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Regeneration of shallow borehole heat exchanger fields: A literature review

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A R T I C L E I N F O

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A B S T R A C T

Ground source heat pumps (GSHP) coupled to shallow borehole heat exchangers (BHE) represent a low emission technology to provide space heating and cooling. However, ongoing long-term heating or cooling of the ground caused by unbalanced loads leads to a performance decline and in the worst case to a system shutdown. Enhanced regeneration can increase the system efficiency, reduce the necessary borehole length or compensate unbalanced loads. In this study, a literature review about the regeneration of shallow BHE fields to counteract ground thermal imbalance is conducted to give an overview about the state-of-the-art and identify research gaps. The most common heat sources for artificial regeneration in heating-dominated applications are space cooling and solar thermal flat-plate collectors, while the most common heat sinks in cooling-dominated applications are space heating and cooling towers. In heating-dominated applications, mostly single buildings are studied. There is a lack of studies on district heating and cooling applications, which are especially needed as the benefit of regeneration increases with system size. There is also a lack of long-term, large system size experimental work to validate theoretical studies.

Contents

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1. Introduction

In the Paris Agreement, 195 states agreed on reducing greenhouse gas (GHG) emissions to mitigate climate change [1]. A very important lever is the built environment. In 2021, buildings alone represented around 37% of global CO_2 emissions and building operation reached an all time peak of around 10 Gt CO_2 [2]. Buildings' operational emissions (from space heating and cooling, water heating, lighting, cooking and other uses) will need to drop by more than 95% compared to current levels to reach the goals of the Paris Agreement [2]. Ground source heat pumps (GSHP) coupled to shallow borehole heat exchangers (BHE) represent a low emission technology to provide space heating and cooling. However, an area-wide usage of BHEs presents certain challenges. It is well known, that unbalanced thermal loads lead to a long-term temperature change in the ground, which is usually constrained by regulations, and leads eventually to a decline of the system performance. This affects, in particular, BHE fields / large-scale GSHP applications as well as districts with a high density of individual BHEs. Thermal interaction between BHEs increases the required BHE length [3]. Likewise BHE lengths need to be considerably higher when thermal loads are unbalanced without additional regeneration [4,5]. As drilling costs usually make up a high share of the investment costs [6], ground thermal imbalance also leads to a decreased economic competitiveness of such systems, as well as operational cost increases due to an increased reliance on the heat pumps. In order to limit the ground temperature change without reducing the useful amount of extracted (injected) heat, it is possible to either enhance the natural regeneration or to inject (extract) additional thermal energy into (from) the BHE field, which is referred to as artificial regeneration in the following.

For example, Olgun et al. [4] simulated the long-term behaviour of a single BHE in different climates. They conclude that the median annual air temperatures and the resulting borehole temperatures after 30 years of operation are linearly proportional for the same application (heating and cooling of an office building) and ground thermal properties, due to the influence of the climate-dependent thermal loads. Sakata et al. [7] minimised the total borehole length for heating and cooling in different Japanese locations and find, that the minimum total BHE length shows a second-order polynomial relationship with the net heating and cooling demands, indicating lower necessary total BHE lengths at more balanced loads.

The usage of alternative heat sources / sinks and additional storage for peak load reduction covers the same load profile while reducing thermal anomalies in the ground. For example, the direct use of solar thermal energy in times of matching generation and demand might be preferable to regenerating the ground in order to minimise pump electricity or pipe losses and maximise the heat pump efficiency. Düber et al. [8] investigated the effect of uninsulated horizontal connection pipes on a BHE field in different climate zones and observed a reduction of the BHE load except in severe cold climates, highlighting the potential use of ambient energy to reduce the load on BHEs. Wu et al. [9] propose to use absorption heat pumps in severe cold climates, as they extract less heat from the ground and inject more heat to it than compression heat pumps. Assuming a coal boiler and a coal-fired electricity plant for the provision of auxiliary energy, the primary energy efficiency (PEE) is also beneficial. However, a dependency of the ecological benefit on the driving sources is implied. Martins and Bourne-Webb [10] propose night ventilation to reduce the cooling loads and balance the load of a GSHP system in Portugal. They report a cooling load reduction of 65 to 90% and a ground temperature increase of 8 to 12 K after 50 years of operation. What makes regeneration especially interesting in comparison to other hybrid ground source heat pump (HGSHP) systems is the fact, that similar to (seasonal) thermal energy storage (TES), renewable heat sources/sinks like solar thermal energy, ambient air or the ground itself can be used in a time-delayed manner to the energy demand to increase the overall system efficiency and reduce the overall GHG emissions.

The Swiss standard SIA-384-6 already sets special requirements to accommodate future neighbouring BHEs. Passive floor cooling, solar thermal and photovoltaic thermal (PVT) collectors and air heat exchangers (HX) are named there as standard regeneration methods. The specified temperature must not be exceeded for at least 50 years, which is argued to still be not sufficient according to Kriesi [11], who is committed to a fully sustainable operation.

Structure of this work Two main types of regeneration can be distinguished: Natural and artificial regeneration (compare [12]). The methods that can be used depend on the respective boundary conditions and are summarised in Fig. 1. It is also useful to distinguish between two applications of regeneration with different system boundaries and boundary conditions:

1. Area-wide usage of single BHEs (for example in a suburb with individually supplied single family houses). In this case enhancing natural regeneration is not an option, because the field geometry and operation cannot be influenced. A further complication for small plants is that normally no test drilling is carried out, which means the need for artificial regeneration must be determined by measurements. An increasing number of corresponding studies has been commissioned by the Swiss authorities [13,11,14,15].
2. Isolated centrally controlled BHE fields (for example district heating and cooling). In this case artificial and enhancing natural regeneration as well as a combination of both are possible.

In this study, we give an overview about natural regeneration and methods of enhancing it (Section 2), as well as artificial regeneration (Section 3). The literature used was mainly searched using the data base *Web of Science* and the cited literature of the resulting papers. In the detailed analysis (Section 4) we focus on artificial regeneration, especially in heating-dominated applications (Section 4.2). The present study is meant to give an overview about the state-of-the-art of shallow (<400 m, usually <150 m BHE length) BHE field regeneration and identify possible research gaps. Global and technology-specific conclusions are drawn directly from, and from the holistic analysis of the reviewed literature (Section 5).

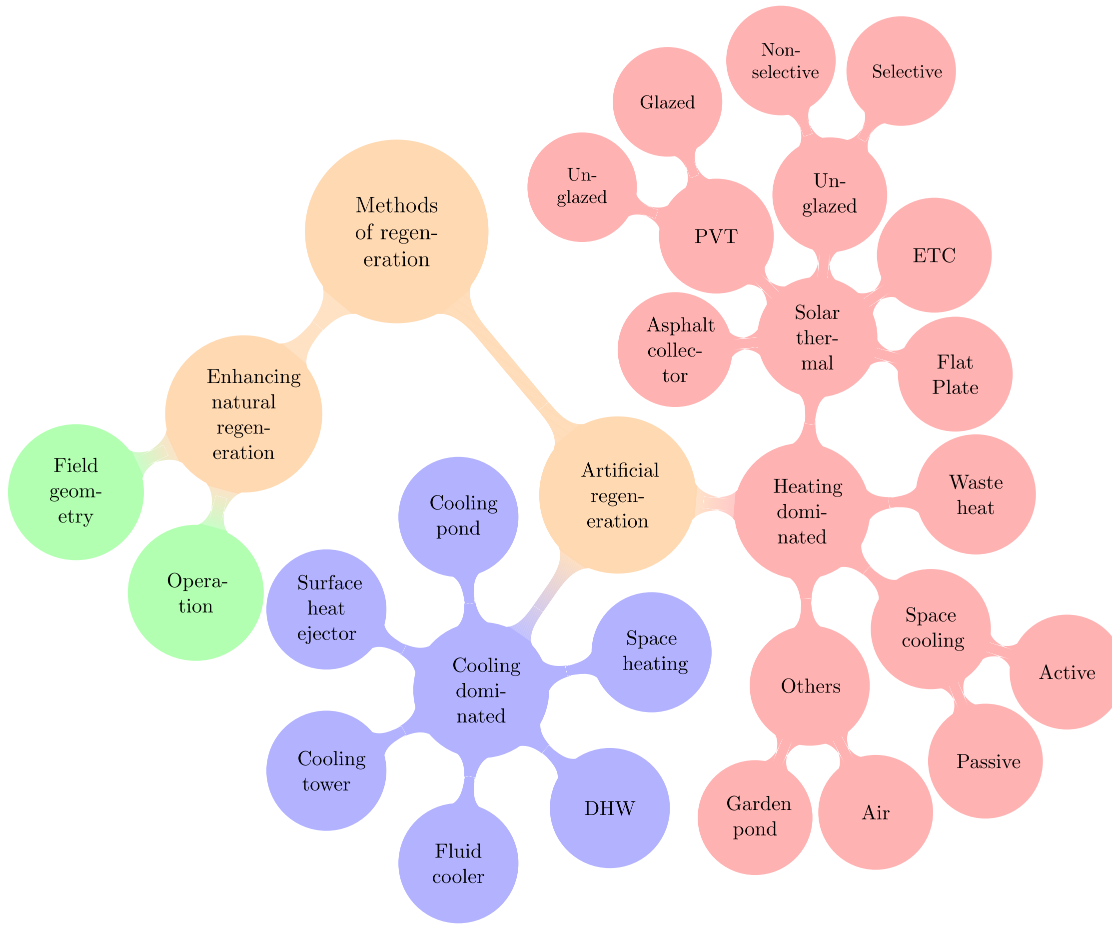

Fig. 1. Methods of regeneration.

As the terminology varies strongly among the reviewed literature, we summarise the most important or differently named respectively used terms in Table A.4 in the appendix.

2. Natural regeneration

Natural regeneration and thereby the long-term performance of the BHE field is influenced by influencing factors independent of the BHE field itself (Section 2.1), as well as factors that may be influenced during the planning or operation stage (Section 2.2).

2.1. Influencing factors

The former mainly involve groundwater (GW) flow [16–20], the type of the (layered) soil/rock [19,21,16], fracturing [22] and the load profile [23,16]. According to Hein et al. [24] it is crucial to determine the soil thermal conductivity and thermal load as accurately as possible, especially for large BHE fields, to avoid thermal depletion and system breakdown. While GW flow is beneficial for the regeneration around a BHE, it causes thermal anomalies downstream [25,23] and should thus not replace balancing the load in case of area-wide usage of BHEs. Sliwa and Rosen [12] name weather conditions like solar irradiance and wind on the surface as further sources of natural regeneration (the latter mainly for short BHEs).

Eugster and Rybach [26] investigated the natural regeneration around a single BHE after 30 years of operation. They describe the dynamic conductive processes in the ground as a superposition of:

1. the heavy temperature change in the immediate vicinity of the BHE up to some 10 cm during an operational (hourly) cycle.
2. the funnel-like propagation of this temperature change to several meters during a seasonal operation.
3. a large-scale, but only minimal temperature change of the surrounding ground up to several 10's of meters during the full lifetime of the BHE.
4. the increase of vertical heat fluxes from the atmosphere and from the ground.

Long-term heat extraction causes a high temperature drop in the first years of operation, which tends asymptotically towards zero in the subsequent years. Similarly, the natural regeneration after shut-down of BHE operation is strong in the beginning and decreases asymptotically afterwards. Simulations with different operation periods show, that recovery duration roughly equals that of operation (30 years for 1.7 K at 50 m depth and in a distance of 1 m from the BHE in this case). Based on this, Signorelli et al. [27] find that due to the thermal interference of multiple (in this case six) BHEs with 7.5 m spacing, the temperature drop is much more pronounced and that recovery time at the central BHE takes 70 years after 30 years of operation. Piotrowska-Woroniak [28] evaluated the ground temperature and natural regeneration in a BHE field consisting of 52 BHEs over four years with only heating loads. The author reports a long-term temperature drop of 2.2 K. The regeneration during summer is faster at the beginning and then slows down. Rybach [29] further describe the temperature profile that forms around the BHE in heating mode. The author describes the isotherm pattern around the BHE as 'cigar-leaf shaped', indicating an strong heat flow towards the BHE during operation.

Javed et al. [30] report, that according to their measurements, the recovery of the ground temperature after a geothermal response test in low to medium conductivity formations can take significantly longer than suggested by existing guidelines. Boban et al. [31] confirm that natural ground regeneration after heat extraction / injection is a slow and asymptotic process.

Koohi-Fayegh and Rosen [32] find that the soil temperature far from the BHE field is not affected by the placement of BHEs with different heat fluxes within the field, but rather by the total extracted / injected amount of heat. Accordingly, Erol et al. [33] find that the recovery period of the subsurface is not based on the duration of the production period, but depends on the total amount of heat that is extracted.

According to Spitler and Bernier [34], the ground thermal balance must be taken into account when choosing the modelling methodology. Sizing for an imbalanced system may be more sensitive to the ground heat transfer methodology than sizing for a relatively balanced system. Zeng et al. [5] describe the modelling of BHE's long-term performance. They find that the steady-state borehole wall temperature is affected by the annually averaged heating rate, the ground thermal conductivity, borehole depth and radius. They also suggest to use the integral mean borehole wall temperature as a representative temperature for analysis of the long-term performance.

You et al. [35] investigated the temperature change of the ground caused by an office building in four different Chinese cities with cold climate and observe a temperature drop from 5.8 to 11.7 K in the heating cases and a temperature drop of 3.4 to 8.2 K and rise of 0.02 to 5.5 K in the heating and cooling cases. Roy et al. [36] investigated the feasibility of BHE systems in ten metropolitan cities in tropical and subtropical climates. They declare that ground source heat pumps are not economically feasible in tropical climates, especially close to the equator, due to inefficient performance and significantly greater cooling than heating demand, which causes thermal imbalance of the ground.

In urban areas, thermal interference between BHEs needs to be taken into account to assess the shallow geothermal potential [37,38]. Choi et al. [39] assessed the effect of long-term citywide usage of BHEs in a cooling-dominated climate and emphasise the importance of legal regulations regarding the load imbalance in such cases. Persdorf et al. [13] report an additional ground temperature decrease of 7 K after 50 years in Zurich when neighbouring BHEs are considered.

Climate change and urban heating, meaning the increased heat input from cities to the ground, may have a considerable 'natural' regenerating effect in heating-dominated climates as shown by Rybach et al. [40] and Rivera et al. [41].

2.2. Enhancing natural regeneration

There are several factors that may be influenced during the planning or operation stage of BHE fields to enhance the natural regeneration. These include the BHE field geometry and operation. Methods for enhancing natural regeneration are seen to be independent of the direction of the load imbalance (heating or cooling dominated).

2.2.1. Geometry

The goal of adapting the BHE field geometry in this context is usually to increase the exposed surface area to the surrounding rock or to the ground water flow direction.

Gultekin et al. [42] report that the thermal interaction coefficient and performance loss decrease with a decreasing aspect ratio (the number of BHEs on the shorter to number of BHEs on the longer side) of a rectangular BHE field, and that the effect increases with decreasing borehole distance. Choi et al. [43] analysed different field geometries with GW flow and find that L-type and single line-type arrangements are more sensitive to GW flow rate and direction than rectangular arrangements. Li et al. [44] propose to increase the number of BHEs which are located at the side of the field, and downstream where GW flow is present.

Bayer et al. [45] propose a mathematical optimisation procedure to sequentially remove the least effective (usually centrally located) BHEs in a regular field, in order to reduce investment costs with a low effect of the overall system performance. They find that these BHEs are mainly found in non-optimised BHE fields without additional regeneration. Beck et al. [46] carried out a combined optimisation approach regarding BHE positions and load distribution, which leads to slightly better results than optimising either the position or the load distribution individually. The ground temperature change is reduced about 12% in each case. They conclude that in BHE fields with negligible GW flow an optimal BHE placement might be less complex than optimal load distribution and thus be the favourable option. Beck et al. [47] use evolutionary algorithms to optimise borehole positions and load distribution. The reference lattice shape BHE field could only reach 33% of the heat extraction of the optimised BHE fields without violating the temperature constraints. Several more studies on field geometry have been performed [17,23].

2.2.2. Operation

Operation strategies include the spatial (and temporal) distribution of heating/cooling loads among the BHEs in a field.

