources to evaluate their advantages and disadvantages in terms of environmental impact. They evaluated eight environmental impact indicators and observed that geothermal heating systems are generally environmentally preferable, even if, in some cases, geothermal heat could

have more significant impacts than fossil fuels. In particular, Pratiwi and Trutnevte [49] showed that geothermal systems could have higher impacts, among the various indicators, both in terms of water consumption and land use. In this regard, they estimated water consumption values ranging from 57 to 81 m³/MWh and land use values ranging from 0.2 to 0.44 m²· year crop eq/MWh for the analyzed configurations. They also found that the environmental impacts of a given geothermal resource are lower when installing decentralized connected heat pumps in place of traditional district heating and cooling. Moreover, combining shallow wells with connected decentralized heat pumps seems to lower the impacts further.

The literature analysis shows an evident prevalence of studies focused on particular GSHP systems configuration and a lack in investigating the overall impact of these systems. In particular, there are several studies regarding GSHP, while geothermal systems involving groundwater extractions from low and medium enthalpy—systems that represent most of the geothermal district heating in Europe [50]—are less represented in terms of LCA studies [51].

Moreover, available studies generally limited their investigations to a few impact categories, and climate change emerges as the most frequently considered in the evaluations. Thus, carbon footprint emerges as primarily investigated, while there is a scarce investigation of other relevant footprints (i.e., energy, water, and land use) and impacts.

Therefore, environmental studies focused on shallow to medium-depth geothermal heating and cooling are desirable to obtain a complete picture of exploiting the geothermal energy for building air-conditioning. Moreover, to properly assess the sustainability of geothermal systems used for building air-conditioning, the evaluation should focus on a broader range of environmental indicators, since potential interactions with other environmental spheres—such as underground and groundwater—may occur and be quantifiable ([52,53]).

3. Sustainability of a Ground-Source Heat-Pump System by Energy Performance

According to the conclusions of the literature review shown in Section 2, the energy consumption of GSHPs and used energy mix are indicated as the main drivers of their environmental impacts. In this section, impacts are analyzed and discussed as a function of their energy performance in thermodynamic cycle and efficiency, component optimization, and building management strategies. Table 1 summarizes the environmental issues distinguished by stage and the strategies to improve the sustainability of geothermal heat pumps emerging from the literature.

3.1. Thermodynamic Cycle and Efficiency

The thermodynamic cycle of a heat pump consists of transferring heat from a cold to a hot source using the work of a compressor (Figure 2). Standard systems operate a Rankine inverse vapor-compression cycle. The cycle starts in the evaporator, where the low-temperature heat (\dot{Q}_L), withdrawn from the cold source, heats the refrigerant to the saturation state. The compressor overheats the refrigerant by the input work (\dot{W}) and flows it to the condenser, where the heat-transfer fluid of the hot source receives the whole output heat:

$$\dot{Q}_H = \dot{W} + \dot{Q}_L. \quad (1)$$

The exhaust refrigerant returns to the evaporator through a throttling valve, which reduces the pressure and temperature to the level of the evaporator (i.e., throttling process [54]), and the cycle restarts. When used for space heating, ground-source heat pumps for air-conditioning transfer heat from the shallow layer of the ground (cold source) to the building space (hot source, see Figure 2a). In cooling mode, the cycle is reversed (i.e., evaporator and condenser are switched), and the GSHP uses the ground (cold source) to dissipate the excess heat (Figure 2b).

The Coefficient of Performance (COP) is an index used to quantify the heating performance of an HP. It is defined as the ratio of the total output heat over the work by the compressor, and it is related to the efficiency of the cycle:

$$COP = \dot{Q}_H / \dot{W}. \quad (2)$$

It is straightforward to see that the work of the compressor adds up to the heat extracted from the ground (see Equation (1)). The performance of an HP used in cooling mode is commonly described by the Energy Efficiency Ratio (EER), defined as the ratio of the heat subtracted from the building to the external work:

$$EER = \dot{Q}_L / \dot{W}. \quad (3)$$

In this case, the work of the compressor does not sum up in the numerator of the performance index. Having remarked such a difference between the two indices, it is somehow common to only refer to COP even when assessing the cooling performance of an HP. The cooling COP has to be calculated according to Equation (3).

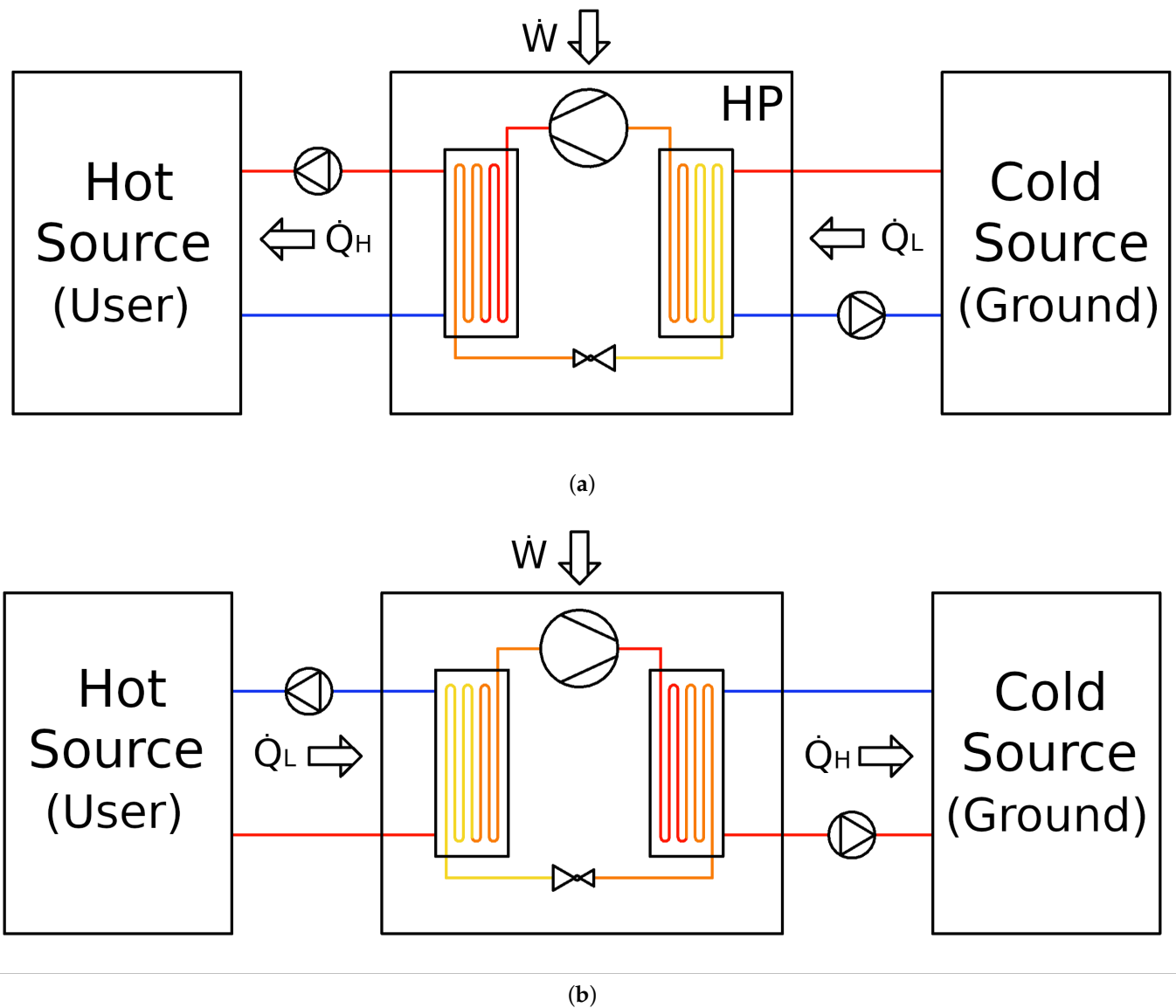


Figure 2. Ground-source heat pump working cycles in heating (a) and cooling (b) mode.