Retkowski et al. [48] investigated optimal heat flux distributions for four different operation strategies: equal ground temperature distribution, maximal fluid temperature, maximal producible ground thermal energy and maximal borehole wall temperature. Fixing the extracted amount of thermal energy but not the total borehole length, they come to the conclusion that the optimisation for a maximum borehole wall temperatures as well as the fluid temperatures improve the average heat pump efficiency by more than 2%. Zhang et al. [49] propose to use the same inlet temperature in every BHE rather than the same heat load to improve long-term performance. In their case the first approach leads to a 2 K lower ground temperature change after 7 years in a field of 36 BHEs at 5 m distance. Bayer et al. [45] propose a combined optimisation of individual BHE workloads for a minimum ground temperature change, considering seasonal heating and cooling. They find, that the benefit of mathematical optimisation increases with an increasing imbalance of the thermal load, while full seasonal replenishment of the ground makes workload optimisation redundant. Coen et al. [50] reduced the maximum simulated ground temperature change by using central BHEs only in times of peak load. This leads to an increased maximum temperature change of 0.19 K at an edge BHE, while reducing the temperature change at a central BHE by 0.82 K in a 5 x 5 BHE field with 6 m distance after ten years of operation. de Paly et al. [51] optimised the spatial distribution of thermal loads using linear programming while Hecht-Méndez et al. [52] considered the presence of groundwater using temporally and spatially superimposed moving line source equations. Fan et al. [53] propose different pipe connection schemes in summer and winter operation, depending on the thermal load and GW flow. They use only the BHEs with the highest mutual distance for heating in winter, but the whole field for nightly pre-cooling in summer in a cooling-dominated climate. Yu et al. [54] propose a zoning strategy, where only the central part of the BHE field is operated in the heating season in a cooling-dominated climate. This leads to a decrease in the peak and average ground temperatures, especially for soil with a low thermal conductivity. At a thermal conductivity of 1.5 $Wm^{-1}K^{-1}$, the average ground temperature change is reduced by 4 and 3.7 K for a square and rectangular arrangement, respectively. Li et al. [44] find that it is beneficial to increase the thermal load on the side BHEs while reducing the load on the middle BHEs in fields with negligible GW flow, whereas increasing the load on side and downstream BHEs is preferable considering GW flow. Luo et al. [55] investigated three different operation strategies in a large-scale cooling-dominated GSHP system: even load distribution, and two variants of partial usage of the BHEs depending on the thermal load. They find that in their case, partial operation has a noticeable influence on the operating costs, but no large influence on the heat transfer efficiency and ground thermal accumulation.

Shang et al. [56] investigated the influence of backfill material, air temperature and inlet volume flow rate under different intermittent operation modes. They came to the conclusion that an optimum recovery time on a daily time scale has a beneficial influence on the system performance.

TES, like water-filled buffer tanks above ground, can reduce short-term thermal anomalies in the ground due to peak loads. However, following the definition given in Table A.4, regeneration should improve the long-term ground thermal balance. Therefore TES is not considered a regeneration method, although it is mentioned in the literature as a method for reducing thermal anomalies.

3. Artificial regeneration - balancing the load

Unlike enhancing natural regeneration methods, artificial or active regeneration methods depend on whether the load is heating (Section 3.1) or cooling (Section 3.2) dominated. Sliwa and Rosen [12] present several natural and artificial regeneration methods and experimented with some of them in a cold climate. They conclude that in real projects it is necessary to consider all possible heat sources. Xu et al. [57] performed a literature review of HGSHP systems for overcoming ground thermal imbalance, including different control strategies. According to the authors, in most literature a serial configuration of solar thermal collectors and GSHP is favoured. They also name subways, substations and industrial processes as possible waste heat sources. Bisengimana et al. [58] give an overview mainly about artificial regeneration methods and other HGSHP systems. Based on the reviewed studies, they propose to focus more on a balanced load profile when designing a GSHP system. They also conclude that more experimental work that addresses frosting and soil thermal imbalance is needed to verify the findings based on simulation results.

Persdorf et al. [13] emphasise that regeneration is preferable to a larger dimensioning of the BHEs from an economical as well as from an environmental point of view. Walch et al. [59] present a framework to estimate the technical and useful potential of GSHP systems in heating-dominated regions considering regeneration by space cooling. They report an increase of the maximum annual technical potential density in western Switzerland from 15 $kWh \cdot m^{-2}$ to above 300 $kWh \cdot m^{-2}$. In this case study, 35% of the heating and cooling demand could be covered, which would rise to around 55% if artificial regeneration was used. Assuming district heating and cooling (DHC) grids rather than individual BHEs, 63% of the demand could be covered, which would rise to around 85% with artificial regeneration.

When storing external (for example solar) thermal energy in a borehole thermal energy storage (BTES), the overall load direction – extracting or injecting – is shifted. BTES is therefore closely related to regenerating BHE fields. It is practical to define the tipping point of whether a system is a BTES system or a BHE field with artificial regeneration, as whether natural regeneration is still beneficial or whether it is favourable to adjust a BHE field geometry in a way to obtain a usable compact storage volume. In the literature these two approaches are usually clearly separated, probably because a transition state is not economically favourable. BTES are often operated at temperatures further from the undisturbed ground temperature, which further highlights the separation, as natural regeneration is not beneficial at all. Due to the different requirements of the two approaches and the numerous available literature reviews on the subject of BTES [60–65], we do not consider it further in this study.

3.1. Heating-dominated applications

In heating-dominated applications, usually in cold climates, the goal of regeneration is to inject thermal energy into the ground. Ruesch et al. [14] give an overview about costs and regeneration fractions of different heat sources for regeneration of area-wide usage of single BHEs (as introduced in Section 1) in Switzerland. According to the authors, full regeneration is only possible with active cooling without passive summer thermal protection (like shading or night ventilation), glazed, and selective unglazed solar thermal collectors considering a modern multi-family home.

3.1.1. Solar thermal energy

Solar thermal energy belongs to the most common sources of regeneration in heating-dominated climates. The potential benefits are well known: The high renewable heat production in summer can be made use of in winter, when it is needed. Solar thermal energy can also be used for domestic hot water (DHW) production in summer. Additionally, collector damage from stagnation, when collectors are not used during the summer, is prevented. In case of photovoltaic-thermal (PVT) collectors, the electrical efficiency increases through the cooling effect.

Sparber et al. [66] describe 'integrated' solar thermal heat pump systems as systems where the solar collectors are integrated in several ways into the overall heating system (parallel, serial, for regeneration). They present some monitoring results including regeneration within IEA SHC Task44 / HPP Annex 38.

System performance Several studies investigate the effect of solar regeneration on the seasonal coefficient of performance (SCOP), seasonal performance factor (SPF) and the necessary borehole length. Emmi et al. [67] analysed the effect of the reduction of the borehole length with solar regeneration on the SCOP in several cold climates. They report a performance decrease of about 10% after 10 years without regeneration, while the performance with regeneration remains constant. Furthermore they conclude that with solar regeneration a reduction of the total borehole length by 50% achieves similar SCOPs as without length reduction after three years. Bertram et al. [68] evaluated a BHE field with short BHEs using numerical simulation. Regeneration with unglazed collectors allows for lower BHE distances without significantly decreasing the performance. Similarly, Bertram et al. [69] performed an experiment and simulations on a BHE field that is regenerated by unglazed PVT collectors. They report a decrease of heat pump electricity use and an increase of 4% in solar electricity in comparison to using PV panels. They also report that the regeneration effectively counteracts the measured over-consumption by the residents. Fidorów and Szulgowska-Zgrzywa [70] conducted a one year experiment in which they recharged one of nine BHEs with solar thermal energy and one with waste heat from passive space cooling. They report 0.6 and 0.4 K higher average borehole temperatures at the beginning of the next heating season than without regeneration. You et al. [71] give an overview about coupled GSHP and PVT systems. They conclude, among other things, that among the considered studies the PV efficiency increases by around 11% in cold climates, the required BHE length is reduced by 18% for the same SPF, or the SPF increases by around 55%. They also emphasise that long-term simulations are essential to achieve optimal design schemes and that there is a lack of reported technical considerations with regards to the maintenance and safety of hybrid PVT-GSHP systems for long-term use. Chhugani et al. [72] compared different heat supply systems for a single family house and report a 30-35% smaller dimensioning of the BHE with regeneration by an unglazed PVT collector. Similar values (25-30% reduction of borehole length) are reported by Weiland et al. [73] using solar steel sandwich panels as a regenerating source. They also report a reduction of the necessary installation area up to 80% and an increased robustness against undersizing of the BHEs.

Operation strategies Trillat-Berdal et al. [74,75] performed an experiment with flat plate collectors as a regenerating heat source for two BHEs. They conclude that the operation of the circulating pumps is crucial regarding the SPF. Kjellsson [76] and Kjellsson et al. [77] compared different solar assisted GSHP systems for single family houses. The authors conclude that for reducing electricity consumption, the best option is to use solar thermal energy for DHW generation in the summer and to inject solar heat for regeneration in the winter, rather than using all solar heat at the heat pump (HP), for regeneration, DHW production or store it in a brine tank before the HP and BHE. The authors also emphasise the importance of a good operation strategy and efficient circulation pumps in order to minimise additional electricity consumption. Miglani et al. [78] optimised the operation of an integrated system consisting of BHE, HP, flat plate collectors and natural gas boiler using mixed integer linear programming (MILP) and seasonal typical days. In contrast to Kjellsson [76], their optimal operation schedule in winter involves direct solar heating while nearly all solar heat in summer is used for regeneration. Miglani et al. [79] performed a similar study but take into account the temperature change in the ground using g-functions. They also considered different building retrofit solutions, which have a large impact on overall emissions and costs.

Design aspects In the following, system design aspects like the choice and positioning of the solar collector are addressed. Bertram [80] analysed the impact of a flat plate collector at the condenser side respectively an uncovered collector at the evaporator side (regeneration of one BHE) of the heat pump. The author concludes (1) that the solar collectors on the condenser side increase the SPF significantly while the collectors on the evaporator side especially allow for a reduced borehole length and (2) that pre-pipes have a significant influence on the system performance of short BHEs, allowing a reduction of the borehole length. Persdorf et al. [13] report that the cooling of the ground decreases proportionally with increasing regeneration fraction within an infinite BHE field, simulated with the software Polysun. The targeted regeneration fraction is based on the minimum desired temperature at which a steady state condition is established. They analysed different variants of solar regeneration among others. One result is that an additional thermal storage leads to a higher solar yield and reduced electricity consumption. Selective collectors have a special coating to absorb short-wave radiation and reflect long-wave radiation. This is intended to minimise the heat losses of unglazed solar collectors. The authors find that they reach higher regeneration fractions than non-selective unglazed collectors. Like Kjellsson [76], they also find that a direct usage of glazed solar thermal collectors is beneficial to the reduction of electricity consumption. Additionally, they report that the levelised cost of heat (LCOH) is similar for all analysed regeneration sources (glazed, unglazed, PVT, air HX, passive cooling). Wasik et al. [81] studied the influence of insulation and air gap thickness of PVT collectors on ground regeneration. They find that unglazed collectors yield a higher amount of heat than glazed ones for all considered ground temperatures. This is due to the fact that unglazed collectors use the ambient air as a heat source as well, enabling nightly regeneration. Sauter et al. [82] and Hun [15] analysed the case of a suburban and an urban district in Zurich, Switzerland. They find that flat plate collectors need 1/3 less space than uncovered PVT to achieve full regeneration. They also report a decreasing marginal utility of using different heat sources for regeneration due to concurrence. When the total BHE length is reduced due to the regeneration, the total electricity consumption increases. This effect can be equalised by the usage of PVT collectors. The authors conclude that in urban districts small buildings can be regenerated by solar heat, while an inclusion of further heat sources (air, facade solar collectors, space cooling) is necessary for bigger buildings with small roof areas. Hemmatabady et al. [83] assessed different BHE and solar system layouts using an artificial neural network in an intermediate step of the multi-objective optimisation procedure. Compared with a fossil-based reference layout the most economical BHE layout accomplishes a 60% emission reduction at an increase of levelised cost of energy of 13% without emission penalty costs.

Further studies are summarised in Table 1. Several more case studies with flat plate collectors as regenerating heat source have been performed using numerical simulations [84–89] and/or experiments [90–92].

3.1.2. Space cooling

Due to climate change, cooling loads are increasing in many countries [103]. BHE coupled reversible heat pumps or passive space cooling offer interesting alternatives to reversible air source heat pumps, ideally increasing the efficiency in the heating and in the cooling season and / or reducing spacing or dimension requirements.

Lazzari et al. [104] investigated the long-term performance of a BHE field with and without regeneration from space cooling for different field geometries with negligible GW flow. They conclude that regeneration is not necessary for a single BHE, partially necessary for a single line and two staggered lines of BHEs, and almost complete regeneration is necessary for an infinite square of BHEs. Halaj et al. [105] used finite element modelling to evaluate the influence of injecting waste heat from cooling on the BHE field temperature, and find that the minimum ground temperature at 50 m depth is 2.1 °C higher than without heat injection. They describe an increased initial cooling of the ground at the BHE field centre, shifting towards the direction of the groundwater flow with time.

Passive space cooling In climates with moderate cooling loads, the heat transfer medium can be used directly for cooling without using a chiller. In this case, the heat transfer to the building is usually managed via radiant, often floor cooling in order to make use of a larger heat exchange area and the thermal mass of the building. The supply temperature is not only limited by the natural fluid temperature, but also to avoid condensation in the radiant floor, leading to a relatively small temperature difference of the fluid and the cooling power. Usually the heat pump is bypassed and a heat exchanger separates the BHE and the building circuit. According to Belliardi [106] the efficiency of passive space cooling is usually poorly known and too often roughly estimated and field information of practical, measured and documented experiences is almost non-existent.

Pahud et al. [107] present design sizing keys for BHE fields used for heating and passive cooling of low energy office buildings. They define optimal design as the shortest possible BHE length that fulfills the heating criterion (BHE inlet fluid temperature never falls below 0 °C for 50 years) and the geocooling criterion (not exceeding the maximum room temperature for more than 100 h per year). They also perform a parameter study and find, that Bologna presents an example for the climatic limit of passive space cooling, and that a conventional floor heating system presents more difficulties than thermally activated building structures (TABS) to keep the room within the comfort limits. The authors find that the geocooling HX size has a strong influence on the geocooling sizing key, while the borehole distance does not. Additionally the geocooling criterion shows a strong sensitivity to the regeneration fraction and conditions borehole sizing at larger regeneration fractions. An optimal borehole length is obtained for a ground recharge ratio of about 50 to 60%.

Dott et al. [108] report that most passive cooling circuits in the market use a mixing valve to control the supply temperature to prevent condensation on the room surfaces and pipes. In parallel mode, the cooling capacity is increased by the heat pump producing domestic hot water. The authors emphasise that in passive cooling mode the floor HX and the BHEs have a strong interdependence and that a simultaneous simulation is therefore crucial to analyse the interactive dynamic system behaviour. They also analysed the summer thermal comfort and conclude that the passive floor cooling covers the cooling needs of the considered residential building up to 94%. Furthermore they emphasise the importance of the design of the heat exchanger between BHE and building circuit. In contrast, in the study performed by Hamada et al. [109] no HX is used between the energy piles and floor cooling circuit. According to Kriesi [11] this is possible when the BHE is operated with water. They also emphasise the importance of a temperature spread of at least 3 K in the floor heat exchanger and BHEs which results in lower cooling powers. The authors state that a full regeneration (in Switzerland) is only possible in buildings with high energy stan-

Table 1
Further studies considering artificial regeneration with solar thermal heat.