Table 1. The environmental issues distinguished by installation and operation phases and the strategies for enhancing the sustainability of geothermal heat pumps.

Phase	Environmental Issues	Strategies for Sustainability
Installation	<ul style="list-style-type: none"> Fuel use by drilling machines. Fuel/materials use for the construction of geothermal probes. Land excavation and occupation. Ground surface swelling. Risks of subsidence and flooding. Contamination of underground and superficial aquifers. 	<ul style="list-style-type: none"> Selection of the GHE setup most suitable to installation site (e.g., U-tube, co-axial). Optimization of the boreholes number, length and depth. High thermal conductivity grouting. Optimization of the GHE heat transfer efficiency. Accurate sizing of the heat pump compared to the building thermal demand. HP running at its nominal capacity Inclusion of a thermal storage
Operation	<ul style="list-style-type: none"> GHG emissions by electricity consumption. Unstable COP and SPF over long term. Component specific inefficiencies and entropy sources. Direct and indirect emissions related to the refrigerant. Soil and aquifer contamination by anti-freeze leakages. Propagation of contaminants. Alteration of the undisturbed ground temperature. 	<ul style="list-style-type: none"> Balanced annual thermal injection/extraction to facilitate the soil temperature recovery. Minimization of mutual interference among GHEs. Minimization of power use and entropy generation of the compression group. Maximization of compressor and evaporator efficiency. Optimization of the compressor configuration. Energy recover from the expansion valve. Energy recover from the expansion valve. Hybrid compression-absorption systems. Low-GWP/natural refrigerants. Use of the electricity from renewable energy sources. Dual-source HP/operation mode and innovative system configurations (e.g. [55–57]). Dynamic management of GSHP system according to building energy needs.

3.1.1. Energy

The European Directive 28/2009 [58] defines heat pumps as renewable systems only if the heat supplied to the user significantly exceeds the consumed energy over the whole climatic season (yearly averaged COP ≥ 1.5), de facto making the COP the first indicator of the sustainability of a heat pump system. The European Code 14511:2018 [59] indicates to manufacturers the standard conditions for the COP calculation and prescribes to include the electrical needs of auxiliary devices and circulation pumps in the input energy (W). However, the assumption of a constant COP presents poor accuracy, especially in long-term analysis, since the operating conditions that influence the COP change along the operating cycle [60]. Furthermore, the continuous heat extraction from the ground changes its temperature with consequent degradation of the system performance over the long period [61].

Several works investigate the relations between the GSHP operating conditions and COP. For example, Sivasakthivel et al. [62] indicate the heating load, water temperature from the cold source, the thermal conductivity of heat exchanger pipe material, and mass flow rate of fluid per kW of load as the main parameters affecting the COP with variations of $\pm 26\%$.

Staffell et al. [63] derive the following empirical relation, specific for domestic heat-pump, based on data from manufactures:

$$\text{COP} = 0.000734 \cdot \Delta T^2 - 0.15 \cdot \Delta T + 8.77 \quad (4)$$

The temperature difference between the average temperature of the water entering and leaving the condenser and evaporator (ΔT) should be between 20 and 60°C.

Figueroa et al. [64] apply a model predictive controller methodology to a GSHP system. They model the COP by non-linear equations, including the inlet and outlet temperatures of the ground and variable mass flow rates of the heat transfer fluid. Results show that enhancing the accuracy of the COP model increases the economic savings from 0.46% to 2.71%, depending on the electricity-to-gas price ratio scenario.

Ommen et al. [65] propose a COP prediction model for HP in industrial applications, which includes three main groups of variables representing the (i) the inlet and outlet temperature from the cold source, (ii) component-specific parameter (e.g., the compressor efficiency), and (iii) the characteristics of refrigerant.

Pieper et al. [66] model the COP of an HP for district heating at off-design conditions by linear correlations. They estimate an offset of the COP between the design and off-design conditions, including the temperature of the cold source and the user's temperature.

Qian and Wang [67] model the heat transfer around a vertical boreholes (see Section 3.2) field and calculate the COP by the soil temperature distribution. The latter depends on the soil thermal properties, the distance between the boreholes, cooling and heating loads, and ambient air temperature. Results show accurate predictions for balanced heating and cooling loads. Furthermore, the irregular cycles facilitate the soil temperature recovery, and therefore, these present higher COPs than full-day operations.

The energy analysis is the standard approach to formulate COP prediction models. However, the analysis of system performance limited to energy flows does not distinguish the quality of energy inputs and is independent of the environmental conditions [68,69]. Thus, such an approach may result inaccurate to evaluate the impacts of the system on the environment.

3.1.2. Exergy

Exergy analysis studies entropy generation in heat exchange and conversion processes. The review by Lucia et al. [70] resumes the thermodynamic assessments of GSHP systems available in the literature. Based on studies following the entropy minimization criteria, au-

thors estimate a seasonal average exergy efficiency around 68% (with further optimization potential), and achievable savings on installation costs by 5.5%.

The exergy efficiency is the ratio of the output to input exergy flows [70] and the exergy loss represents the amount of exergy destroyed in each component by the entropy generation [71]. The exergy analysis of a GSHP measures its performance considering the quality of the energy flows and their relation with the environment (i.e., dead-state) [72]. Such an approach quantifies the entropy generation of a GSHP system: it indicates the potential energy savings of each component and distinguishes the different impacts of the system on the environment.

The pioneering study by Hepbasli and Akdemir [73] presents the energy and exergy analysis of a GSHP system with vertical boreholes. Results show the highest entropy generation in the compressor due to electrical, mechanical, and isentropic inefficiencies. The irreversibility of the condenser depends on the super-heating of refrigerant in the compression process, producing a significant temperature difference from the evaporation point. The third-highest entropy generation is in the expansion valve because of the pressure drop.

Akpinar and Hepbasli [74] study the exergy performance of two GSHP systems installed in Turkey based on the actual operational data. The first one is a GSHP system designed and constructed for investigating geothermal resources with low temperatures, while the second one is a GSHP system with a vertical ground heat exchanger (see Section 3.2). Results show the exergy efficiencies varying in the range from 0.0144 to 0.0384. The highest irreversibility is in the motor–compressor.

Bi et al. [75] calculates the exergy losses in all components of a GSHP system, distinguishing the cooling and heating mode. Results indicate the compressor and Ground Heat Exchanger (GHE) as the components with the most promising energy savings potential because these present the highest exergy destruction rate and the minimum exergy efficiency, respectively; exergy losses in heating mode are higher than cooling mode.