Study	Regeneration technology	Investigation (I) and findings (F) relevant to the current research
Bakirci et al. [93] (2011)	flat plate	**(I)** Evaluation of an experimental operation of two BHEs coupled with flat plate collectors during a heating period in Turkey. **(F)** Monthly COPs between 3 and 3.4 with radiators as heat exchangers in the building.
Xi et al. [94] (2011)	ETC	**(I)** Experiment during the coldest month in Shijiazhuang, China, using evacuated tube collectors (ETC) for the regeneration of short boreholes. **(F)** Regeneration improves the collector efficiency by 8%.
Eslami-Nejad and Bernier [95,96] (2011, 2012)	flat plate	**(I)** Proposal of a double-U configuration with two independent circuits, one connected to a solar collector and one connected to the heat pump, and a saturated sand ring around the BHE which may freeze during operation. **(F)** Regenerating single boreholes leads to a small decrease in HP electricity consumption (3.5 and 6.5% for the proposed system and conventional solar assisted GSHP) but to a large decrease in borehole length (17.6 and 33.1%). **(I)** Simulation study in three Canadian cities. **(F)** Maximum decrease in BHE length of 18% and of 5.3% in HP electricity consumption.
Danielewicz et al. [97] (2013)	flat plate, passive floor cooling	**(I)** Comparison of the regenerative effect of flat plate collectors and passive floor cooling in a simulation study. **(F)** Both perform similar regarding the regeneration fraction.
Reda and Laitinen [98] (2015)	flat plate	**(I)** Comparison of different operation strategies for a small BHE field coupled with solar thermal collectors. **(F)** The optimal operation strategy depends on the BHE length and collector area.
Dai et al. [99] (2015)	ETC	**(I)** Experimental comparison of different operation modes of a heat pump with ETC and BHEs as heat sources in the coldest month in Dalian, China. **(F)** Recommendation of a serial operation of the collector and the BHEs based on average COP and solar fraction.
Busato et al. [100] (2015)	flat plate	**(I)** Simulation study comparing solar, GSHP and combined systems. **(F)** Recommendation to size the BHEs to allow for a minimum ground inlet temperature of −2 °C and invest the savings in solar collectors.
Yang et al. [101] (2015)	ETC	**(I)** Experimental comparison of different operation modes with ETC. **(F)** Recommendation of a combined BHE and solar operation based on the SCOP.
Ooi and Noguchi [102] (2017)	unglazed PVT	**(I)** Proposal of a BHE based heating system with regeneration by PVT without heat pump for a small residential building in Melbourne. **(F)** Thermal comfort could be achieved using a PVT collector for regeneration.

dard, decreasing thermal comfort. They propose a mixture of passive floor cooling and active cooling and drying of the supply air flow, using sensible and latent heat for regeneration.

Belliardi [106] provide a detailed report on the monitoring results of a residential building in Switzerland. As minimum inlet temperature they chose 21 °C. The greatest temperature difference occurred at the heat exchanger between BHE field and building, which lead to a much lower temperature difference of the floor heat exchanger than the expected 5 K. As improvements after two years they reduced the pump flow rates in summer in order to reduce electricity consumption. According to the authors a temperature difference based control of the underfloor circuit pump would increase the efficiency of the floor cooling. They also increased the temperature of the floor cooling circuit in order to stay above the dew point. Belliardi et al. [110] later derived a generalised method for analysing the effectiveness of passive floor cooling.

Further studies concerning regeneration with passive cooling are listed in Table 2.

Active space cooling Using active instead of passive space cooling for regeneration, the thermal energy converted by the compressor is injected into the BHEs in addition to the heat that is removed from the conditioned space. Schibuola et al. [125] investigated the performance of an inverter-driven GSHP system in Italy. They report that even though the heating demand of the building exceeds the cooling demand, the thermal load on the ground is almost perfectly balanced due to the compressor contribution. This fact leads to a low sensitivity of BHE spacing regarding the system performance. Similar to Wu et al. [118], Wu et al. [126] investigated different absorption heat pump systems for heating and cooling in Beijing and Shenyang, China, with the result of a reduced ground imbalance ratio compared to compression heat pumps. Wu et al. [127] propose a combination of absorption and compression HP to make use of the higher long-term heating primary energy efficiency (PEE) of the absorption HP and the higher cooling PEE of the compression HP. Ally et al. [128] performed an exergy analysis of a GSHP for space heating and cooling of a residential building in USA equipped with PCM. They find that the total irreversibility is highest during the peak cooling and heating season when runtimes are high, with the highest irreversibility occurring at the condenser, followed by the indoor heat exchanger. Ruesch et al. [14] propose to use active cooling for regeneration of the ground in suburban districts in Switzerland with area-wide usage of GSHP. According to the authors passive cooling is cheaper in less intensively used areas (up to extraction rates of 40 to 60 $kWh \cdot m^{-2}$). Further sources of regeneration are necessary in densely populated and stock districts. However, when the potential for PV electricity production is made use of, the extra electricity needed for cooling can be covered locally.

Many authors have analysed systems with active space heating and cooling, but do not focus on ground regeneration [129–135]. As these studies show potential for the analysis of regeneration, but do not actually address it, they are not considered in the detailed analysis in Section 4.

3.1.3. Further heat sources

Heat extraction of outside air has the additional advantage of improving the microclimate in hot summers. However, no studies could be found to quantify this effect. Persdorf et al. [13] simulated an outside air/brine heat exchanger directly in the BHE circuit. They report a regeneration fraction of maximum 50% for a multi-family home in a Swiss district with area-wide usage of BHEs. According to Kriesi [11] an outside air cooler needs to be operated all day in Switzerland, implicating the necessity of a battery if PV electricity is to be used for the additional pump electricity. As further heat sources the authors propose a street collector and a garden pond. They estimate the additional costs

Table 2
Studies considering artificial regeneration with passive cooling.

Study	Investigation (I) and findings (F) relevant to the current research
Gasparella et al. [111] (2005)	**(I)** A cooling system with an air handling unit with dessicant dehumidification including heat recovery and passive cooling of the fan-coils by the BHEs. **(F)** Primary energy savings of 30% compared to gas-fired heater and compression chiller and a BHE length reduction of nearly 50% compared to a GSHP system without desiccant dehumidification.
Eicker and Vorschulze [112] (2009)	**(I)** Proposal of a low pressure drop design for passive space cooling. **(F)** Annual efficiencies of above 20 at a cooling power of 26 Wm^{-1}, limited by the building side. **(I)** Parameter study considering different climates. **(F)** Even in office buildings in warm climates like Crete the BHE outlet temperature does not exceed 21 °C.
Saner et al. [113] (2010)	**(I)** Comparison of CO_2 emission savings for GSHP systems in European countries to conventional systems. **(F)** These savings can significantly increase by using passive cooling when compared to additional air conditioning systems, in particular in warm climates.
Desideri et al. [114] (2011)	**(I)** Active and passive space cooling for a residential building near Perugia, Italy. A parameter study with different BHE lengths, distances, parallel and series configurations and soil properties. **(F)** Passive cooling is beneficial for regeneration due to the more continuous operation than active cooling. A parallel BHE configuration leads to higher average ground temperatures.
Arteconi et al. [115] (2013)	**(I)** Proposal of a system with passive cooling in spring and autumn and active cooling in summer. **(F)** The storage temperature and volume are the most sensitive values regarding the system performance.
Luo et al. [116,117] (2013, 2015)	**(I)** Experimental comparison of three BHE fields with different borehole diameters for heating and cooling of an office building in Germany. **(F)** A larger diameter increases the performance slightly. **(F)** A clearly increasing trend for the cooling and decreasing trend for the heating SCOP is shown.
Wu et al. [118] (2014)	**(I)** Combination of an absorption heat pump with free cooling. **(F)** Regeneration increases the ground temperature >3 K after ten years in different cold locations in China.
Man et al. [119] (2015)	**(I)** Proposal of a low energy consumption cooling mode to prevent floor condensation. **(F)** A cooling COP of 25.
Persdorf et al. [13] (2015)	**(I)** Investigation of GSHP long-term performance with different regeneration methods in Switzerland. **(F)** Geocooling increases the minimum BHE inlet temperature but does not decrease the necessary BHE length comparable to solar regeneration.
Piscaglia et al. [120] (2016)	**(I)** Experimental performance analysis of a GSHP with passive and active cooling of a commercial building in Italy. **(F)** The SCOP (including pump electricity) rises noticeably using free cooling. During the three years of monitoring the decrease in heating SCOP and increase in cooling SCOP are already apparent. **(F)** Report of the impact of a weather anomaly, where intense snow fall and subsequent melting influenced the GW temperature and thereby the sedimentary heat reservoir for almost a year.
Speerforck and Schmitz [121], Niemann et al. [122] (2016, 2019)	**(I)** Combination of a cooling ceiling with desiccant assisted air dehumidification. **(F)** Balanced heating and cooling load for an office building in Germany.
Allaerts et al. [123] (2017)	**(I)** Comparison of different retrofit possibilities for a school building in Belgium: Proposal of an additional cooling coil in the exhaust air stream and passive floor cooling. **(F)** They find that the cooling demand during the holidays is low, but in combination with the cooling coil the primary energy demand can be reduced by 11% due to an increased SCOP and thermal load coverage factor of the heat pump.
Fidorow-Kaprawy and Stefaniak [124] (2022)	**(I)** A case study with sensitivity analysis of passive cooling by two BHEs in Warsaw, Poland. **(F)** The brine temperature drop is reduced by 0.5 to 1 K over 25 years, saving 4.5% electricity for heating and almost emission-free cooling.
Ruesch et al. [14] (2022)	**(I)** Comparison of different space cooling methods for BHE regeneration in Switzerland. **(F)** Passive cooling is the best option regarding costs and commissioning, when the influence of neighbouring plants is moderate and low regeneration fractions are acceptable.

for the street collector as quite low, when road works are due anyway. An additional benefit could be the cooling effect of the asphalt and thus increased lifetime. The authors prefer this approach to the more expensive pond collector and the utilisation of excess PV electricity. Xiang et al. [136] perform a 10 year simulation of a photovoltaic thermal road as heat source for regenerating a BHE field, and report an average SPF of 2.31 for the examined case in Beijing, China. Besides solar heat, space cooling and outside air, Sliwa and Rosen [12] analysed a system for snow melting on a parking lot as regenerating heat source. They report a maximum heating power of 17.5 Wm^{-2}.

Waste heat that is generated all year round, but whose potential cannot be fully utilised in summer, can be used for BHE regeneration. Possible sources are waste water, exhaust air, industrial processes, commercial cooling applications, substations, tunnels and so on. Ideally, a dependency on a specific industry for the functionality of a heating grid should be avoided. However, few scientific studies that combine these heat sources with BHE regeneration could be found. Wang et al. [137] propose a HX to make use of kitchen exhaust air of new commercial buildings with open fire cooking and high temperature exhaust air, aiming at a minimum of HX pollution. They report a reduction of the ground temperature decrease of 3.2 K in 15 simulated years of operation in Beijing, China.

3.1.4. Combinations

Some authors investigate the combination of different heat sources for regeneration. Wu and Zheng [138] describe an experimental setup with PCM storage for a detached house in Harbin, China. Half of the BHEs are used for passive space cooling and half for solar thermal injection during the cooling period while during the heating period solar thermal collectors and BHEs are used in parallel for space heating. Wang et al. [139] analysed a similar setup for a detached house in Harbin and report a negative influence of the solar thermal heat injection on the cooling performance, exceeding the heat extraction in winter. Rad et al. [84] report that a higher flow diversion to solar thermal collectors is beneficial for the performance in the heating season, but the opposite in the cooling season. In their case the system does not function properly in the cooling season due to too high inlet temperatures at the reversible HP. However, stopping the flow to the solar panels would impede the potential benefit of preventing overheating of the collectors. Wang et al. [140] propose a system using a BHE field for cooling and heating as well as a BTES charged with solar heat from evacuated tube collectors for heating. They emphasise the importance of the first operation time regarding the advantageous ground temperature when injecting heat into the ground before the first extraction period. They also determined a suitable control strategy and find, that the solar collectors' and thermal storage's upper and lower temperature limits have a significant impact on the system performance. You et al. [141] propose a HGSHP for heating and cooling with a heat compensation unit that makes use of the high outside air temperature in summer using a thermosyphon / air source heat pump. Reda et al. [142] analysed different operation strategies in three Italian cities with dominating heating, cooling and balanced demand respectively using solar thermal collectors and passive space cooling. They conclude that solar thermal heat injection into the ground makes sense in humid subtropical (Cfa) climates like Milan, but not (only to prevent overheating of the solar collectors) in hot-summer mediterranean (Csa) climates like Rome and Palermo. They also find that it is important to limit solar injection into the ground in order to minimise the final energy demand by providing passive space cooling in the heating-dominated Cfa climate, where the solar collector area should also be largest. Wang et al. [143] introduce a double-evaporator heat pump for an integrated PVT and GSHP system with passive cooling. In their study they assume a constant ground temperature.

3.2. Cooling-dominated applications

In cooling-dominated applications, usually in hot climates, the goal of regeneration is to extract heat from the ground. In comparison to heating-dominated climates, BHE fields usually need to be dimensioned larger due to higher peak loads. Qi et al. [144] conducted a literature review on hybrid GSHP systems and report, that in combination with a cooling tower the BHE field can be dimensioned for the heating loads (see Section 3.2.2). Yang et al. [145] discuss several technologies for balancing the load in cooling-dominated climates: fluid coolers, cooling towers, surface heat rejecters, cooling ponds and desuperheaters for preheating domestic hot water. They conclude, among other things, that an optimal design methodology for HGSHP systems, which can solve the simultaneous interactions between the building systems, supplemental heat rejecters/absorbers and BHEs, is highly needed. Similarly, Balaji and Sharma [146] describe ejector cooling, cooling towers and absorption heat pumps for balancing the load on the ground. Zhai et al. [147] give an overview about system integrated approaches of GSHP including the usage of cooling towers. They suggest to establish an optimal operational control strategy according to the climatic conditions, building functions and thermal balance of the ground.

3.2.1. Space heating

Most of the GSHP systems in cooling-dominated areas are used for space heating or domestic hot water production as well, already mentioned for example in 1998 by Zogou and Stamatelos [148]. Within a research project the GSHP system for space cooling and heating of a university building in Valencia, Spain was studied and monitored over an observation period of several years [149–152]. Although the loads are cooling dominated, the authors report an unchanged temperature response (BHE outlet temperature) over the years, accounted for by natural regeneration by groundwater flow and load reduction during holiday season.

Rather than regenerating the ground, Yu et al. [153] used heat recovery of the exhaust air to limit the amount of heat rejected to the ground in an archive building in Shanghai, China. As an optimisation measure, Zhai et al. [154] propose to increase the indoor set temperature of the archive. Zhao et al. [155] further investigated the benefit of heat recovery in Shanghai and find, that after 20 years of operation ground thermal balance is reached at a heat recovery ratio of 53%, decreasing the total BHE length at the same time. Several more case studies have been performed addressing GSHP space cooling and heating [156–159].

Cooling-dominated buildings in heating-dominated climates Wrobel and Schmitz [160] and Wrobel et al. [161] analysed similar systems as Speerforck and Schmitz [121] and Niemann et al. [122] took up later. However, they used a chiller for cooling purposes. According to the authors, the combination of floor cooling and ventilation leads to reduced energy consumption compared to air conditioning only. Allaerts et al. [162] split the BHE field supplying an office building using passive space cooling and active heating in Belgium into a hot and a cold part and used supplementary dry coolers for additional heat injection/rejection. They report a total borehole length reduction of 47%. Beckers et al. [163] propose to use a GSHP system for the thermal conditioning of cellular tower shelters. They included an air-economiser, which directly blows cold ambient air into the shelter, and dry-fluid cooler, which uses cold ambient air to cool down the BHE fluid.

3.2.2. Cooling towers

The combination of a GSHP with cooling tower as additional heat ejector is widely spread. There are several studies, where an additional heat ejector, often a cooling tower, is dimensioned according to the difference in annual heating and cooling demand [164,165] based on the works of Kavanaugh and Rafferty [166] and Kavanaugh [167].

Yavuzturk and Spitler [168] analysed different control strategies using a cooling tower with a plate HX. They compared three basic control strategies: (1) heat pump entering or exiting fluid temperatures are greater than a set value (2) The difference between either the heat pump entering or the exiting fluid temperatures and the ambient wet-bulb temperature is used as the control criterion (3) The operating and control strategy is based on cooling the ground ('cool storage') to avoid a long-term temperature rise. The cool storage effect is achieved by operating the supplemental heat rejecters for six hours during the night. The authors conclude that for the office building in question, option (2) is the most beneficial, as it avoids operation at unfavourable weather conditions like in option (1) and unnecessary electricity consumption like in option (3). Fan et al. [53,169] used a BHE field for heating in winter and as a cold storage, charged by a cooling tower during nighttime, in summer. Similarly, Zhu et al. [170] used a PCM storage charged by a cooling tower. Shang et al. [171] propose to operate the cooling tower in series with the BHE in transition season in order to extract additional heat.

According to Hackel [172], the operation of the cooling tower is usually most cost effective in series and upstream the BHEs, where it gets the largest temperature difference. Hackel and Pertzborn [173] add, that in areas with high ground temperatures and low wet bulb temperatures (hot and dry climate like Las Vegas, USA), it can make sense to place the cooling tower downstream the BHEs. They also emphasise the importance of a careful dimensioning, reporting potential savings of 37 $ per m^2 in their studied cases. Park et al. [174] again compared the GSHP in series and parallel with a cooling tower and find that a parallel configuration leads to higher performance factors in Daegu, South Korea. According to Qi et al. [144], common control strategies include maximum temperature, temperature difference and schedule control strategy (see also [168]). The authors emphasise the need for more sophisticated control strategies. Cui et al. [175] additionally introduce the fixed load ratio control, activating the cooling tower when the cooling load exceeds a certain level. They find 50% to be the optimum auxiliary cooling ratio both for parallel and serial GSHP and cooling tower systems for a 20 year operation in an office building in Chongqing, China. According to the authors, the fixed load ratio control is best suited for the parallel configuration, while the fixed entering temperature control is best suited for the serial configuration in their case.