Li et al. [76] compare the exergy performance of a GSHP against an air-source heat pump system, distinguishing between the exergy flows from the system to the environment and vice versa, namely, warm and cool exergy. Results show that the exergy efficiency of the GSHP equals 19.1 and 19.9% when the system is operating in cooling mode and dehumidification mode, respectively, against the ASHP that presents an exergy efficiency of 9.3 to 11.9%, respectively. The performance of the GSHP is sensibly higher than the ASHP because of a more spontaneous heat transfer between the ground and cooling water: the temperature difference between the user and the cold source is smaller than in ASHP, and the ground temperature is generally lower than that of the ambient air. Similarly to [73–75], authors observe the highest exergy losses and improving potential in the compressor and refrigerant cycle.

3.2. Optimization of the System Components: Compressor, Ground Heat Exchanger, and Refrigerant

The main components of a ground-source heat pump are the heat pump, the indoor distribution system, and the ground heat exchanger, which includes the geothermal probes (commonly HDPE pipes) and hydraulic connections with heat pump (Figure 3). The GHE can be either an open-loop in case there is both mass and energy flow from the ground to the probes or a closed-loop in case only heat exchange occurs [77]. Closed-loop systems consist of horizontal or vertical heat exchangers. The latter are vertically oriented heat-exchanging pipes, also known as borehole heat exchangers [78]. The heat transfer fluid between the HP and GHE is water mixed with anti-freeze (usually propylene or ethylene glycol).

3.2.1. Ground-Source Heat Exchangers

An LCA study by Aresti et al. [79] investigates the environmental impact of a GSHP system with different GHE configurations and compares them to an ASHP. The case study is a residential building located in moderate climate conditions. Based on referenced inlet fluid temperatures and GSHP characteristics, the authors estimate the GHE sizes to cover

the design heating and cooling load. LCI processes include manufacturing, installation, operation, and transportation.

All mid-point indicators show the operation stage impacting by at least 83% of the total. The GWP is the category with the highest impact, the ASHP system presenting the highest emissions, followed by the coaxial vertical GHE configuration. The vertical slinky GHE (horizontal exchanger) presents the lower GWP. The same remarks emerge for all other indicators: acidification potential (AP), eutrophication potential (EP), freshwater aquatic ecotoxicity (FAETP), terrestrial ecotoxicity (TAETP), human ecotoxicity (HDP), and the stratospheric ozone depletion (ODP) follow the same trend of GWP. Among vertical borehole GHEs, the impact of single and double U-tube is similar. However, this impact is slightly higher for the double U-tube and reaches the maximum with the coaxial GHE due to its highest impact in the manufacturing process. Horizontal GHEs present lower impacts than vertical GHEs.

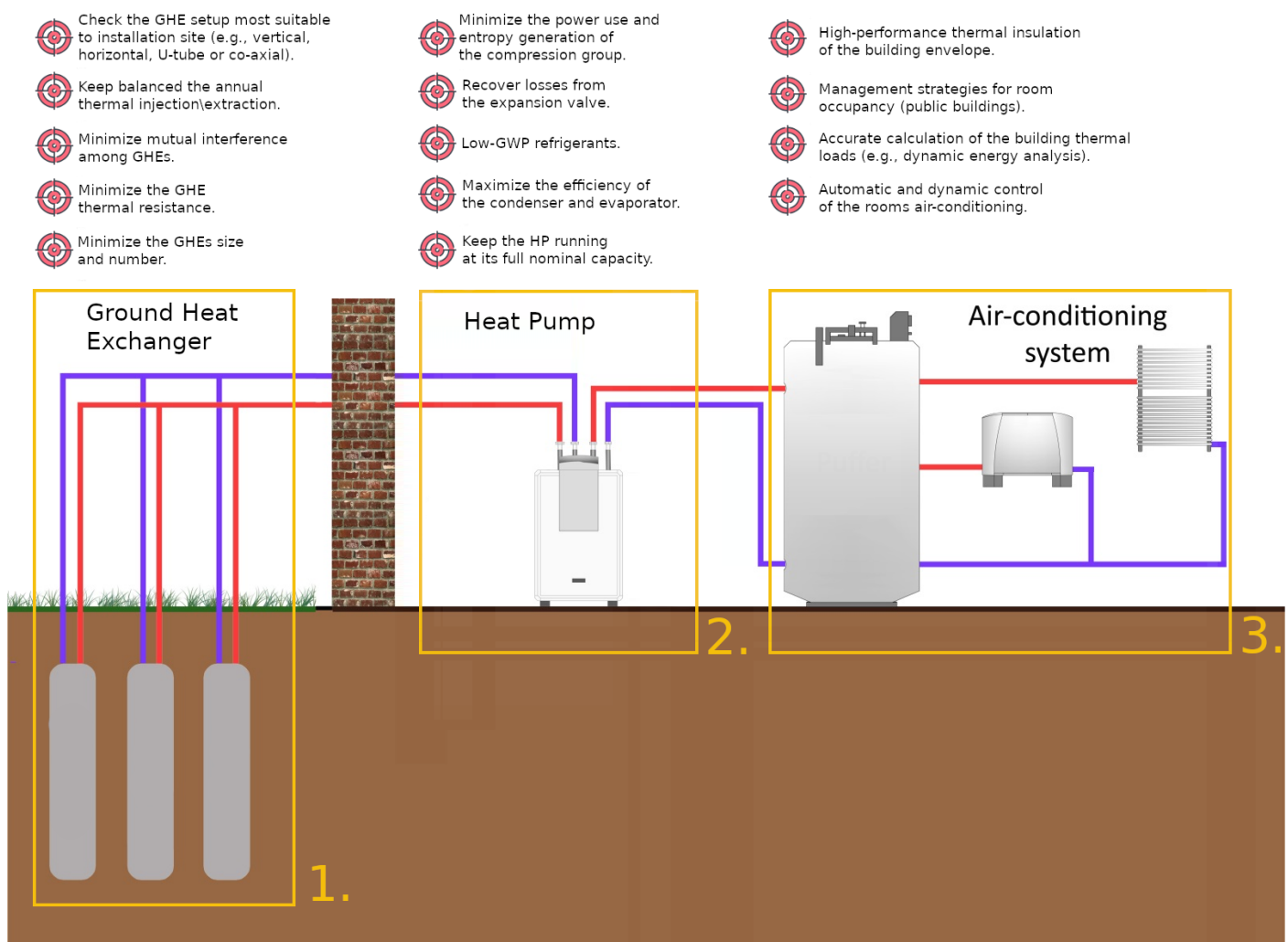


Figure 3. Components of a ground source heat pump : (1) ground heat exchanger; (2) heat pump; (3) the air-conditioning distribution system. Main optimization strategies emerging from literature are shown for each component.

In particular, the slinky and spiral (vertical slinky) present the highest impact on the manufacturing stage because these require longer HDPE pipes. However, at fixed COP, the horizontal configuration needs a land area up to 6.5 times higher than the vertical boreholes.

3.2.2. Compressor

From a thermodynamic point of view, the HP compressor is the component presenting the highest margin of improvement, with potential benefits on the whole system COP, and many works study the specific optimization of this component.