3.2.3. Further heat sinks

Yavuzturk and Spitler [168] name (closed-circuit) fluid coolers and surface heat rejecters as additional heat rejecters besides (open-circuit) cooling towers. Like the before mentioned asphalt collectors, surface heat rejectors refer to a series of pipes inserted in pavements, parking lots or ponds. Singh and Foster [176] describe two examples employing a closed circuit cooler as additional heat sink. Ramamoorthy et al. [177] analysed the usage of a cooling pond connected in series with the BHEs. Man et al. [178] propose a nocturnal cooling radiator on the roof of a building for nocturnal regeneration of the BHE field. Several more case studies have been performed in cooling-dominated climates [179,180].

4. Detailed analysis of artificial regeneration methods

The actual number of installed GSHP systems using artificial regeneration is not comprehensively possible to estimate, as well as the number of system failures due to a lack of regeneration. There are reviews on the usage of GSHP systems, for example in Europe [181] or worldwide [182]. However, few data is available on the performance of these systems, as monitoring is usually not mandatory. IEA HPT Annex 52 (end of term 2022) aimed to refine and extend current methodology to better characterise GSHP system performance serving commercial, institutional and multi-family buildings, and to provide a set of benchmarks for comparisons of such GSHP systems around the world. They describe the current situation as follows [183]: 'Though some field measurements have been reported in the literature, there is little or no consistency on how to measure the performance or how to report the results.' Furthermore, a poor SCOP may indicate undercooling or overheating of the ground, but may have a variety of other reasons, like incorrect installation, undersizing of components or poor control strategies [184]. Hence, we are focusing on the previously presented literature rather than giving a comprehensive overview about installed systems.

4.1. General statistics

Of the available literature, 103 studies meet the criterion of covering artificial regeneration and are analysed in more detail in this section. Of these studies only 5 fall into Category 1 introduced in Section 1 (area-wide usage of single BHEs), all in Switzerland. All other studies fall in Category 2 (centrally controlled BHE fields).

In Fig. 2 the spacial distribution of the analysed studies is shown. China is by far the most frequently chosen country. Apart from that, many studies are conducted in Europe, especially in Switzerland, Italy and Germany.

The temporal distribution of publications is shown in Fig. 3. Since 2005, 2 to 9 studies have been published annually, with an exceptionally high number of 18 publications in 2015.

The regeneration technologies investigated in these studies are shown in Fig. 4 for heating and cooling-dominated climates. In heating-dominated climates space cooling and flat plate collectors are by far the most used technologies. In cooling-dominated climates all studies use space heating respectively DHW production as heat sink. Additionally, in 4 studies cooling towers are used.

4.2. Heating-dominated applications

The following analyses are focused on heating-dominated applications, covered by 64 papers. Regarding the methods, in 38 publications numerical simulations are conducted, 14 use experiments and 12 publications cover both (see Fig. 5). The latter often use monitoring data of a short time span to validate the numerical model and conduct a simulation for a longer time span. In general, most experimental works investigate energy systems with up to 25 BHEs and up to four years of monitoring. Simulation studies show a higher diversity with some long-term investigations up to 50 years and most BHE field sizes up to 70 BHEs. 12 studies consider only one BHE. The median of the investigated number of BHEs is 6.

The most frequently used software for energy system simulations is TRNSYS (see Fig. 6a), which is very flexible in terms of system design. The often used BHE model Type 557 (duct ground heat storage or DST model) does not take into account ground water flow, irregular geometries, grout and fluid heat capacity and ground stratification. Not considering the heat capacity leads to deviations in the short-term behaviour. However, as the typical heat pump running time is in the range of several minutes, a high short-term accuracy of the BHE model is important [185]. The heat pump can be included using catalog data [186]. Polysun and Energy Plus are also used in several studies. Polysun makes use of the EWS model presented by Huber and Schuler [187]. For the standalone BHE field simulation, EED is the most frequently used software, followed by Pilesim. In EED monthly and peak loads are considered. The COP of the heat pump is fixed [186].

Of the 64 considered studies, only 5 investigate districts. Of category 2 (centrally controlled BHE fields) introduced in Section 1, only one paper considers a district. All other studies investigate single buildings, mainly residential buildings, also some office, university and accommodation buildings (see Fig. 6b). The most common room heat exchanger is the radiant floor (see Fig. 6c). Heat transfer by air and radiators is also common. 14 of the studies do not specify the room heat exchanger. Of the simulation studies, 21 integrate the building load as multizone model (see Fig. 6d). In 12 studies the load integration is not specified, and in 11 a load profile with unknown origin is used.

The reported nominal power lies between 0.2 and 886 kW with a median of 18 kW. The BHE depth varies between 21 and 400 m with a median of 90 m, not considering studies with varying BHE depth. Three of them range from 200 to 400 m and are thereby deeper than typical shallow systems. Regarding the ground, the level of detail differs a lot between the studies. Some report bore profiles, while most specify an assumed effective thermal conductivity.

Evaluation criteria Depending on the research question a variety of evaluation criteria for the studied system designs are used in the literature (see Table 3).

Most of the enumerated characteristics only give an idea about a temporary performance of a system section. For a comparable system evaluation the usage of relatively independent and comprehensive values like the SPF would be desirable. As regeneration only makes sense in the long run, the evaluation period should at least cover the time span until the annual heat exchange between the BHEs and the surrounding ground reaches steady state and the average borehole temperature does not increase/decrease further. This is already done in many simulation studies (see Fig. 5).

In the considered studies SCOPs from 1.4 (absorption HP) to 6.2 and SPFs from 2.3 to 4.97 are reported, but the system boundaries are not always clearly defined. Due to highly location, market and project specific evaluation criteria and boundary conditions like weather conditions, geological and hydro-geological situation, available technology, emission factors, energy prices, investment costs, financing and so on, it is difficult to compare the system performance between the different studies. Thus it is useful – and already done in some studies – to perform a sensitivity analysis.

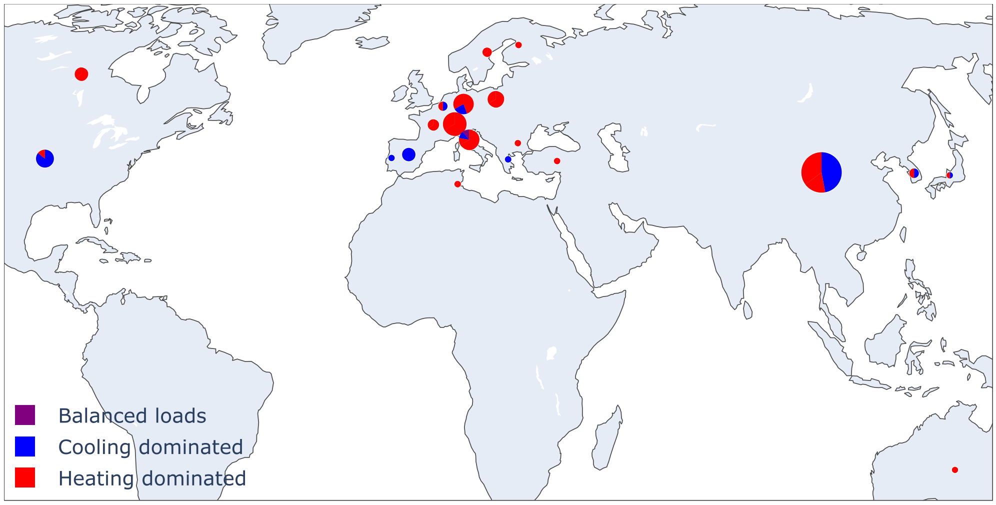

Fig. 2. Spacial distribution of the investigated studies. The size of the circles indicates the number of studies conducted in the respective country.

Table 3
Evaluation criteria used in the literature.

Criterion	Studies
(average) COP	[128,141,117,119,99,89,143]
SCOP	[138,108,90,84,139,114,95,96,115,125,91,101,67,120,123,106,110,124,74]
SPF	[76,68,77,85,94,140,69,87,80,98,122,92,73,136,72]
operating emissions	[93,115,79,83,124,72]
embodied emissions	[78,79]
operating costs	[115,116,78,79]
invest	[116,79]
present value	[93]
levelised cost of energy (LCOE)	[84,91,127,100,106,73,110,83]
payback time	[111,87]
BHE length	[111,84,85,95,96,86,107,91,80,73]
final energy demand	[69,86,141,137,82,14,15]
final energy efficiency	[106,110]
external energy import	[136]
primary energy demand	[111,87,115,125,98,123]
primary energy ratio	[9,126,118,127,100]
exergy losses	[128]
regeneration fraction, ground thermal balance	[97,106,82,136,14,15,124]
ground temperature	[90,9,126,118,127]
average/bottom borehole temperature	[70,105]
operating temperatures	[116,137,102]
room temperature	[108]
power	[12]
extraction potential	[59]

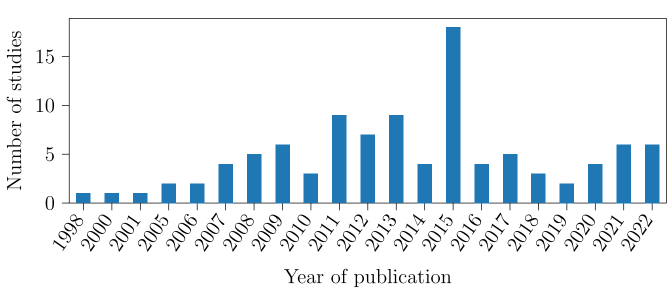

Fig. 3. Number of publications regarding artificial BHE regeneration over time.

5. Conclusion and outlook

In this study we conducted a literature review about the regeneration of shallow borehole heat exchanger fields, focusing on artificial regeneration in heating-dominated applications in the detailed analysis. The following conclusions can be drawn:

5.1. *Universally applicable conclusions drawn directly from the reviewed literature*

- Regeneration can be used to increase the SPF, reduce the necessary BHE length or compensate over-consumption (including neighbouring plants).
- The benefit of artificial regeneration increases with system size.
- A systemic approach requires systemic evaluation criteria like SPF, overall GHG emissions and LCOE.
- In order to achieve a justifiable heat transfer compared to the auxiliary energy, a minimum temperature difference between the source of regeneration and the ground should be maintained.
- All possible heat sources and sinks should be taken into account in the system design.

5.2. *Specific conclusions for individual technologies*

- Parallel usage of solar heat is usually preferable over regeneration operation, which should be activated when the solar heat can not be used directly and at a certain temperature difference to the

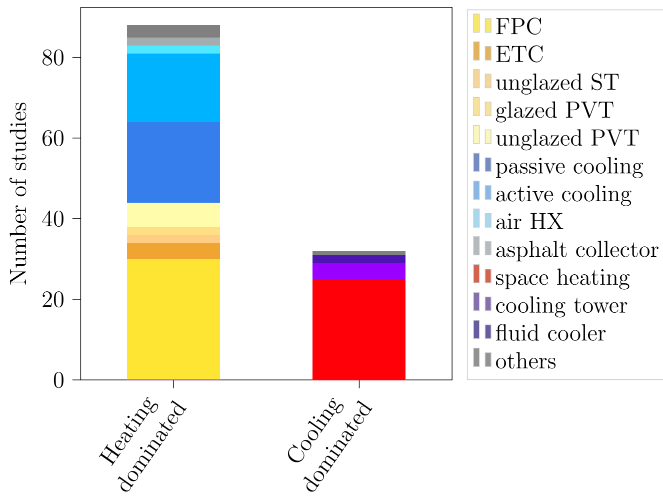

Fig. 4. Investigated regeneration technologies in heating and cooling-dominated climates. For studies with more than one regeneration technologies, each one is counted (that means the shown number of studies exceeds the investigated number of studies).

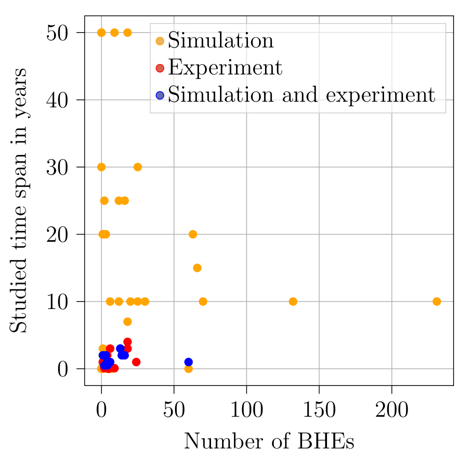

Fig. 5. Type of the study and investigated time span over the BHE field size (heating dominated). Typical days and no specification are set to zero, one heating or cooling period is set to 0.5 years, monitoring time is taken for studies which do both simulation and experiment. One outlier with 1761 BHEs [14] is not considered.

ground. Regarding the usage of different collector types, different studies come to different solutions, depending on the main goals and boundary conditions. Selective collectors reach higher regeneration fractions than unselective ones.

- In heating-dominated buildings without high cooling load peaks, passive space cooling is a good option for regeneration. The combination with TABS leads to a more even load. Special care has to be taken designing the HX separating ground and building circuit and the pump sizes. To guarantee a cooling effect the regeneration fraction should be limited.
- The cooling power of passive space cooling is limited by its supply temperature to avoid condensation. To cover higher cooling loads, passive space cooling may be combined with air cooling and dehumidification of the room air.
- A reversible heat pump leads to higher heat rejection to the ground. However, the auxiliary energy increases at the same time.
- Cooling towers are reported to be more beneficial upstream of the BHEs, with an exception of hot and dry climates, or in parallel operation to the BHEs. The optimum operation strategy depends on the placement of the additional heat sink.

5.3. Overarching conclusions drawn from the holistic analysis of the reviewed literature

- In cooling-dominated climates, reversible heat pumps are an obvious choice to minimise ground thermal imbalance. In heating-dominated climates, mostly space cooling and flat plate collectors are used for regeneration.
- There is a lack of long-term, large BHE field size experimental work in heating-dominated climates.
- Most studies consider one additional heat source/sink. There is a lack of studies about the detailed interaction of different heat sources/sinks.
- Very few studies combine waste heat with BHE regeneration.
- While studies about enhancing natural regeneration methods usually consider BHE fields with a focus on the ground properties, there is a lack of system integrated studies. In contrast, studies about artificial methods are usually system integrated, but mostly consider small systems/single buildings and only consider the ground superficially. In particular there are barely any integrated studies about the regeneration of BHE fields for district heating or cooling.
- TRNSYS is the most commonly used software for the simulation of artificial ground regeneration.
- There are only few studies that consider combined enhancing natural and artificial regeneration methods.
- Regeneration seems especially useful in climates with hot summers and cold winters (or hot days and cold nights), where PE efficient regeneration technologies can be used off peak operation.

5.4. Future work as proposed in the reviewed literature

According to the examined studies, the following points require further investigation:

- Optimisation of control strategies. This is especially emphasised for HGSHP systems.
- Design optimisation of system integrated GSHP systems.
- Energy flexibility potential of these systems. This refers to locally produced PV(T) electricity which can be used for regeneration purposes, while the electricity demand of the heat pump is decreased in times of low electricity production, especially in cold climates.
- User behaviour with passive cooling.
- Technical barriers for using shallow geothermal energy in future DHC grids and impact of groundwater flow on the technical potential.
- Environmental consequences of long-term warming or cooling trends of the ground.

5.5. Recommendations for further case studies

From the holistic literature analysis the following recommendations can be made for further case studies, regarding methodology and possible focus:

- Transparent description of boundary conditions including load specifics and the simulated time period.
- Inclusion of transparent evaluation criteria, preferably SPF (for the whole year including heating and cooling season) as defined by IEA SHC Task 44 / HPP Annex 38 respectively IEA HPT Annex 52 if applicable.
- Conduction of a sensitivity analysis at least regarding evaluation criteria (emission factors, costs,...).

An interesting point, which should be studied further, is the thematic overlap of regeneration with demand side management. Regeneration usually causes an increased electricity demand for circulation pumps.

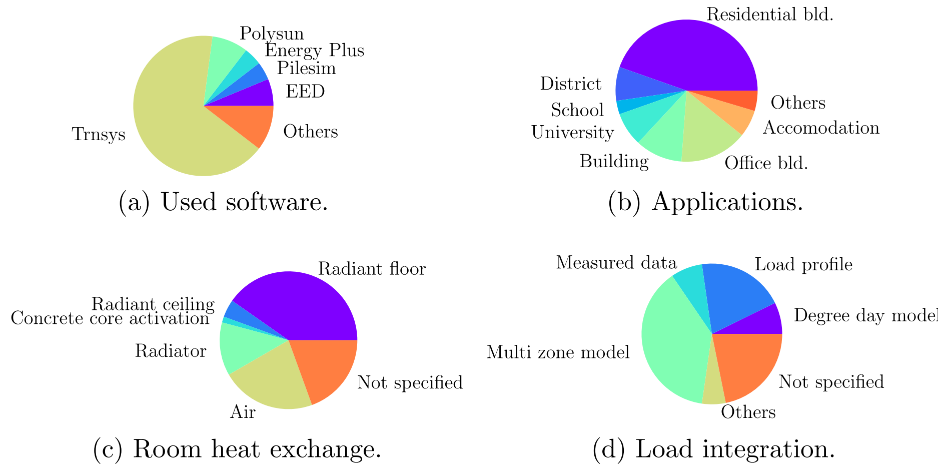

Fig. 6. Comparison of studies investigating artificial regeneration in heating-dominated climates. For studies with more than one suitable property, each one is counted (that means the total number of studies varies).

However, in heating-dominated climates, this demand occurs at times of high renewable electricity production, while the electricity demand in times of low renewable electricity production decreases (not necessarily to the same extent though).

Another interesting point is regeneration and the human factor: On one hand, it can counteract unbalanced use. On the other hand, passive space cooling can help to prevent an increase in individual air conditioning in climates where active space cooling is not common, but summer thermal comfort gains importance with progressing climate change.

Abbreviations The following abbreviations are used in this manuscript:

BHE	Borehole heat exchanger
BTES	Borehole thermal energy storage
DHC	District heating and cooling
DHW	Domestic hot water
ETC	Evacuated tube collector
FPV	Flat plate collector
GHG	Green house gas
GSHP	Ground source heat pump (BHE coupled in this study)
GW	Groundwater
HGSHP	Hybrid ground source heat pump
HP	Heat pump
HX	Heat exchanger
LCOE	Levelised cost of energy
PCM	Phase change material
PEE	Primary energy efficiency
PV	Photovoltaic
PVT	Photovoltaic-thermal
SCOP	Seasonal coefficient of performance
SPF	Seasonal performance factor
ST	Solar thermal
TABS	Thermally activated building structures
TES	Thermal energy storage

CRediT authorship contribution statement

Xenia Kirschstein: Writing – review & editing, Writing – original draft, Visualization, Investigation, Conceptualization. **Max Ohagen:** Writing – review & editing. **Joscha Reber:** Writing – review & editing. **Philip J. Vardon:** Writing – review & editing. **Nadja Bishara:** Writing – review & editing, Supervision, Project administration, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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Appendix A

Table A.4
Terminology.

Term	Explanation	Synonyms
Borehole heat exchanger (BHE)	heat exchanger in a vertical borehole; shallow / surface-near: up to 400 m depth (typically up to 150 m [188]); field/array: multiple BHEs, thermally influencing each other.	vertical borehole, vertical ground heat exchanger, vertical (closed) loop (includes energy piles), geothermal probe.
Regeneration	reducing long-term thermal anomalies in the ground in the vicinity of the BHE field due to predominant heat extraction or injection (without replacing the useful heat flow from/to the BHEs with other heat sources/sinks).	recovery, compensating thermal imbalance / accumulation / depletion, replenishment, recharge.
Ground source heat pump (GSHP)	a HP coupled to a vertical or horizontal, open or closed system; in this study always refers to a BHE-coupled HP.	ground coupled heat pump (GCHP).
Reversible heat pump	a heat pump used for active heating and cooling.	

(continued on next page)

Table A.4 (*continued*)

Term	Explanation	Synonyms
Hybrid ground source heat pump (HGSHP) systems	using additional heat sources / sinks besides the ground. According to this definition, HGSHP systems include GSHP systems with artificial regeneration, but also other heat sources/sinks in parallel or serial operation.	
Regeneration fraction	$f_R = \frac{min(Q_i,Q_e)}{max(Q_i,Q_e)}$ with Q_i being the annually injected and Q_e extracted heat into/from the BHE field.	ground recharge ratio. Similar: ground thermal imbalance ratio (positive: heat injection) (IEA HPT Annex 52)
Passive space cooling	direct heat transfer (without chiller) from the building(s) into the BHE (field), usually by floor heat exchanger.	geocooling, (geothermal) free cooling, free ground cooling, natural cooling.
COP, EER	the coefficient of performance (COP) for heating, and energy efficiency ratio (EER) for cooling applications are the ratio between the heating/cooling capacity of the heat pump and its overall electricity consumption, both measured under steady-state operating conditions.[a]	
SCOP, SEER	the seasonal COP (SCOP) in heating applications, or seasonal EER (SEER) in cooling application express the calculated seasonal efficiency of the heat pump for an assumed climate, building load etc. The system boundary is the heat pump.[a]	
SPF	the seasonal performance factor (SPF) gives the final energy efficiency of the whole system or a defined subsystem, calculated as the overall useful energy output to the overall driving final energy input for an adopted system boundary over a year or a season.[a]	

[a] IEA SHC Task 44 / HPP Annex 38.

References

[1] Bundesministerium für wirtschaftliche Zusammenarbeit und Entwicklung, Klimaabkommen von Paris, available online, https://www.bmz.de/de/service/lexikon/klimaabkommen-von-paris-14602. (Accessed 7 September 2023), 2023.

[2] United Nations Environment Programme, Environment programme, global status report for buildings and construction: towards a zero-emission, efficient and resilient buildings and construction sector, resreport, United Nations, Nairobi, https://www.unep.org/resources/publication/2022-global-status-report-buildings-and-construction, 2022.

[3] T. Kurevija, D. Vulin, V. Krapec, Effect of borehole array geometry and thermal interferences on geothermal heat pump system, Energy Convers. Manag. 60 (2012) 134–142, https://doi.org/10.1016/j.enconman.2012.02.012, https://www.sciencedirect.com/science/article/pii/S0196890412000702.

[4] C.G. Olgun, M. Geyin, T.Y. Ozudogru, Long-term performance of heat exchanger boreholes at different climatic conditions, in: T.L. Brandon, R.J. Valentine (Eds.), Geotechnical Frontiers 2017: Geotechnical Materials, Modeling, and Testing, Amer. Soc. Civil Engineers, New York, 2017, pp. 153–164, https://www.webofscience.com/wos/woscc/full-record/WOS:000406408700016, iSSN: 0895-0563 Issue: 280 Num Pages: 12 Series Title: Geotechnical Special Publication Web of Science ID: WOS:000406408700016.

[5] H.Y. Zeng, N.R. Diao, Z.H. Fang, A finite line-source model for boreholes in geothermal heat exchangers, Heat Transf. Asian Res. 31 (2002) 558–567, https://doi.org/10.1002/htj.10057, https://onlinelibrary.wiley.com/doi/10.1002/htj.10057.

[6] P. Blum, G. Campillo, T. Kölbel, Techno-economic and spatial analysis of vertical ground source heat pump systems in Germany, Energy 36 (2011) 3002–3011, https://doi.org/10.1016/j.energy.2011.02.044, https://www.sciencedirect.com/science/article/pii/S036054421100140X.

[7] Y. Sakata, T. Katsura, K. Nagano, Nationwide determination of required total lengths of multiple borehole heat exchangers under variable climate and geology in Japan, ISPRS Int. J. Geo-Inf. 10 (2021) 205, https://doi.org/10.3390/ijgi10040205, https://www.mdpi.com/2220-9964/10/4/205.

[8] S. Düber, R. Fuentes, G. Narsilio, Effect of horizontal connection pipes on operation of borehole heat exchangers under different climatic conditions, Geothermics 110 (2023) 102679, https://doi.org/10.1016/j.geothermics.2023.102679, https://www.sciencedirect.com/science/article/pii/S0375650523000330.

[9] W. Wu, B. Wang, T. You, W. Shi, X. Li, A potential solution for thermal imbalance of ground source heat pump systems in cold regions: ground source absorption heat pump, Renew. Energy 59 (2013) 39–48, https://doi.org/10.1016/j.renene.2013.03.020, https://www.sciencedirect.com/science/article/pii/S0960148113001766.

[10] N. Martins, P. Bourne-Webb, Hybridization of heat pump systems with natural ventilation to improve energy efficiency in cooling dominated buildings, Renew. Energy Environ. Sustain. 6 (2021) 33, https://doi.org/10.1051/rees/2021032, https://www.researchgate.net/publication/354861096_Hybridization_of_Heat_Pump_Systems_With_Natural_Ventilation_To_Improve_Energy_Efficiency_in_Cooling_Dominated_Buildings.

[11] R. Kriesi, Methoden der Erdsonden - Regeneration mit Sekundärnutzen oder tiefen Wärmekosten, Tech. Report, Amt Für Hochbauten, Zürich, Switzerland, 2017, https://www.stadt-zuerich.ch/hbd/de/index/hochbau/bauen-fuer-2000-watt/grundlagen-studienergebnisse/archiv-studien/2017/2017-03-egt-methoden-der-erdsonden.html.

[12] T. Sliwa, M.A. Rosen, Natural and artificial methods for regeneration of heat resources for borehole heat exchangers to enhance the sustainability of underground thermal storages: a review, Sustainability 7 (2015) 13104–13125, https://doi.org/10.3390/su71013104, https://www.mdpi.com/2071-1050/7/10/13104.

[13] P. Persdorf, F. Ruesch, M.Y. Haller, RegenOpt Optionen zur Vermeidung nachbarschaftlicher Beeinflussung von Erdwärmesonden: energetische und ökonomische Analysen, Technical Report, Amt Für Hochbauten, Zürich, Zürich, Switzerland, 2015, https://www.stadt-zuerich.ch/hbd/de/index/hochbau/bauen-fuer-2000-watt/grundlagen-studienergebnisse/archiv-studien/2015/2015-05-egt-regen-opt.html.

[14] F. Ruesch, L. Füglister, M. Haller, T. Sommer, A. Zakovorotnyi, Aktives Kühlen von Cool2Regen - Gebäuden mit Wärmepumpen und Erdsonden für hohe Regenerationsgrade, tech. Report, Bundesamt Für Energie, Bern, Switzerland, 2022, https://zenodo.org/record/7472824.

[15] SolSeasStore: saisonale Wärmespeicherung in städtischen Quartieren mit Erdwärmesonden, https://digitalcollection.zhaw.ch/handle/11475/27320, 2022, https://doi.org/10.21256/ZHAW-27320, medium: application/pdf Publisher: Bundesamt für Energie (BFE).

[16] M. Jaszczur, T. Śliwa, The analysis of long-term borehole heat exchanger system exploitation, Comput. Assist. Mech. Eng. Sci. 20 (2017) 227–235, https://cames.ippt.pan.pl/index.php/cames/article/view/68.

[17] E. Zanchini, S. Lazzari, A. Priarone, Long-term performance of large borehole heat exchanger fields with unbalanced seasonal loads and groundwater flow, Energy 38 (2012) 66–77, https://doi.org/10.1016/j.energy.2011.12.038, https://www.sciencedirect.com/science/article/pii/S0360544211008644.

[18] Z. Zhao, Y.-F. Lin, A. Stumpf, X. Wang, Assessing impacts of groundwater on geothermal heat exchangers: a review of methodology and modeling, Renew. Energy 190 (2022) 121–147, https://doi.org/10.1016/j.renene.2022.03.089, https://www.sciencedirect.com/science/article/pii/S0960148122003731.

[19] Y. Li, X. Han, Z. Xiaosong, S. Geng, C. Li, Study the performance of borehole heat exchanger considering layered subsurface based on field investigations, Appl. Therm. Eng. 126 (2017) 296–304, https://doi.org/10.1016/j.applthermaleng.2017.07.109, https://www.webofscience.com/api/gateway?GWVersion=2&SrcAuth=DOISource&SrcApp=WOS&KeyAID=10.1016, wOS:000412251200028.

[20] J. Hu, An improved analytical model for vertical borehole ground heat exchanger with multiple-layer substrates and groundwater flow, Appl. Energy 202 (2017) 537–549, https://doi.org/10.1016/j.apenergy.2017.05.152, https://www.sciencedirect.com/science/article/pii/S0306261917307006.

[21] H. Cho, J.M. Choi, The quantitative evaluation of design parameter's effects on a ground source heat pump system, Renew. Energy 65 (2014) 2–6, https://doi.org/10.1016/j.renene.2013.06.034, https://www.sciencedirect.com/science/article/pii/S0960148113003273.

[22] S.E. Dehkordi, B. Olofsson, R.A. Schincariol, Effect of groundwater flow in vertical and horizontal fractures on borehole heat exchanger temperatures, Bull. Eng. Geol. Environ. 74 (2015) 479–491, https://doi.org/10.1007/s10064-014-0626-4, https://gateway.webofknowledge.com/gateway/Gateway.cgi?GWVersion=2&SrcAuth=DOISource&SrcApp=WOS&KeyAID=10.1007, wOS:000358381900014.

[23] S. Geng, Y. Li, X. Han, H. Lian, H. Zhang, Evaluation of thermal anomalies in multi-boreholes field considering the effects of groundwater flow, Sustainability 8 (2016) 577, https://doi.org/10.3390/su8060577.

[24] P. Hein, O. Kolditz, U.-J. Görke, A. Bucher, H. Shao, A numerical study on the sustainability and efficiency of borehole heat exchanger coupled ground source heat pump systems, Appl. Therm. Eng. 100 (2016) 421–433, https://doi.org/10.1016/j.applthermaleng.2016.02.039, https://www.sciencedirect.com/science/article/pii/S135943111630182X.

[25] J.A. Rivera, P. Blum, P. Bayer, Ground energy balance for borehole heat exchangers: vertical fluxes, groundwater and storage, Renew. Energy 83 (2015) 1341–1351, https://doi.org/10.1016/j.renene.2015.05.051, https://www.sciencedirect.com/science/article/pii/S0960148115300148.

[26] W.J. Eugster, L. Rybach, Sustainable production from borehole heat exchanger systems, in: Proceedings World Geothermal Congress, Secretariat of WGC2000, Tokyo, Japan, 2000, pp. 825–830, https://www.researchgate.net/profile/Ladislaus-Rybach/publication/267998330_Sustainable_production_from_borehole_heat_exchanger_systems/links/5469f2b50cf2397f782f8fe7/Sustainable-production-from-borehole-heat-exchanger-systems.pdf.

[27] S. Signorelli, T. Kohl, L. Rybach, Sustainability of production from borehole heat exchanger fields, in: 29th Workshop on Geothermal Reservoir Engineering, Stanford University Stanford, California, 2004, pp. 1–6.

[28] J. Piotrowska-Woroniak, Assessment of ground regeneration around borehole heat exchangers between heating seasons in cold climates: a case study in bialystok (NE, Poland), Energies 14 (2021) 4793, https://doi.org/10.3390/en14164793, https://www.mdpi.com/1996-1073/14/16/4793.

[29] L. Rybach, Geothermal heat pump production sustainability-the basis of the Swiss GHP success story, Energies 15 (2022) 7870, https://doi.org/10.3390/en15217870, https://www.webofscience.com/api/gateway?GWVersion=2&SrcAuth=DynamicDOIArticle&SrcApp=WOS&KeyAID=10.3390, wOS:000882283300001.

[30] S. Javed, J. Claesson, R. Beier, Recovery times after thermal response tests on vertical borehole heat exchangers, in: Proceedings of 23rd IIR International Congress of Refrigeration (ICR2011), Prague, Czech Republic, 2011.

[31] L. Boban, V. Soldo, J. Stosic, E. Filipovic, F. Tremac, Ground thermal response and recovery after heat injection: experimental investigation, Trans. FAMENA 42 (2018) 39–50, https://doi.org/10.21278/TOF.42Si104, https://gateway.webofknowledge.com/gateway/Gateway.cgi?GWVersion=2&SrcAuth=DynamicDOIArticle&SrcApp=WOS&KeyAID=10.21278, wOS:000456081400005.

[32] S. Koohi-Fayegh, M.A. Rosen, Examination of thermal interaction of multiple vertical ground heat exchangers, Appl. Energy 97 (2012) 962–969, https://doi.org/10.1016/j.apenergy.2012.02.018, https://www.sciencedirect.com/science/article/pii/S0306261912001122.