As an example, Schiffmann and Favrat [80] present the design of an innovative radial compressor for a domestic heat pump. Authors derive the specifications of an appropriate refrigerant fluid and study the relation between the impeller characteristics, the seasonal heat demand, and the bearing and rotor dynamics for stable operation. Biao et al. [81] propose a novel three-cylinder two-stage variable volume ratio (TSVVR) rotary compressor. Experiments show the two-cylinder mode presenting a larger volume ratio than the single-stage and two-stage setup; such a mode is more suitable for high-temperature and low-load conditions. In the three-cylinder mode, the TSVVR system has a smaller volume ratio, and the compression efficiency and flow rate of refrigerant increase at low evaporation temperatures. Switching between these two modes ensures that the TSVVR system always works in optimal conditions.

Wang et al. [82] present a new dual-cylinder rotary compressor with refrigerant circulating in two separate loops, each one with independent suction and discharge ports. Experimental results show that the potential performance of the double-loop system in winter testing conditions is higher by 17% than that of the traditional single loop, with a maximum COP of approx. 10. In summer conditions, the maximum COP is 4.7, and the performance of the dual-loop system could be up to 33% higher than that of the traditional system.

3.2.3. Refrigerant

The works cited above limit the optimization of the HP compressor to a thermodynamic point of view, aiming at the best COP and minimum entropy generation; however, the compression group continuously releases the circulating refrigerant in the atmosphere. For example, the case study by [83] considers as ordinary maintenance one refill of refrigerant a year. All refrigerants act as greenhouse gases when released into the atmosphere, each with the proper global warming potential depending on their chemical composition. The emission of such fluid in the environment can be another critical source of impact of a GSHP system.

Standard refrigerants used to be chlorofluorocarbons (CFCs) and hydrochlorofluorocarbons (HCFC), characterized by GWPs exceeding 10,000 and 2000, respectively (i.e., producing effects 10,000 and 2000 larger, respectively, than those of CO₂ in terms of global warming per unit mass released). In particular, R410A long dominated the market of domestic heat pumps, with a GWP of approx. 2088 [84].

Current alternatives are the hydrofluorocarbons (HFC) as R32, with a GWP of 543 [85]; however, HFCs are still far from fulfilling the most recent regulations (e.g., the Japan FGas control policy, the European F-Gas Directive, EU Regulation No. 517/2014 on fluorinated greenhouse gases). Present works aim at investigating less impacting alternatives as a natural refrigerant (e.g., CO₂ and ammonia), low GWP synthetic refrigerant, and new mixtures.

The review by Wu and Skye [86] studies specifically the diffusion of natural refrigerant as CO₂, NH₃ (ammonia), water, and hydrocarbons for replacing the synthetic refrigerants in GSHP systems. First, the authors compare the thermodynamic properties of each refrigerant in a standard vapor-compression cycle. Second, they report several case studies of GSHP systems with natural refrigerants as working fluids.

CO₂ presents the highest volumetric capacity and operation pressures, yet with the COP settling to the minimum value. Its discharge temperature is low (<55 °C).

Ammonia and hydrocarbons need moderate operating pressures and volumetric capacity, and these produce higher COP values. The discharge temperature of hydrocarbons is the lowest, while ammonia increases by 20K compared to the CO₂. Both these refrigerants present flammability issues, and ammonia also has little toxicity.

Water produces relatively high COPs; it presents the lowest operating pressures, volumetric capacity, and the highest discharge temperature.

As key findings, CO₂ has the widest diffusion in experimental GSHP systems such as advanced vapor-compression cycles [87,88], direct-expansion systems [89–91], multi-source hybrid GSHPs [92–94], and hybrid GSHPs for lower ground thermal imbalance [95,96]. Ammonia is the second most studied natural refrigerant for GSHP systems.

Case studies for standard vapor compression systems [97–99] indicate NH₃ as a promising alternative to synthetic refrigerants due to the high performance ($3 \lesssim \text{COP} \lesssim 4$), comparable with commercial applications (e.g. [100]).

Hydrocarbons present rare applications in GSHP systems, and there are many restrictions on their use as a refrigerant because of flammability issues [101]. Available case studies using propane [102,103] present interesting COP values between 3.5 and 4.5. In particular, the propane GSHP in [104] has a seasonal COP of 3.5 and 4.3 in the heating and cooling mode, respectively.

Sagia and Rakopoulos [105] study low-GWP refrigerants for a GSHP in an office building. As alternative to R-22, the authors calculate the performance of the HP system filled with binary and ternary mixtures of refrigerants: R-32/R-134a, R-407B, R-152a/R-125/R32, R-410B, and R-507A. Results show the system with standard R22 presenting the highest COP, followed by R-32/R-134a and R-152a/R-125/R-2 mixtures.

Maddah et al. [106] study the energy and exergy performance of a ground-source and air-source heat pumps comparing scenarios with six different refrigerants. Results show that the best and worst COP and exergy efficiency for GSHP systems are obtained with R134A and R125, respectively.

The analysis by Bobbo et al. [107] studies R32 and R454B as alternatives to the standard R410A. Both refrigerants present intermediate GWP (<1000) and could mediate in the short-term the transition toward very low GWP refrigerants (<150). Authors compare the performance of a GSHP system, paying particular attention to the volume heating effect (refrigeration effect per unit volume), the isentropic efficiency of the compressor, and standard COP and exergy efficiencies. Furthermore, they compare the standard HP compression cycle with an improved configuration that includes a thermal regenerator to preheat the refrigerant at the upward of the compressor. R454B produces the best performance; however, it presents the lower volumetric heating effect, and therefore, larger components are needed, with inevitably higher costs.

Eslami-Nejad et al. [108] present a direct expansion GSHP system, with refrigerant evaporating directly in a vertical GHE with U-shape pipe, and study the feasibility of using the CO₂ (R744) as natural refrigerant by comparing the system performance with common synthetic refrigerants as R410A, R22, R407C, R12345yf, and R134a. The sensitive parameters are the fluid temperature, pressure, mass flow rate, pipe dimensions, and power for fluid circulation. The performance indicators for each refrigerant are the heat exchange capacity for a unit of mass flow rate and pipe surface. Results show the potential benefits of using the CO₂ as refrigerant: (i) at equal heat extraction rate, the CO₂ system needs the smallest pipe size; however, the pipe diameter and the borehole thermal resistance are inversely correlated [109], and therefore, the borehole with CO₂ presents the highest thermal resistance; (ii) at equal heat extraction, the system needs the lowest mass flow rate; (iii) the CO₂ shows the lowest pressure drop along the borehole, and therefore it needs the least circulating power.

3.2.4. Absorption Cycles

Ammonia, as a refrigerant, is mostly used in applications using absorption cycles [110]. Absorption systems transfer heat from a cold to a hot source using heat, instead of electricity, as input energy. Their main advantage is reducing electricity consumption, especially in the summer season, but the COP of an absorption cycle is lower than vapor-compression. However, absorption systems extract less heat from the soil in winter than that injected in

the summer, and such an effect reduces the thermal imbalance in the ground that causes the performance degradation in the long term.

Most recent works propose hybrid compression–absorption systems to improve the global COP further. Water finds poor application as a working fluid for GSHP systems due to its low operation pressure, volumetric capacity, and high discharge temperature. The available studies focus on absorption systems for solar cooling [111,112], district heating [113,114], and thermal imbalance in cold regions [115].