[33] S. Erol, M.A. Hashemi, B. François, Analytical solution of discontinuous heat extraction for sustainability and recovery aspects of borehole heat exchangers, Int. J. Therm. Sci. 88 (2015) 47–58, https://doi.org/10.1016/j.ijthermalsci.2014.09.007, https://www.sciencedirect.com/science/article/pii/S1290072914002658.

[34] J.D. Spitler, M. Bernier, 2 - Vertical Borehole Ground Heat Exchanger Design Methods, Woodhead Publishing, 2016, pp. 29–61, https://www.sciencedirect.com/science/article/pii/B9780081003114000029.

[35] T. You, W. Wu, B. Wang, W. Shi, X. Li, Dynamic soil temperature of ground-coupled heat pump system in cold region, in: A. Li, Y. Zhu, Y. Li (Eds.), Proceedings of the 8th International Symposium on Heating, Ventilation and Air Conditioning, in: Lecture Notes in Electrical Engineering, Springer, Berlin, Heidelberg, 2014, pp. 439–448, https://link.springer.com/chapter/10.1007/978-3-642-39581-9_44.

[36] D. Roy, T. Chakraborty, D. Basu, B. Bhattacharjee, Feasibility and performance of ground source heat pump systems for commercial applications in tropical and subtropical climates, Renew. Energy 152 (2020) 467–483, https://doi.org/10.1016/j.renene.2020.01.058, https://www.sciencedirect.com/science/article/pii/S096014812030063X.

[37] S. Miglani, K. Orehounig, J. Carmeliet, A methodology to calculate long-term shallow geothermal energy potential for an urban neighbourhood, Energy Build. 159 (2018) 462–473, https://doi.org/10.1016/j.enbuild.2017.10.100, https://www.webofscience.com/api/gateway?GWVersion=2&SrcAuth=DOISource&SrcApp=WOS&KeyAID=10.1016, wOS:000423008200036.

[38] S. Miglani, K. Orehounig, J. Carmeliet, Assessment of the Ground Source Heat Potential at Building Level Applied to an Urban Case Study, ETH, Zurich, 2016, https://www.research-collection.ethz.ch/handle/20.500.11850/187429.

[39] W. Choi, R. Ooka, Y. Nam, Impact of long-term operation of ground-source heat pump on subsurface thermal state in urban areas, Sustain. Cities Soc. 38 (2018) 429–439, https://doi.org/10.1016/j.scs.2017.12.036, https://www.sciencedirect.com/science/article/pii/S221067071731750X.

[40] L. Rybach, P. Bayer, J.A. Rivera, P. Blum, Influence factors in the depth domain of borehole heat exchangers–global warming and urban heating, Eur. Geotherm. Congr. (2016) 2–5.

[41] J.A. Rivera, P. Blum, P. Bayer, Increased ground temperatures in urban areas: estimation of the technical geothermal potential, Renew. Energy 103 (2017) 388–400, https://doi.org/10.1016/j.renene.2016.11.005, https://www.sciencedirect.com/science/article/pii/S0960148116309673.

[42] A. Gultekin, M. Aydin, A. Sisman, Effects of arrangement geometry and number of boreholes on thermal interaction coefficient of multi-borehole heat exchangers, Appl. Energy 237 (2019) 163–170, https://doi.org/10.1016/j.apenergy.2019.01.027, https://www.webofscience.com/api/gateway?GWVersion=2&SrcAuth=DOISource&SrcApp=WOS&KeyAID=10.1016, wOS:000459845100015.

[43] J.C. Choi, J. Park, S.R. Lee, Numerical evaluation of the effects of groundwater flow on borehole heat exchanger arrays, Renew. Energy 52 (2013) 230–240, https://doi.org/10.1016/j.renene.2012.10.028, https://www.sciencedirect.com/science/article/pii/S0960148112006738.

[44] C. Li, J. Mao, H. Zhang, Y. Li, Z. Xing, G. Zhu, Effects of load optimization and geometric arrangement on the thermal performance of borehole heat exchanger fields, Sustain. Cities Soc. 35 (2017) 25–35, https://doi.org/10.1016/j.scs.2017.07.018, https://www.sciencedirect.com/science/article/pii/S2210670717305309.

[45] P. Bayer, M. de Paly, M. Beck, Strategic optimization of borehole heat exchanger field for seasonal geothermal heating and cooling, Appl. Energy 136 (2014) 445–453, https://doi.org/10.1016/j.apenergy.2014.09.029, https://www.webofscience.com/api/gateway?GWVersion=2&SrcAuth=DOISource&SrcApp=WOS&KeyAID=10.1016, wOS:000345725800043.

[46] M. Beck, P. Bayer, M. de Paly, J. Hecht-Méndez, A. Zell, Geometric arrangement and operation mode adjustment in low-enthalpy geothermal borehole fields for heating, Energy 49 (2013) 434–443, https://doi.org/10.1016/j.energy.2012.10.060, https://www.sciencedirect.com/science/article/pii/S036054421200847X.

[47] M. Beck, J. Hecht-Méndez, M. de Paly, P. Bayer, P. Blum, A. Zell, Optimization of the energy extraction of a shallow geothermal system, in: IEEE Congress on Evolutionary Computation, 2010, pp. 1–7, https://ieeexplore.ieee.org/abstract/document/5585921, iSSN: 1941-0026.

[48] W. Retkowski, G. Ziefle, J. Thöming, Evaluation of different heat extraction strategies for shallow vertical ground-source heat pump systems, Appl. Energy 149 (2015) 259–271, https://doi.org/10.1016/j.apenergy.2015.03.004, https://www.sciencedirect.com/science/article/pii/S0306261915002883.

[49] Y. Zhang, X. Yang, J. Liu, B. Liu, F. Tang, H. Nowamooz, Long-term investigation of a borehole heat exchanger (BHE) array with the influence of same inlet temperature (SIT) and same heat load (SHL) boundaries, Adv. Civ. Eng. 2023 (2023) e3232062, https://doi.org/10.1155/2023/3232062, https://www.hindawi.com/journals/ace/2023/3232062/.

[50] T. Coen, B. Francois, P. Gerard, Analytical solution for multi-borehole heat exchangers field including discontinuous and heterogeneous heat loads, Energy Build. 253 (2021) 111520, https://doi.org/10.1016/j.enbuild.2021.111520, https://www.webofscience.com/api/gateway?GWVersion=2&SrcAuth=DynamicDOIArticle&SrcApp=WOS&KeyAID=10.1016, wOS:000711371300004.

[51] M. de Paly, J. Hecht-Mendez, M. Beck, P. Blum, A. Zell, P. Bayer, Optimization of energy extraction for closed shallow geothermal systems using linear programming, Geothermics 43 (2012) 57–65, https://doi.org/10.1016/j.geothermics.2012.03.001, https://www.webofscience.com/api/gateway?GWVersion=2&SrcAuth=DOISource&SrcApp=WOS&KeyAID=10.1016, wOS:000306050800006.

[52] J. Hecht-Méndez, M. de Paly, M. Beck, P. Bayer, Optimization of energy extraction for vertical closed-loop geothermal systems considering groundwater flow, Energy Convers. Manag. 66 (2013) 1–10, https://doi.org/10.1016/j.enconman.2012.09.019, https://www.sciencedirect.com/science/article/pii/S019689041200369X.

[53] R. Fan, Y. Jiang, Y. Yao, D. Shiming, Z. Ma, A study on the performance of a geothermal heat exchanger under coupled heat conduction and groundwater advection, Energy 32 (2007) 2199–2209, https://doi.org/10.1016/j.energy.2007.05.001, https://www.sciencedirect.com/science/article/pii/S0360544207000801.

[54] M. Yu, K. Zhang, X. Cao, A. Hu, P. Cui, Z. Fang, Zoning operation of multiple borehole ground heat exchangers to alleviate the ground thermal accumulation caused by unbalanced seasonal loads, Energy Build. 110 (2016) 345–352, https://doi.org/10.1016/j.enbuild.2015.11.022, https://www.sciencedirect.com/science/article/pii/S0378778815303868.

[55] J. Luo, H. Zhao, J. Jia, W. Xiang, J. Rohn, P. Blum, Study on operation management of borehole heat exchangers for a large-scale hybrid ground source heat pump system in China, Energy 123 (2017) 340–352, https://doi.org/10.1016/j.energy.2017.01.136, https://www.sciencedirect.com/science/article/pii/S0360544217301433.

[56] Y. Shang, M. Dong, S. Li, Intermittent experimental study of a vertical ground source heat pump system, Appl. Energy 136 (2014) 628–635, https://doi.org/10.1016/j.apenergy.2014.09.072, https://www.sciencedirect.com/science/article/pii/S0306261914010204.

[57] L. Xu, L. Pu, S. Zhang, Y. Li, Hybrid ground source heat pump system for overcoming soil thermal imbalance: a review, Sustain. Energy Technol. Assess. 44 (2021) 101098, https://doi.org/10.1016/j.seta.2021.101098, https://www.sciencedirect.com/science/article/pii/S2213138821001089.

[58] E. Bisengimana, J. Zhou, M. Binama, K. Zhao, S. Abbas, Y. Yuan, The frosting and soil imbalance performance issues of building heat pumps: an overview, Energy Build. 273 (2022) 112387, https://doi.org/10.1016/j.enbuild.2022.112387, https://www.sciencedirect.com/science/article/pii/S0378778822005588.

[59] A. Walch, X. Li, J. Chambers, N. Mohajeri, S. Yilmaz, M. Patel, J.-L. Scartezzini, Shallow geothermal energy potential for heating and cooling of buildings with regeneration under climate change scenarios, Energy 244 (2022) 123086, https://doi.org/10.1016/j.energy.2021.123086.

[60] M. Lanahan, P.C. Tabares-Velasco, Seasonal thermal-energy storage: a critical review on BTES systems, modeling, and system design for higher system efficiency, Energies 10 (2017) 743, https://doi.org/10.3390/en10060743, https://www.mdpi.com/1996-1073/10/6/743.

[61] H. Mahon, D. O'Connor, D. Friedrich, B. Hughes, A review of thermal energy storage technologies for seasonal loops, Energy 239 (2022) 122207, https://doi.org/10.1016/j.energy.2021.122207, https://www.sciencedirect.com/science/article/pii/S0360544221024555.

[62] F.M. Rad, A.S. Fung, Solar community heating and cooling system with borehole thermal energy storage, Rev. Syst., Renew. Sustain. Energy Rev.

60 (2016) 1550–1561, https://doi.org/10.1016/j.rser.2016.03.025, https://www.sciencedirect.com/science/article/pii/S1364032116002604.

[63] H. Skarphagen, D. Banks, B.S. Frengstad, H. Gether, Design considerations for borehole thermal energy storage (BTES): a review with emphasis on convective heat transfer, Geofluids 2019 (2019) e4961781, https://doi.org/10.1155/2019/4961781, https://www.hindawi.com/journals/geofluids/2019/4961781/.

[64] Q. Gao, M. Li, M. Yu, J.D. Spitler, Y. Yan, Review of development from GSHP to UTES in China and other countries, Renew. Sustain. Energy Rev. 13 (2009) 1383–1394, https://doi.org/10.1016/j.rser.2008.09.012, https://linkinghub.elsevier.com/retrieve/pii/S136403210800141X.

[65] R. Elhashmi, K.P. Hallinan, A.D. Chiasson, Low-energy opportunity for multi-family residences: a review and simulation-based study of a solar borehole thermal energy storage system, Energy 204 (2020) 117870, https://doi.org/10.1016/j.energy.2020.117870, https://www.sciencedirect.com/science/article/pii/S0360544220309774.

[66] W. Sparber, K. Vajen, S. Herkel, J. Ruschenburg, A. Thür, R. Fedrizzi, M. D'Antoni, Overview on solar thermal plus heat pump systems and review of monitoring results, https://publica.fraunhofer.de/handle/publica/375286, 2011.

[67] G. Emmi, A. Zarrella, M. De Carli, A. Galgaro, An analysis of solar assisted ground source heat pumps in cold climates, Energy Convers. Manag. 106 (2015) 660–675, https://doi.org/10.1016/j.enconman.2015.10.016, https://www.sciencedirect.com/science/article/pii/S0196890415009371.

[68] E. Bertram, J. Glembin, J. Scheuren, G. Zienterra, Soil Regeneration by Unglazed Solar Collectors in Heat Pump Systems, International Solar Energy Society, Johannesburg, South Africa, 2009.

[69] E. Bertram, J. Glembin, G. Rockendorf, Unglazed PVT collectors as additional heat source in heat pump systems with borehole heat exchanger, Energy Proc. 30 (2012) 414–423, https://doi.org/10.1016/j.egypro.2012.11.049, https://www.sciencedirect.com/science/article/pii/S1876610212015652.

[70] N. Fidorów, M. Szulgowska-Zgrzywa, The influence of the ground coupled heat pump's labor on the ground temperature in the boreholes – study based on experimental data, Appl. Therm. Eng. 82 (2015) 237–245, https://doi.org/10.1016/j.applthermaleng.2015.02.035, https://www.sciencedirect.com/science/article/pii/S135943111500143X.

[71] T. You, W. Wu, H. Yang, J. Liu, X. Li, Hybrid photovoltaic/thermal and ground source heat pump: review and perspective, Renew. Sustain. Energy Rev. 151 (2021) 111569, https://doi.org/10.1016/j.rser.2021.111569, https://www.sciencedirect.com/science/article/pii/S1364032121008479.

[72] B. Chhugani, P. Pärisch, S. Helmling, F. Giovannetti, Comparison of PVT - heat pump systems with reference systems for the energy supply of a single-family house, Adv. Sol. Energy 3 (2022) 100031, https://doi.org/10.1016/j.seja.2022.100031, https://www.researchgate.net/publication/366074836_Comparison_of_PVT_-_heat_pump_systems_with_reference_systems_for_the_energy_supply_of_a_single-family_house.

[73] F. Weiland, M. Kirchner, F. Huesing, F. Giovannetti, Solar steel sandwich panels for industrial and commercial buildings: system simulations and potential analysis, in: A. Charalambides, W. Streicher, D. Mugnier (Eds.), Proceedings of the Ises Eurosun 2020 Conference - 13th International Conference on Solar Energy for Buildings and Industry, Intl Solar Energy Soc, Freiburg, 2020, pp. 139–148, https://www.webofscience.com/api/gateway?GWVersion=2&SrcAuth=DOISource&SrcApp=WOS&KeyAID=10.18086, wOS:000836179100014.

[74] V. Trillat-Berdal, B. Souyri, G. Fraisse, Experimental study of a ground-coupled heat pump combined with thermal solar collectors, Energy Build. 38 (2006) 1477–1484, https://doi.org/10.1016/j.enbuild.2006.04.005, https://www.sciencedirect.com/science/article/pii/S0378778806001022.

[75] V. Trillat-Berdal, B. Souyri, G. Achard, Coupling of geothermal heat pumps with thermal solar collectors, Appl. Therm. Eng. 27 (2007) 1750–1755, https://doi.org/10.1016/j.applthermaleng.2006.07.022, https://www.sciencedirect.com/science/article/pii/S1359431106002559.

[76] E. Kjellsson, Solar Heating in Dwellings with Analysis of Combined Solar Collectors and Ground Source Heat Pump, phdthesis, Lund University, Lund, Sweden, 2009, https://lup.lub.lu.se/search/files/3650590/1501885.pdf.

[77] E. Kjellsson, G. Hellström, B. Perers, Optimization of systems with the combination of ground-source heat pump and solar collectors in dwellings, Energy 35 (2010) 2667–2673, https://doi.org/10.1016/j.energy.2009.04.011, https://www.sciencedirect.com/science/article/pii/S036054420900108X.

[78] S. Miglani, K. Orehounig, J. Carmeliet, Design and optimization of a hybrid solar ground source heat pump with seasonal regeneration, Energy Proc. 122 (2017) 1015–1020, https://doi.org/10.1016/j.egypro.2017.07.468, https://www.sciencedirect.com/science/article/pii/S1876610217334288.

[79] S. Miglani, K. Orehounig, J. Carmeliet, Integrating a thermal model of ground source heat pumps and solar regeneration within building energy system optimization, Appl. Energy 218 (2018) 78–94, https://doi.org/10.1016/j.apenergy.2018.02.173, https://www.sciencedirect.com/science/article/pii/S0306261918303076.

[80] E. Bertram, Solar assisted heat pump systems with ground heat exchanger, Simul. Stud., Energy Proc. 48 (2014) 505–514, https://doi.org/10.1016/j.egypro.2014.02.060, https://www.sciencedirect.com/science/article/pii/S1876610214003221.

[81] M. Wasik, M.A. Bugaj, K. Mik, M. Klein, T.S. Wisniewski, P. Chaja, Optimization of PVT geometry in application of ground heat source regeneration, in: Computational Technologies in Engineering (tki'2018), vol. 2078, Amer Inst Physics, Melville, 2019, 020091, https://gateway.webofknowledge.com/gateway/Gateway.cgi?GWVersion=2&SrcAuth=DynamicDOIConfProc&SrcApp=WOS&KeyAID=10.1063, wOS:000472949600091.

[82] D. Sauter, M. Hunziker, J. Poppei, F. Cochand, M. Hubbuch, J. Rohrer, Solar thermal regeneration of borehole heat exchangers in urban and suburban districts, in: J.L. Scartezzini, B. Smith (Eds.), Carbon-Neutral Cities - Energy Efficiency and Renewables in the Digital Era (cisbat 2021), vol. 2042, Iop Publishing Ltd, Bristol, 2021, p. 012094, https://gateway.webofknowledge.com/gateway/Gateway.cgi?GWVersion=2&SrcAuth=DOISource&SrcApp=WOS&KeyAID=10.1088, wOS:000724676100094.

[83] H. Hemmatabady, B. Welsch, J. Formhals, I. Sass, AI-based enviro-economic optimization of solar-coupled and standalone geothermal systems for heating and cooling, Appl. Energy 311 (2022) 118652, https://doi.org/10.1016/j.apenergy.2022.118652, https://www.sciencedirect.com/science/article/pii/S0306261922001209.

[84] F.M. Rad, A.S. Fung, W.H. Leong, Combined solar thermal and ground source heat pump system, in: Proceedings of Building Simulation 2009: 11th Conference of IBPSA, Glasgow, Scotland, 2009, http://ibpsa.org/proceedings/BS2009/BS09_2297_2305.pdf.

[85] C. Xi, L. Lin, Y. Hongxing, Long term operation of a solar assisted ground coupled heat pump system for space heating and domestic hot water, Energy Build. 43 (2011) 1835–1844, https://doi.org/10.1016/j.enbuild.2011.03.033, https://www.sciencedirect.com/science/article/pii/S0378778811001113.

[86] X. Chen, H. Yang, Performance analysis of a proposed solar assisted ground coupled heat pump system, Appl. Energy 97 (2012) 888–896, https://doi.org/10.1016/j.apenergy.2011.11.073, https://www.sciencedirect.com/science/article/pii/S0306261911007793.

[87] R.M. Lazzarin, Dual source heat pump systems: operation and performance, Energy Build. 52 (2012) 77–85, https://doi.org/10.1016/j.enbuild.2012.05.026, https://www.sciencedirect.com/science/article/pii/S0378778812002812.

[88] Q. Si, M. Okumiya, X. Zhang, Performance evaluation and optimization of a novel solar-ground source heat pump system, Energy Build. 70 (2014) 237–245, https://doi.org/10.1016/j.enbuild.2013.11.065, https://www.sciencedirect.com/science/article/pii/S037877881300772X.

[89] S. Awani, R. Chargui, S. Kooli, A. Farhat, A. Guizani, Performance of the coupling of the flat plate collector and a heat pump system associated with a vertical heat exchanger for heating of the two types of greenhouses system, Energy Convers. Manag. 103 (2015) 266–275, https://doi.org/10.1016/j.enconman.2015.06.032, https://www.sciencedirect.com/science/article/pii/S0196890415005737.

[90] H. Wang, C. Qi, Performance study of underground thermal storage in a solar-ground coupled heat pump system for residential buildings, Energy Build. 40 (2008) 1278–1286, https://doi.org/10.1016/j.enbuild.2007.11.009, https://www.sciencedirect.com/science/article/pii/S037877880700271X.

[91] F.M. Rad, A.S. Fung, W.H. Leong, Feasibility of combined solar thermal and ground source heat pump systems in cold climate, Canada, Energy Build. 61 (2013) 224–232, https://doi.org/10.1016/j.enbuild.2013.02.036, https://www.sciencedirect.com/science/article/pii/S0378778813001126.

[92] A. Georgiev, R. Popov, E. Toshkov, Investigation of a hybrid system with ground source heat pump and solar collectors: charging of thermal storages and space heating, Renew. Energy 147 (2020) 2774–2790, https://doi.org/10.1016/j.renene.2018.12.087, https://www.webofscience.com/api/gateway?GWVersion=2&SrcAuth=DOISource&SrcApp=WOS&KeyAID=10.1016, wOS:000504526000019.

[93] K. Bakirci, O. Ozyurt, K. Comakli, O. Comakli, Energy analysis of a solar-ground source heat pump system with vertical closed-loop for heating applications, Energy 36 (2011) 3224–3232, https://doi.org/10.1016/j.energy.2011.03.011, https://www.sciencedirect.com/science/article/pii/S0360544211001678.

[94] C. Xi, Y. Hongxing, L. Lin, W. Jinggang, L. Wei, Experimental studies on a ground coupled heat pump with solar thermal collectors for space heating, Energy 36 (2011) 5292–5300, https://doi.org/10.1016/j.energy.2011.06.037, https://www.sciencedirect.com/science/article/pii/S0360544211004233.

[95] P. Eslami-Nejad, M. Bernier, Coupling of geothermal heat pumps with thermal solar collectors using double U-tube boreholes with two independent circuits, Appl. Therm. Eng. 31 (2011) 3066–3077, https://doi.org/10.1016/j.applthermaleng.2011.05.040, https://www.sciencedirect.com/science/article/pii/S1359431111003000.

[96] P. Eslami-Nejad, M. Bernier, Simulations of a new double u-tube borehole configuration with solar heat injection and ground freezing, in: Proceedings of eSim 2012: The Canadian Conference on Building Simulation, 2012, http://www.solarbuildings.ca/documents/Simulations_of_a_New_Double_U-tube_Borehole_Configuration_with_Solar_Heat_Injection_and_Ground_Freezing.pdf.

[97] J. Danielewicz, N. Fidorow, M. Szulgowska-Zgrzywa, A ground source heat pump with the heat exchanger regeneration-simulation of the system performance in a single family house, in: A. Pawlowski, M.R. Dudzinska, L. Pawlowski (Eds.), Environmental Engineering Iv, Crc Press-Taylor & Francis Group, Boca Raton, 2013, pp. 357–367, https://www.webofscience.com/wos/woscc/full-record/WOS:000342680300050, wOS:000342680300050.

[98] F. Reda, A. Laitinen, Different strategies for long term performance of SAGSHP to match residential energy requirements in a cold climate, Energy Build. 86

(2015) 557–572, https://doi.org/10.1016/j.enbuild.2014.10.056, https://www.sciencedirect.com/science/article/pii/S0378778814009025.
[99] L. Dai, S. Li, L. DuanMu, X. Li, Y. Shang, M. Dong, Experimental performance analysis of a solar assisted ground source heat pump system under different heating operation modes, Appl. Therm. Eng. 75 (2015) 325–333, https://doi.org/10.1016/j.applthermaleng.2014.09.061, https://www.sciencedirect.com/science/article/pii/S1359431114008333.
[100] F. Busato, R. Lazzarin, M. Noro, Ground or solar source heat pump systems for space heating: which is better? Energetic assessment based on a case history, Energy Build. 102 (2015) 347–356, https://doi.org/10.1016/j.enbuild.2015.05.053, https://www.sciencedirect.com/science/article/pii/S0378778815300281.
[101] W. Yang, L. Sun, Y. Chen, Experimental investigations of the performance of a solar-ground source heat pump system operated in heating modes, Energy Build. 89 (2015) 97–111, https://doi.org/10.1016/j.enbuild.2014.12.027, https://www.sciencedirect.com/science/article/pii/S0378778814010780.
[102] K.B. Ooi, M. Noguchi, Verification of the performance of a vertical ground heat exchanger applied to a test house in Melbourne, Australia, Energies 10 (2017), https://doi.org/10.3390/en10101558, https://www.mdpi.com/1996-1073/10/10/1558.
[103] S.S. Abolhassani, M.M. Joybari, M. Hosseini, M. Parsaee, U. Eicker, A systematic methodological framework to study climate change impacts on heating and cooling demands of buildings, J. Build. Eng. 63 (2023) 105428, https://doi.org/10.1016/j.jobe.2022.105428, https://linkinghub.elsevier.com/retrieve/pii/S2352710222014346, num Pages: 34 Patent Number: a Place: Amsterdam Publisher: Elsevier Web of Science ID, WOS:000890659700002.
[104] S. Lazzari, A. Priarone, E. Zanchini, Long-term performance of BHE (borehole heat exchanger) fields with negligible groundwater movement, Energy 35 (2010) 4966–4974, https://doi.org/10.1016/j.energy.2010.08.028, https://www.sciencedirect.com/science/article/pii/S0360544210004640.
[105] E. Halaj, L. Pajak, B. Papiernik, Finite element modeling of geothermal source of heat pump in long-term operation, Energies 13 (2020) 1341, https://doi.org/10.3390/en13061341, https://gateway.webofknowledge.com/gateway/Gateway.cgi?GWVersion=2&SrcAuth=DynamicDOIArticle&SrcApp=WOS&KeyAID=10.3390, wOS:000528727500046.
[106] M. Belliardi, Applied analysis of geocooling technology for a residential building in Lugano, Technical Report, University of Applied Sciences and Arts of Southern Switzerland (SUPSI), 2020.
[107] D. Pahud, M. Belliardi, P. Caputo, Geocooling potential of borehole heat exchangers' systems applied to low energy office buildings, Renew. Energy 45 (2012) 197–204, https://doi.org/10.1016/j.renene.2012.03.008, https://www.sciencedirect.com/science/article/pii/S0960148112001942.
[108] R. Dott, C. Wemhoener, T. Afjei, Hydraulics, performance and comfort of ground coupled heating-cooling systems, in: Y. Jiang, Y.X. Zhu, X.D. Yang, X.T. Li (Eds.), Building Simulation 2007, vols. 1-3, Proceedings, Tsinghua University Press, Beijing, 2007, pp. 657–664, https://www.webofscience.com/wos/woscc/full-record/WOS:000253394500096, wOS:000253394500096.
[109] Y. Hamada, H. Saitoh, M. Nakamura, H. Kubota, K. Ochifuji, Field performance of an energy pile system for space heating, Energy Build. 39 (2007) 517–524, https://doi.org/10.1016/j.enbuild.2006.09.006, https://www.sciencedirect.com/science/article/pii/S037877880600226X.
[110] M. Belliardi, N. Cereghetti, P. Caputo, S. Ferrari, A method to analyze the performance of geocooling systems with borehole heat exchangers. Results in a monitored residential building in southern Alps, Energies 14 (2021) 7407, https://doi.org/10.3390/en14217407, https://www.mdpi.com/1996-1073/14/21/7407.
[111] A. Gasparella, G.A. Longo, R. Marra, Combination of ground source heat pumps with chemical dehumidification of air, Appl. Therm. Eng. 25 (2005) 295–308, https://doi.org/10.1016/j.applthermaleng.2004.06.009, https://www.sciencedirect.com/science/article/pii/S1359431104001644.
[112] U. Eicker, C. Vorschulze, Potential of geothermal heat exchangers for office building climatisation, Renew. Energy 34 (2009) 1126–1133, https://doi.org/10.1016/j.renene.2008.06.019, https://www.sciencedirect.com/science/article/pii/S0960148108002644.
[113] D. Saner, R. Juraske, M. Kuebert, P. Blum, S. Hellweg, P. Bayer, Is it only CO2 that matters? A life cycle perspective on shallow geothermal systems, Renew. Sustain. Energy Rev. 14 (2010) 1798–1813, https://doi.org/10.1016/j.rser.2010.04.002, https://www.webofscience.com/api/gateway?GWVersion=2&SrcAuth=DOISource&SrcApp=WOS&KeyAID=10.1016, wOS:000279258000007.
[114] U. Desideri, N. Sorbi, L. Arcioni, D. Leonardi, Feasibility study and numerical simulation of a ground source heat pump plant, applied to a residential building, Appl. Therm. Eng. 31 (2011) 3500–3511, https://doi.org/10.1016/j.applthermaleng.2011.07.003, https://www.sciencedirect.com/science/article/pii/S1359431111003449.
[115] A. Arteconi, C. Brandoni, G. Rossi, F. Polonara, Experimental evaluation and dynamic simulation of a ground coupled heat pump for a commercial building, Int. J. Energy Res. 37 (2013) 1971–1980, https://doi.org/10.1002/er.3059, https://onlinelibrary.wiley.com/doi/abs/10.1002/er.3059, _eprint: https://onlinelibrary.wiley.com/doi/pdf/10.1002/er.3059.
[116] J. Luo, J. Rohn, M. Bayer, A. Priess, Thermal performance and economic evaluation of double U-tube borehole heat exchanger with three different borehole diameters, Energy Build. 67 (2013) 217–224, https://doi.org/10.1016/j.enbuild.2013.08.030, https://www.sciencedirect.com/science/article/pii/S0378778813005276.
[117] J. Luo, J. Rohn, M. Bayer, A. Priess, L. Wilkmann, W. Xiang, Heating and cooling performance analysis of a ground source heat pump system in Southern Germany, Geothermics 53 (2015) 57–66, https://doi.org/10.1016/j.geothermics.2014.04.004, https://www.sciencedirect.com/science/article/pii/S0375650514000418.
[118] W. Wu, T. You, B. Wang, W. Shi, X. Li, Evaluation of ground source absorption heat pumps combined with borehole free cooling, Energy Convers. Manag. 79 (2014) 334–343, https://doi.org/10.1016/j.enconman.2013.11.045, https://www.sciencedirect.com/science/article/pii/S0196890413007668.
[119] Y. Man, H. Yang, Y. Qu, Z. Fang, Feasibility investigation of the low energy consumption cooling mode with ground heat exchanger and terminal radiator, Proc. Eng. 121 (2015) 423–429, https://doi.org/10.1016/j.proeng.2015.08.1088, https://www.sciencedirect.com/science/article/pii/S1877705815028167.
[120] F. Piscaglia, A. Blasi, S. Del Moro, F. Polonara, A. Arteconi, L. Zanarelli, A. Renzulli, Monitoring of a vertical borehole ground-coupled heat pump system: a case study from a marly-limestone heat reservoir (Urbino, Central Italy), Geothermics 62 (2016) 61–69, https://doi.org/10.1016/j.geothermics.2016.02.008, https://www.webofscience.com/api/gateway?GWVersion=2&SrcAuth=DOISource&SrcApp=WOS&KeyAID=10.1016, wOS:000376709300006.
[121] A. Speerforck, G. Schmitz, Experimental investigation of a ground-coupled desiccant assisted air conditioning system, Appl. Energy 181 (2016) 575–585, https://doi.org/10.1016/j.apenergy.2016.08.036, https://www.sciencedirect.com/science/article/pii/S0306261916311230.
[122] P. Niemann, F. Richter, A. Speerforck, G. Schmitz, Desiccant-assisted air conditioning system relying on solar and geothermal energy during summer and winter, Energies 12 (2019) 3175, https://doi.org/10.3390/en12163175, https://www.mdpi.com/1996-1073/12/16/3175.
[123] K. Allaerts, J. Al Koussa, J. Desmedt, R. Salenbien, Improving the energy efficiency of ground-source heat pump systems in heating dominated school buildings: a case study in Belgium, Energy Build. 138 (2017) 559–568, https://doi.org/10.1016/j.enbuild.2016.09.046, https://www.webofscience.com/api/gateway?GWVersion=2&SrcAuth=DOISource&SrcApp=WOS&KeyAID=10.1016, wOS:000394061200049.
[124] N. Fidorow-Kaprawy, L. Stefaniak, Potential of co2 emission reduction via application of geothermal heat exchanger and passive cooling in residential sector under Polish climatic conditions, Energies 15 (2022), https://doi.org/10.3390/en15228531.
[125] L. Schibuola, C. Tambani, A. Zarrella, M. Scarpa, Ground source heat pump performance in case of high humidity soil and yearly balanced heat transfer, Energy Convers. Manag. 76 (2013) 956–970, https://doi.org/10.1016/j.enconman.2013.09.002, https://www.sciencedirect.com/science/article/pii/S0196890413005323.
[126] W. Wu, T. You, B. Wang, W. Shi, X. Li, Simulation of a combined heating, cooling and domestic hot water system based on ground source absorption heat pump, Appl. Energy 126 (2014) 113–122, https://doi.org/10.1016/j.apenergy.2014.04.006, https://www.sciencedirect.com/science/article/pii/S0306261914003390.
[127] W. Wu, X. Li, T. You, B. Wang, W. Shi, Combining ground source absorption heat pump with ground source electrical heat pump for thermal balance, higher efficiency and better economy in cold regions, Renew. Energy 84 (2015) 74–88, https://doi.org/10.1016/j.renene.2015.06.025, https://www.sciencedirect.com/science/article/pii/S0960148115300483.
[128] M.R. Ally, J.D. Munk, V.D. Baxter, A.C. Gehl, Exergy analysis of a two-stage ground source heat pump with a vertical bore for residential space conditioning under simulated occupancy, Appl. Energy 155 (2015) 502–514, https://doi.org/10.1016/j.apenergy.2015.06.004, https://www.sciencedirect.com/science/article/pii/S0306261915007497.
[129] A. Hepbasli, Performance evaluation of a vertical ground-source heat pump system in Izmir, Turkey, Int. J. Energy Res. 26 (2002) 1121–1139, https://doi.org/10.1002/er.839, https://onlinelibrary.wiley.com/doi/abs/10.1002/er.839, _eprint: https://onlinelibrary.wiley.com/doi/pdf/10.1002/er.839.
[130] A. Hepbasli, O. Akdemir, E. Hancioglu, Experimental study of a closed loop vertical ground source heat pump system, Energy Convers. Manag. 44 (2003) 527–548, https://doi.org/10.1016/S0196-8904(02)00073-0, https://www.sciencedirect.com/science/article/pii/S0196890402000730.
[131] Y. Hwang, J.-K. Lee, Y.-M. Jeong, K.-M. Koo, D.-H. Lee, I.-K. Kim, S.-W. Jin, S.H. Kim, Cooling performance of a vertical ground-coupled heat pump system installed in a school building, Renew. Energy 34 (2009) 578–582, https://doi.org/10.1016/j.renene.2008.05.042, https://www.sciencedirect.com/science/article/pii/S096014810800236X.
[132] T. Magraner, A. Montero, S. Quilis, J.F. Urchueguía, Comparison between design and actual energy performance of a HVAC-ground coupled heat pump system in cooling and heating operation, Energy Build. 42 (2010) 1394–1401, https://doi.org/10.1016/j.enbuild.2010.03.008, https://www.sciencedirect.com/science/article/pii/S037877881000085X.
[133] S. Ikeda, W. Choi, R. Ooka, Optimization method for multiple heat source operation including ground source heat pump considering dynamic variation in ground temperature, Appl. Energy 193 (2017) 466–478, https://doi.org/10.1016/j.apenergy.2017.02.047, https://www.sciencedirect.com/science/article/pii/S0306261917301903.
[134] N. Pandey, K. Murugesan, H.R. Thomas, Optimization of ground heat exchangers for space heating and cooling applications using Taguchi method and utility concept, Appl. Energy 190 (2017) 421–438, https://