3.2.5. Life-Cycle Climate Performance

Although the work by Yang et al. [116] does not explicitly consider a GSHP system, it calculates the Life-Cycle Climate Performance (LCCP) of common refrigerants for domestic heat pumps. Introduced by UN [117], the LCCP finds application in many studies that calculate the environmental impact of HP systems according to their refrigerant fluid and point to select the lowest-GWP alternative [118–121].

Such an indicator distinguishes between direct and indirect emissions of a refrigerant. The first group measures the GWP caused by the refrigerant leakage from the conditioning system, and it depends on the time for its atmospheric degradation. The latter includes the CO₂ emitted by the production and recycling of refrigerant, and it measures emissions related to energy consumption, manufacturing, and disposal at the end of life. In [116], authors compare the LCCP and thermodynamic performance of R410A, HFC32, and low-GWP mixtures.

Results show that R410 and R32 have the highest direct emissions; however, these synthetic refrigerants also provide the highest COP of the system, and their indirect emissions are lower than low-impact alternatives. Considering the whole LCCP, no sensible differences emerge because indirect emissions have a crucial weight on the environmental impact. Further, the authors compare the LCCP of different operating periods showing that the environmental performance of low-GWP mixtures is advantageous over short operating time.

3.2.6. Temperature Optimization

A further approach optimizes the GSHP performance by reducing the temperature difference between the condenser and evaporator, and therefore, the electric energy input. Such temperatures depend on the heat transfer efficiency with the cold source as well as the thermal loads. In particular, the more efficient is the thermal exchange with the ground, the closest these temperatures are.

Kerme and Fung [122] compare the thermal performance of two vertical GHE, configured as a double and single U-tube, simulating the temperature profiles along the GHE and in surrounding soil, as well as the heat transfer rate per unit borehole depth. Results of the numerical analysis show the double U-tube setup presenting a higher heat injection and extraction rate than the single U-tube by approx. 77% and 71.8%, respectively. Further, the single U-tube presents a thermal resistance of 0.47 mK/W, higher than the double U-tube, with values of 0.31 mK/W. Other effects on performance are due to the anti-freeze solution. Such values of thermal resistance are slightly higher than the typical range observed in the literature (~ 0.1 mK/W); however, the authors calculate them by theoretical models specific for the single [123], and double U-tube [124] configuration and then validate their numerical method against the experimental results in [125].

Li et al. [126] propose a heat extraction model of a vertical GHE with a coaxial tube, studying the effects on thermal performance due to the soil stratigraphy. The authors model the heat extraction with the outer diameter of the buried pipe and the water flow, and they observe that the COP of the system with the coaxial tube increases by more than half compared with that coupled to a conventional U-tube setup. Crucial effects on thermal exchange occur when the thermal conductivity of the grouting material is lower than 1.5 W/(m °C).

Yu et al. [127] evaluate the thermal performance of an innovative GHE that includes a high thermal conductivity layer at the bottom (i.e., soilcrete) obtained by the jet grouting technique. A numerical model simulates the thermal extraction of a case study consisting of a GHE coupled to a soilcrete of given dimensions (radius and height) and for which the authors assume a uniform thermal conductivity of $50 \text{ W/(m } ^\circ\text{C)}$. Compared to a standard vertical GHE, the proposed configuration increases the average annual heat extraction rate by 1.27 to 1.6 times over 30 years. Finally, a sensitivity analysis investigates the effects on the GHE performance of three critical parameters of the soilcrete, adjustable in the grouting operations: the height, the radius, and the thermal conductivity. The radius of the grouting column is the parameter with the most substantial influence on the heat extraction rate while the thermal conductivity has slightly influence.

Liu et al. [128] study the energy exploitation of medium depth geothermal sources, assessing the main parameters that influence the thermal extraction and the energy efficiency of a GHE of 2500 m depth by a transient heat transfer model. Factors influencing the decline of system performance on a long-term cycle are the specific heat transfer rate, rock thermal conductivity, the geothermal gradient, and pipe depth. The optimal season performance is achievable by controlling the inlet velocity and the inner pipe diameter. In particular, increasing the inlet fluid velocity or decreasing the inner pipe diameter leave the performance unaltered in the long term. The optimal operating conditions are a specific heat transfer rate of 142 W/m and a fluid velocity of 0.7 m/s . These guarantee an averaged annual COP of 4, higher than standard GSHP systems.

The study by Zhou et al. [129] focuses on the borehole thermal resistance and internal thermal resistance (i.e., mutual interactions between the upward and downward pipe of the GHE), which highly influences the length and initial cost of the GHE. The authors study the influence on such parameters by the flow rate, pipe size, borehole diameter, pipe–pipe distance, layered soil, grout thermal conductivity, pipe thermal conductivity, and borehole depth. In particular, they present a numerical analysis of 32 boreholes, and for each simulation case they derive the optimal combination for these eight features by the Taguchi method [130]. In all cases, the optimized parameters decrease the whole borehole and its internal thermal resistance; the maximum decreases are by 67.64% and 148.29%, respectively. The heat transfer could be enhanced from 9.63% up to 77.07%. The distance between two pipes has the most significant impact on the borehole thermal resistance, while the pipe size and water flow rate are crucial for the internal thermal resistance.

Keshavarzadeh et al. [131] define the optimum operating conditions and borehole configurations by a multi-objective evolutionary algorithm. The assessed design parameters, specific for the GHE, are the borehole radius, inner pipe radius, shank spacing (i.e., the distance between inward and outward pipe), borehole spacing, and fluid velocity in the pipes. An exergo-economic optimization finds the Pareto frontier conjugating the optimal economic cost and maximum exergy efficiency of 42.2%. The nature of refrigerants also affects the exergy efficiency of the system, producing a potential increase of 8%.

3.2.7. Borehole Optimization

Many works study the optimization of thermal exchange with the ground for the air-conditioning of vast building spaces when a single borehole is not sufficient to cover the thermal loads of the heat pump. Such systems need the excavation of many wells (the number and depth depend on the user thermal load), which form a borehole field.

Bayer et al. [132] study the optimization of GHE fields in terms of heat extraction and injection over the winter and summer climatic seasons. Balancing the thermal exchange with the ground produces a uniform heat exchange which preserves the system performance in the long term and maximizes the energy exchange. The authors also study how to reduce the number of boreholes (and consequently installation costs) keeping unaltered the thermal loads. Their findings show a lower performance for the GHEs located in the center of the field because the surrounding GHEs inhibit the lateral heat supply.

Similar to the work above, Li et al. [133] study the optimal geometry of vertical GHEs field according to the building thermal load, ground temperature distribution, and the presence of a groundwater flow. The authors aim at reducing the reciprocal thermal interactions between boreholes that disturb the thermal exchange with the ground and affect the system COP. The temperature of the water from the GHE to the HP is the target function of the optimization. Results show that the space between the upward and downward pipes of the GHE and the distance between GHEs are critical parameters to avoid the thermal disturbances in the borehole field. Further improvements are achievable when distributing the thermal loads along the GHE field. Without a groundwater flow, the system presents the best performance when most of the thermal exchange with the ground is on the external side boreholes. When groundwater flow occurs, the GHEs producing the best performance are those at the downstream of the groundwater flow and on the outer side of the field.

Finally, additional studies focus specifically on the optimization of GHE in horizontal setup or the grouting material. Thangavel et al. [134] investigate the optimization of a horizontal GHE by the Taguchi optimization technique. In the space of five influencing parameters, authors calculate the maximum, the minimum, and the optimal length of the GHE. The inner pipe diameter and mass flow rate are the main parameters influencing the GHE length, weighting for 90% and 7.5%, respectively. Hesse et al. [135] specifically study the grouting materials of a GHE, which usually contains clays and rheological additives to adjust the stability and flowability in the injection phase. Authors investigate the thermophysical, hydraulic, and mechanical properties of geothermal grouts with swelling or non-swelling clays. Their results show the thermal conductivity increased by 5% when grouting with swelling clays than with non-swelling clays.

3.3. Building Management Strategies

Another critical research trend seeks the optimization of the GSHP performance in combination with the building energy needs. Such an approach consists of the dynamic control of the installed geothermal systems according to several factors: the building materials and orientation, behavior of the occupants, climate, and energy prices.

3.3.1. Thermal Output Sizing and Thermal Storage

Previous works [136,137] demonstrate that accurate sizing of the heat pump compared to the building thermal demand is crucial to optimize the energy performance, as well as costs for the user. An oversized system works intermittently for most of the climatic year, and it presents a low COP because it is running far below its nominal capacity. For example, Seo and Lee [138] study how the COP varies with the part load ratio (PLR), namely, the current cooling effect of an HP over the maximum cooling effect available, and they calculate the maximum efficiency when the HP operates at a PLR of 90 to 100%.

The inclusion of thermal storage in the GSHP system separates the HP operation from the building thermal demand, allowing the installation of reduced size geothermal systems that work for a longer time at their maximum capacity, in the hours of the day with the lowest electricity tariffs [139]. This solution saves energy and materials (i.e., a lower environmental impact) and reduces the costs for the user.

Bode et al. [140] focus on control strategies for a geothermal heat pump coupled to thermal storage systems. The case study is a multi-purpose building with offices, laboratories, and conference rooms. Authors present heating and cooling operations to minimize the thermal imbalance in the ground (with the consequent depletion of the GSHP performance [61,141]) and optimize the exergy performance by exploiting the heat wasted from server rooms and the free cooling effect of a glycol chiller.

Seo et al. [142] study the annual operation time and related energy use of three systems for the air-conditioning of an apartment: (1) a conventional setup with a boiler and a window air-conditioner, (2) an open-loop GSHP system, and (3) a GSHP coupled to a thermal storage tank. The annual loads of the user on a daily scale derive from dynamic

energy simulations with EnergyPlus [143]. For the boiler and GSHP, authors study the efficiency and COP varying with PLR, and both systems present the highest performance when running at their total capacity. Results show that the conventional system presents the highest annual electricity consumption in both heating and cooling modes, followed by the stand-alone GSHP and GSHP with thermal storage. Furthermore, the thermal storage avoids electricity consumption peaks along the day. The first and second cases work for most of the year at a partial load ratio below 10% of the nominal power, while the inclusion of thermal storage guarantees the GSHP system operating at its full PLR. The authors study in detail the benefits of coupling a heat storage tank to a GSHP.

Alkhwildi et al. [144] propose a GSHP system for a multi-family residential building coupled to a thermal storage tank with salt hydrate as Phase-Change Materials (PCM). The research goal is to shift the HP functioning from the peaks loads of the user and reduce the annual thermal load imbalances in the ground; further, the authors show that the inclusion of thermal storage could reduce the size of the GHE by sizing them on daily energy needs of the user instead of peak loads. The sensitivity analysis reveals the PCM melting temperature as the main parameter influencing the storage and GHE size due to the hysteretic nature of the salt hydrate. The optimal system configuration (i.e., the smallest storage) is achievable at a melting temperature of 27 °C. A preliminary economic analysis suggests that the inclusion of thermal storage could reduce the drilling cost of the GHE up to 50%. Similar results are also presented in [145], where PCMs are shown to allow for a reduction of 10 times the thermal storage volume and a reduction between 11 and 18% of mid-point indicators.

Bottarelli and González Gallero [55] present a dual-source heat pump (DSHP) able to switch the cold source between the air and ground. The system includes a horizontal GHE configured as a flat panel with different mixtures of sand and paraffin (PCM) as backfill material. The authors compare the energy performance of standard GHSP systems and different DSHP layouts by numerical simulations, varying the mixtures for thermal storage, trench width, and the GHE length over the building space volume. Results show the dual-source operation mode increases the HP performance and reduces the GHE length by several times compared to standard GSHP systems, with consequent reduction of installation costs. Furthermore, the PCMs in the backfilling mixtures improve the overall energy performance. The benefits augment when increasing the thermal conductivity of the PCM, which is a crucial parameter for latent heat storage applications. The system presents the highest performance in the summer due to the higher temperature difference between the ground and GHE.

3.3.2. Monitoring Systems and Management Optimization

Piselli et al. [146] present the energy retrofitting of a historical building by the installation of a ground source heat pump with horizontal GHE. Using the BIM technique, the authors install indoor and outdoor monitoring systems and model the architectural, mechanical, hydraulics, and electronic building components. They then converted the BIM model into datasheets reporting all information on the architectural and energy systems. These outputs, combined with monitoring systems, form a complete management tool for building maintenance and monitoring indoor conditions, the external environment, and the comfort of occupants. Energy use and indoor/outdoor environmental conditions are also combined with these data for the realization of a management tool able to optimize the energy performance according to the comfort of the occupants.

Duus and Schmitz [147] study new energy management strategies for an office building with a GSHP system. Based on the temperature distributions monitored near piles and depth into the ground, the authors propose the management of the geothermal field that guarantees a balance between the annual energy withdrawal from and injection to the soil. This method prevents the performance degradation of the GSHP due to the excessive warming or cooling of the ground. The strategies for a sustainable energy balance consist in dynamically adjusting the heat/cooling supply according to the thermal demand of the

different building areas. Further, the system includes auxiliary heat exchangers (re-coolers) that re-inject into the ground the heat in excess extracted during the mid-seasons (autumn and spring). Results show that the proposed control strategies increase the performance of the heat pumps over the years, and the monitored temperatures of the geothermal field reveal the possibility of restoring the original ground temperature level after three years.

3.3.3. Advanced and Integrated Solutions

The works Shin et al. [56] propose a GSHP system with two heat pumps sharing the same geothermal field. The two HPs are for the space conditioning and service hot water, respectively. In the hot season, the heat transfer fluid from the GHE takes the waste heat from the condenser of the HP for air-conditioning and uses it to preheat the refrigerant in the evaporator of the heat pump for hot water. In heating mode, the heat transfer water first heats the refrigerant of the air-conditioning heat pump (in the evaporator), and then it releases the residual thermal energy to the HP for service hot water. The authors install the GSHP system and monitoring devices in a hotel, and, compared to a simulated baseline scenario where each HP has its own GHE field, the coupled system presents higher performance: the COP of the heat pump for service hot water increased by 84% and 30% in the heating and cooling seasons, respectively; the COP of the air-conditioning HP increased by 15% and 3%; the annual electricity savings are 19.1% in the cooling season and 9.6% in the heating season.

The authors realize that insufficient energy (and financial) savings occur in the winter season; therefore, they investigate in another work Shin et al. [148] the electricity savings and economic benefits of including an outdoor air reset control (OARC) to regulate the production of domestic hot water according to the outdoor temperature. Further, they include a thermal storage tank for the domestic hot water and test the system functioning in sequential mode, alternating the functioning of the HP for air conditioning and the HP for hot water. This latter runs on when the hot water in the storage tank falls below a set temperature. Compared to a baseline scenario configured as in the previous work, these upgrades reduce the electricity use up to 27% and 25% in the cooling and heating season, respectively, with attractive financial returns along the system lifetime.

Lyu et al. [57] propose a GSHP system integrated with pipe-embedded walls, pipe-embedded windows, and a fresh air pre-handling system. The authors study the benefits of the integrated system for the air-conditioning of an office building by TRNSYS simulations. In particular, they show that the integrated system maintains for a longer time the free-running temperature [149] compared to conventional GSHP. Further benefits include reducing the HP size and building's heating/cooling loads (e.g., pipes embedded in the walls and windows that intercept the external heat gains reducing the cooling loads) and increasing energy saving by 29% with an overall reduction of the CO₂ emissions.

4. Site and Locations

The exploitation of geothermal energy presents many sustainability implications that a sole thermodynamic assessment fails to consider [150]. The performance of GSHP systems depends upon the site characteristics (e.g., climate, ground properties, underground water reservoir). Additionally, these systems can interfere with subsurface and groundwater, causing different environmental risks related to soil swelling or compaction, contamination of shallow aquifers and other water bodies, and habitat loss or disturbance.

García-Gil et al. [151] mapped the low-temperature geothermal potential (LTGP) of the metropolitan area of Barcelona using a GIS 3D model. The LTGP is the maximum heat transferable between the geothermal system and ground, without producing a temperature change or piezometric drop higher than a fixed value in the exploitation point. The authors calculate the LGPT based on the geological and hydrogeological properties of the examined area (i.e., raw data). Results show the highest potentials localized in the proximity of aquifers, while unsaturated layers, tertiary rocks, and crystal-line basement present the

lowest LTGP. Furthermore, the geothermal potential of a location changes by the GHE configuration, i.e., it differs for open- and closed-loop systems.

Tissen et al. [152] analyzed different characteristics of a particular location (Vienna, Austria) to identify the most appropriate sites for shallow geothermal use. In particular, they mapped the anthropogenic heat flux into the urban subsurface, the technical geothermal potential (calculated as in [151]), the sustainable potential, the heat supply rate, and the existing heating infrastructure to identify the most attractive locations for installing a GSHP system; furthermore, the authors calculate all these indicators for both configurations of the GSHP system (open- and closed-loop). Results show the highest sustainable potential and heat supply rate in those districts with the highest anthropogenic heat flux to the ground, compensating for the energy extraction of the GSHPs. Results show the most significant sustainable potential, and heat supply rate in those areas presenting in the ground the highest heat-flow due to anthropogenic heat sources in these four districts is 53% of the current heating demand. The closed-loop is more attractive than the open-loop systems due to their higher supply rate (related to the heating demand of existing buildings) and the smaller space needed between single systems.

Tinti et al. [153] applied a new GIS platform-based multicriteria decision analysis method aimed at comparing as many different shallow geothermal relevant factors as possible to assess the suitability of shallow geothermal systems. They identified 14 parameters related to site characteristics as having an impact on shallow geothermal systems implementation and, based on them, defined five criteria for the comparison: the drilling potential, heating needs, cooling needs, insulation potential of ground from climate, the deviation between ground and ambient temperature. Their study produced a suitability map of use that indicates the zones of Europe most suitable for the introduction of the combination of GSHP technologies proposed. Alluvial plains came out as the most promising zones for the GSHP technologies considered in their case study, and urban agglomerations emerged as favored compared to rural zones—even in the (total or partial) absence of alluvial plains—given the higher energy needs and the impact of subsurface urban heat island on exploitable ground energy.

Viesi et al. [154] elaborated GIS thematic maps representing the parameters that primarily affect the heat exchange with the ground as well as the available geothermal potential for vertical closed-loop systems in terms of specific heat extraction rate (W/m). The mapped area is the Adige Valley in northern Italy, and raw data characterizing the soil derive from on-field measurements as geo-gnostic drillings and hydrogeological measurements. The GIS input parameters are site climate, heating demand from buildings, and geological and hydrogeological characteristics of the ground and underground water. Such a database presents the twofold benefit of contributing to the soil and environmental protections with a highly detailed knowledge of the hydrogeological features in the studied area and supporting local administrations for energy planning, indicating the best sites for the exploitation of low-enthalpy geothermal energy.

Among the geological and environmental conditions influencing the performance of GSHP systems, the heat conductivity of the soil plays a critical role as an increase in this parameter enhances the efficiency of the system. Heat conductivity is significantly affected by the type of material (i.e., grain size, mineralogical content, density), soil moisture, and temperature variations [155–157] and, generally, heat transfer in soils decreases as anhydrous conditions or decreasing temperature are detected [158–161]. Water content depends on meteorological and environmental events (such as rainfall, solar radiation, albedo, fluctuations in air temperature, vegetation cover, and evapotranspiration [162–165]) and variations of climatic data (particularly air temperature and rainfall) can affect the moisture transfer in soils. Even if this effect is mainly evident in the very shallow part of the soil and it reduces with depth, it can produce variations on soil thermal properties that significantly affect the performance of GSHP systems (particularly horizontal ground exchangers) [166–168]. As a reference, a soil saturation degree below 12.5%, above 25%,

and over 50%, generates a decrease, an improvement, and an insignificant variation of the performance, respectively [169].

Di Sipio and Bertermann [170] carried out a long-term investigation (over more than one year) of soil temperatures, environmental parameters, and soil properties in an experimental setup (five helical heat exchangers installed horizontally at 1 m depth surrounded by five different backfilling materials), contributing to understanding the influence of several factors on very shallow geothermal systems. They found that daily and monthly temperature amplitude fluctuations still affect the system performance due to a depth of installation between 0.60 and 1.0 m, but this effect is less than thermal conductivity variations induced by different soil moisture content. Moreover, they investigated the effect of the materials on thermal conductivity, showing that bentonite mixtures and loamy sands are promising materials to increase the system performance (if adequate moisture level remains over time). The authors evidenced that a gradual decrease in moisture content in coarse sand material generates a rapid decrease in thermal conductivity, while on bentonite mixtures or loamy sands, the induced reduction is more gradual. As also shown by the works cited above, when GHSP systems run in heating (cooling) mode, a decrease (increase) in temperature occurs in the surroundings of the heat exchangers and, related to this, the ability of the soil to regenerate the thermal energy content when the heat exchangers are not operating is crucial.

Literature studies, such as [171], showed that in cold climates, the increase in the annual average temperature of the ground is nearly negligible, while in mild climates, it can increase up to about 10 °C after a few years of operation; therefore, this alteration could limit the possibility for further thermal uses in the surroundings, and the GSHPs must ensure the proper operating temperature for both the projected installation (internal sustainability) and the neighboring ones (external sustainability) [52] to operate sustainably. The system design supported by different methods and software tools for closed-loop and open-loop systems represents the key to achieving internal sustainability. At the same time, proper management of the mass and energy exchange with the ground, especially over the long term, is crucial to ensure external sustainability [172–179]. To this regard, Garcia-Gil et al. [180] developed an indicator called relaxation factor, imposing a margin on groundwater temperature that should be unaltered for future installations. Walch et al. [181] proposed a novel method that takes into account potential thermal interference as well as the available area for GHE installations at a regional scale to identify optimal arrangements of boreholes to maximize their technical potential and assure an adequate heat extraction power.

The interception of aquifers during borehole heat exchangers installation may cause the contact of swelling or soluble layers with groundwater and trigger consequent hazardous phenomena. The transformation of anhydrite into gypsum is one of the well-known swelling phenomenon, characterized by an increase in volume resulting in a differential ground uplift that can damage buildings in the site, as documented in [182,183]. Even if less reported in literature [182,184], local-scale subsidence episodes due to salt layer dissolution after groundwater infiltration triggered by the installation of borehole heat exchangers are equally hazardous events.

During their operation, borehole heat-exchangers could generate aquifers pollution both through the potential release of anti-freeze additives from leaking pipes and the potential propagation of contaminants from an aquifer to another in the case of a defective borehole filling [52]. Scarce events of leakage from pipes emerge in literature [182], and few studies [185,186] quantitatively assessed the contaminants propagation, focusing on the flow rate that could cross a poorly grouted borehole heat exchanger, which is proportional to the hydraulic conductivity of the borehole filling.

5. Discussion

The ground source heat pumps are a promising technology that can effectively contribute to the de-carbonization of the building sector. As many LCA studies confirm, the

operation stage presents the highest environmental impact on the whole life-cycle of a GSHP system, and also the current technical regulations incorporate this point by recognizing a GSHP as a renewable system only if its energy efficiency, indicated by the coefficient of performance (COP) and seasonal performance factor (SPF), is above a fixed value.

For this reason, most of the current research pursues the thermodynamic analysis and optimization of geothermal heat pumps to optimize their working cycle and maximize energy performance. A first issue emerging from these studies regards the energy performance calculation: the COP and SPF are unstable and generally vary during the system operation depending on numerous factors such as the configuration of system components and site characteristics; therefore, many energy analyses propose multi-variable prediction models to estimate the COP and SPF in unstable operating conditions. Exergy analysis that extent the GSHPs thermodynamics to a higher level of detail, examining the single components, are of great interest because they indicate the primary irreversibility sources of a GSHP (the compressor, the condenser, and the expansion valve), and therefore, the components that are crucial for optimization studies. Furthermore, exergy studies include a discussion on how the environmental conditions of the installation site (dead-state temperature) affect the system's performance.

Another approach that mitigates the GHSP environmental impact in the operation stage seeks alternative refrigerants to the currently used HCFC and CFC to reduce the Global Warming Potential of the whole geothermal system. Natural refrigerants (e.g., ammonia and CO₂) and hydrocarbons are the promising alternatives that offer the best COP values. However, the former presents many technical limitations due to the high operating pressures and compression ratio. The risks of corrosion and toxicity are specific for ammonia. Applications of hydrocarbons are rare and restricted by many regulations because of their flammability. Even if some investigations focused on these options are available in the literature, further research on the feasibility of these solutions and their potential to optimize GHSP systems sustainability is necessary.

The latest LCA studies show that also the assembling stage presents critical sustainability issues, measured by the main categories of impacts as soil excavation, land transformation, and water consumption. Thus, a research gap emerges in the current literature, which focuses on mitigating the GSHP environmental impact strictly in the operation stage. Based on these remarks, the most promising research trends pursue the twofold mitigation of the GSHP impacts in the installation, as well as the operation stage:

1. The optimization studies of the ground heat exchanger configuration distinguish two main GHE categories, the vertical and horizontal setups. Although horizontal GHEs present lower impact than vertical wells, the choice between two configurations mainly depends on land availability: at fixed COP, the horizontal configuration needs a land area of 6.5 times higher than vertical boreholes. The key parameters influencing the heat exchange from the ground: (i) the flow rate of the heat transfer fluid, (ii) the pipe size, (iii) the borehole heat exchanger diameter, (iv) the pipe–pipe spacing (i.e., shank spacing), (v) the grout thermal conductivity, (vi) the pipe thermal conductivity, and (vii) the borehole depth. The borehole thermal resistance derives from all these parameters, and its reduction enhances the heat exchange with the ground.
2. The optimization of the GSHP system design and operation aims to avoid oversizing the heat pump and GHE, keeping the system functioning as much as possible close to its total nominal capacity, where it delivers the best performance. Furthermore, the SPF tends to decrease over the long term due to the alteration of the undisturbed ground temperature; therefore, the annual operation should balance the annual heat extraction (winter) and injection (summer) from the ground as much as possible. An effective strategy is to couple the GSHP to thermal storage, separating the system operation from the building peak loads; this will reduce the HP and GHE sizes since these components have to cover the daily energy needs of the user instead of the instantaneous peak load. Storing the thermal energy as latent instead of sensible heat will reduce space occupation and increase the energy and environmental performance.

3. The environmental studies investigate the relations between the GSHP sustainability and the properties of the installation site as the thermal conductivity of the ground, the soil properties and its water content, the frequency of meteorological events, the climatic variations, and the soil permeability. Further, several difficulties arise to balance the thermal exchange with the ground and avoid the performance degradation over extended periods in particularly cold or hot climates. Of great interest are the applications of GIS platforms to seek the best installation sites for a GSHP system via multi-criteria decision. Such a technique for site assessment includes both thermo-physical features reported above and energy flows of the buildings and infrastructures, taking into account the grade of the anthropization of the environment. The multi-criteria decision approach is particularly suitable to support the GSHPs installation in high energy-density urban agglomerations, where the environmental benefits are more significant than in rural areas.

6. Conclusions

The GSHPs have a widespread diffusion worldwide because, compared to fossil-fueled systems for building air-conditioning, these present higher performance in output thermal energy over the consumed electricity. Further, the GSHPs release less GHGs in the atmosphere than conventional heating/cooling systems (e.g., gas and oil boiler, wood combustion, and air source heat pumps), and further mitigation of their environmental impact, particularly in the operation stage, is available by increasing the renewable energy production in the national electricity mixing. Finally, their working cycle benefits from the relatively stable temperatures available in the first layer of the ground; thus, their feasibility is less dependent on the availability of primary energy sources on the installation site than other renewable energy systems.

Based on these features, the ground-source heat pumps are a promising technology for reducing energy use and decarbonizing the building sector, particularly if combined with an increase in renewable energy production in the national electricity mixing. However, a sustainable design of such systems is more complex than fossil-fueled and other renewable energy systems for building air-conditioning. It needs a holistic approach that includes the broad environmental boundaries of heat pump installation and operation. The sustainability of a geothermal heat pump depends on the primary energy sources of electricity, the climate and ground properties of the installation site, the installation operations (in particular, the GHE excavation), the HP energy performance and its stability over the long term, the maintenance of the refrigerant circuit, the GWP of the refrigerant, and proper maintenance of the serviced building. Future research needs to deal with the increased complexity of the energetic, environmental, and economic analysis of GSHPs via a multi-disciplinary approach to better understand the environmental consequences and seek the best design and maintenance strategies for all system components.

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