doi.org/10.1016/j.apenergy.2016.12.154, https://www.sciencedirect.com/science/article/pii/S0306261916319341.
[135] S. Kumar, K. Murugesan, Optimization of geothermal interaction of a double U-tube borehole heat exchanger for space heating and cooling applications using Taguchi method and utility concept, Geothermics 83 (2020) 101723, https://doi.org/10.1016/j.geothermics.2019.101723, https://www.sciencedirect.com/science/article/pii/S0375650519300537.
[136] B. Xiang, Y. Ji, Y. Yuan, D. Wu, C. Zeng, J. Zhou, 10-year simulation of photovoltaic-thermal road assisted ground source heat pump system for accommodation building heating in expressway service area, Sol. Energy 215 (2021) 459–472, https://doi.org/10.1016/j.solener.2020.12.056, https://www.sciencedirect.com/science/article/pii/S0038092X20313153.
[137] K. Wang, N. Li, J. Peng, X. Wang, C. Wang, M. Wang, A highly efficient solution for thermal compensation of ground-coupled heat pump systems and waste heat recovery of kitchen exhaust air, Energy Build. 138 (2017) 499–513, https://doi.org/10.1016/j.enbuild.2016.12.023, https://www.sciencedirect.com/science/article/pii/S0378778816318060.
[138] L.-X. Wu, M.-Y. Zheng, Research of combined heating and cooling by solar ground-source heat pump and PCM thermal storage, Am. Soc. Mech. Eng. Digit. Coll. (2005) 275–282, https://doi.org/10.1115/ISEC2005-76045, https://dx.doi.org/10.1115/ISEC2005-76045.
[139] X. Wang, M. Zheng, W. Zhang, S. Zhang, T. Yang, Experimental study of a solar-assisted ground-coupled heat pump system with solar seasonal thermal storage in severe cold areas, Energy Build. 42 (2010) 2104–2110, https://doi.org/10.1016/j.enbuild.2010.06.022, https://www.sciencedirect.com/science/article/pii/S037877881000215X.
[140] E. Wang, A.S. Fung, C. Qi, W.H. Leong, Performance prediction of a hybrid solar ground-source heat pump system, Energy Build. 47 (2012) 600–611, https://doi.org/10.1016/j.enbuild.2011.12.035, https://www.sciencedirect.com/science/article/pii/S0378778811006542.
[141] T. You, B. Wang, W. Wu, W. Shi, X. Li, Performance analysis of hybrid ground-coupled heat pump system with multi-functions, Energy Convers. Manag. 92 (2015) 47–59, https://doi.org/10.1016/j.enconman.2014.12.036, https://www.sciencedirect.com/science/article/pii/S0196890414010759.
[142] F. Reda, N. Arcuri, P. Loiacono, D. Mazzeo, Energy assessment of solar technologies coupled with a ground source heat pump system for residential energy supply in Southern European climates, Energy 91 (2015) 294–305, https://doi.org/10.1016/j.energy.2015.08.040, https://www.sciencedirect.com/science/article/pii/S0360544215011147.
[143] Y. Wang, Y. Zhang, J. Hao, H. Pan, Y. Ni, J. Di, Z. Ge, Q. Chen, M. Guo, Modeling and operation optimization of an integrated ground source heat pump and solar PVT system based on heat current method, Sol. Energy 218 (2021) 492–502, https://doi.org/10.1016/j.solener.2021.03.003, https://www.sciencedirect.com/science/article/pii/S0038092X21001833.
[144] Z. Qi, Q. Gao, Y. Liu, Y.Y. Yan, J.D. Spitler, Status and development of hybrid energy systems from hybrid ground source heat pump in China and other countries, Renew. Sustain. Energy Rev. 29 (2014) 37–51, https://doi.org/10.1016/j.rser.2013.08.059, https://www.sciencedirect.com/science/article/pii/S1364032113005996.
[145] H. Yang, P. Cui, Z. Fang, Vertical-borehole ground-coupled heat pumps: a review of models and systems, Appl. Energy 87 (2010) 16–27, https://doi.org/10.1016/j.apenergy.2009.04.038, https://www.sciencedirect.com/science/article/pii/S0306261909001743.
[146] K. Balaji, V. Sharma, Energy demand reduction in the built environment using shallow geothermal integrated energy systems: Part II—hybrid ground source heat pump for building heating, ASME J. Eng. Sustain. Build. Cities 2 (2021), https://doi.org/10.1115/1.4052215.
[147] X.Q. Zhai, M. Qu, X. Yu, Y. Yang, R.Z. Wang, A review for the applications and integrated approaches of ground-coupled heat pump systems, Renew. Sustain. Energy Rev. 15 (2011) 3133–3140, https://doi.org/10.1016/j.rser.2011.04.024, https://www.sciencedirect.com/science/article/pii/S1364032111001687.
[148] O. Zogou, A. Stamatelos, Effect of climatic conditions on the design optimization of heat pump systems for space heating and cooling, Energy Convers. Manag. 39 (1998) 609–622, https://doi.org/10.1016/S0196-8904(97)00050-2, https://www.sciencedirect.com/science/article/pii/S0196890497000502.
[149] J.F. Urchueguía, M. Zacarés, J.M. Corberán, A. Montero, J. Martos, H. Witte, Comparison between the energy performance of a ground coupled water to water heat pump system and an air to water heat pump system for heating and cooling in typical conditions of the European Mediterranean coast, Energy Convers. Manag. 49 (2008) 2917–2923, https://doi.org/10.1016/j.enconman.2008.03.001, https://www.sciencedirect.com/science/article/pii/S0196890408000939.
[150] C. Montagud, J.M. Corberán, A. Montero, J.F. Urchueguía, Analysis of the energy performance of a ground source heat pump system after five years of operation, Energy Build. 43 (2011) 3618–3626, https://doi.org/10.1016/j.enbuild.2011.09.036, https://www.sciencedirect.com/science/article/pii/S0378778811004385.
[151] C. Montagud, J.M. Corberán, F. Ruiz-Calvo, Experimental and modeling analysis of a ground source heat pump system, Appl. Energy 109 (2013) 328–336, https://doi.org/10.1016/j.apenergy.2012.11.025, https://www.sciencedirect.com/science/article/pii/S0306261912008185.
[152] F. Ruiz-Calvo, J. Cervera-Vázquez, C. Montagud, J.M. Corberán, Reference data sets for validating and analyzing GSHP systems based on an eleven-year operation period, Geothermics 64 (2016) 538–550, https://doi.org/10.1016/j.geothermics.2016.08.004, https://www.sciencedirect.com/science/article/pii/S0375650516300839.
[153] X. Yu, R.Z. Wang, X.Q. Zhai, Year round experimental study on a constant temperature and humidity air-conditioning system driven by ground source heat pump, Energy 36 (2011) 1309–1318, https://doi.org/10.1016/j.energy.2010.11.013, https://www.sciencedirect.com/science/article/pii/S0360544210006390.
[154] X.Q. Zhai, X.L. Wang, H.T. Pei, Y. Yang, R.Z. Wang, Experimental investigation and optimization of a ground source heat pump system under different indoor set temperatures, Appl. Therm. Eng. 48 (2012) 105–116, https://doi.org/10.1016/j.applthermaleng.2012.05.005, https://www.sciencedirect.com/science/article/pii/S1359431112003559.
[155] Z. Zhao, R. Shen, W. Feng, Y. Zhang, Y. Zhang, Soil Thermal Balance Analysis for a Ground Source Heat Pump System in a Hot-Summer and Cold-Winter Region, Energies, vol. 11, Multidisciplinary Digital Publishing Institute, 2018, p. 1206, https://www.mdpi.com/1996-1073/11/5/1206, number: 5 Publisher.
[156] X. Li, Z. Chen, J. Zhao, Simulation and experiment on the thermal performance of U-vertical ground coupled heat exchanger, Appl. Therm. Eng. 26 (2006) 1564–1571, https://doi.org/10.1016/j.applthermaleng.2005.12.007, https://www.sciencedirect.com/science/article/pii/S1359431105004199.
[157] A. Michopoulos, D. Bozis, P. Kikidis, K. Papakostas, N.A. Kyriakis, Three-years operation experience of a ground source heat pump system in Northern Greece, Energy Build. 39 (2007) 328–334, https://doi.org/10.1016/j.enbuild.2006.08.002, https://www.sciencedirect.com/science/article/pii/S0378778806001964.
[158] S. Li, W. Yang, X. Zhang, Soil temperature distribution around a U-tube heat exchanger in a multi-function ground source heat pump system, Appl. Therm. Eng. 29 (2009) 3679–3686, https://doi.org/10.1016/j.applthermaleng.2009.06.025, https://www.sciencedirect.com/science/article/pii/S1359431109002002.
[159] M. Cucumo, V. Ferraro, D. Kaliakatsos, M. Mele, G. Barci, Performance of a field of geothermal probes to support the air conditioning plant of a public building powered by water/water heat pumps, Int. J. Heat Technol. 34 (2016) S535–S544, https://doi.org/10.18280/ijht.34S248, https://www.webofscience.com/api/gateway?GWVersion=2&SrcAuth=DOISource&SrcApp=WOS&KeyAID=10.18280, wOS:000389215800049.
[160] J. Wrobel, G. Schmitz, Geothermal- and solar assisted air conditioning system, in: International Refrigeration and Air Conditioning Conference, Purdue University, West Lafayette, USA, 2012, https://docs.lib.purdue.edu/iracc/1276.
[161] J. Wrobel, P. Sanabria Walter, G. Schmitz, Performance of a solar assisted air conditioning system at different locations, Sol. Energy 92 (2013) 69–83, https://doi.org/10.1016/j.solener.2013.02.030, https://www.sciencedirect.com/science/article/pii/S0038092X13000959.
[162] K. Allaerts, M. Coomans, R. Salenbien, Hybrid ground-source heat pump system with active air source regeneration, Energy Convers. Manag. 90 (2015) 230–237, https://doi.org/10.1016/j.enconman.2014.11.009, https://www.webofscience.com/api/gateway?GWVersion=2&SrcAuth=DOISource&SrcApp=WOS&KeyAID=10.1016, wOS:000348886800023.
[163] K.F. Beckers, G.A. Aguirre, J.W. Tester, Hybrid ground-source heat pump systems for cooling-dominated applications: experimental and numerical case-study of cooling for cellular tower shelters, Energy Build. 177 (2018) 341–350, https://doi.org/10.1016/j.enbuild.2018.08.005, https://www.sciencedirect.com/science/article/pii/S0378778818304444.
[164] G. Phetteplace, W. Sullivan, Performance of a hybrid ground-coupled heat pump system, in: ASHRAE winter meeting, San Francisco, CA (United States), 17-21 Jan 1998, ASHRAE Trans., Part 1B: Symp. Pap. 104 (1998), 1162 p., https://www.osti.gov/biblio/649409.
[165] Y. Man, H. Yang, J. Wang, Study on hybrid ground-coupled heat pump system for air-conditioning in hot-weather areas like Hong Kong, Appl. Energy 87 (2010) 2826–2833, https://doi.org/10.1016/j.apenergy.2009.04.044, https://www.sciencedirect.com/science/article/pii/S0306261909001767.
[166] S.P. Kavanaugh, K. Rafferty, Ground Source Heat Pumps: Design of Geothermal Systems for Commercial and Institutional Buildings, 1997.
[167] S.P. Kavanaugh, A design method for hybrid ground-source heat pumps, ASHRAE Trans. 104 (1998) 691.
[168] C. Yavuzturk, J. Spitler, Comparative study of operating and control strategies for hybrid ground-source heat pump systems using a short time step simulation model, ASHRAE Trans. 106 (2) (2000) 192–209.
[169] R. Fan, Y. Jiang, Y. Yao, Z. Ma, Theoretical study on the performance of an integrated ground-source heat pump system in a whole year, Energy 33 (2008) 1671–1679, https://doi.org/10.1016/j.energy.2008.07.017, https://www.sciencedirect.com/science/article/pii/S0360544208001849.
[170] N. Zhu, P. Hu, Y. Lei, Z. Jiang, F. Lei, Numerical study on ground source heat pump integrated with phase change material cooling storage system in office building, Appl. Therm. Eng. 87 (2015) 615–623, https://doi.org/10.1016/j.applthermaleng.2015.05.056, https://www.sciencedirect.com/science/article/pii/S1359431115005128.
[171] P. Shang, C. Chen, K. Li, J. Lin, J. Wu, Feasibility study of a novel soil thermal recovery method for HGSHP system, Proc. Eng. 146 (2016) 586–593, https://doi.org/10.1016/j.proeng.2016.06.406, https://www.sciencedirect.com/science/article/pii/S1877705816308621.
[172] S. Hackel, Optimization of hybrid geothermal heat pump systems, https://www.semanticscholar.org/paper/OPTIMIZATION-OF-HYBRID-GEOTHERMAL-

HEAT-PUMP-SYSTEMS-Hackel/f66f30fd8804d03468674b244b192fda8accc43e, 2008.

[173] S. Hackel, A. Pertzborn, Effective design and operation of hybrid ground-source heat pumps: three case studies, Energy Build. 43 (2011) 3497–3504, https://doi.org/10.1016/j.enbuild.2011.09.014, https://www.sciencedirect.com/science/article/pii/S0378778811004026.

[174] H. Park, J.S. Lee, W. Kim, Y. Kim, The cooling seasonal performance factor of a hybrid ground-source heat pump with parallel and serial configurations, Appl. Energy 102 (2013) 877–884, https://doi.org/10.1016/j.apenergy.2012.09.035, https://www.sciencedirect.com/science/article/pii/S0306261912006769.

[175] W. Cui, S. Zhou, X. Liu, Optimization of design and operation parameters for hybrid ground-source heat pump assisted with cooling tower, Energy Build. 99 (2015) 253–262, https://doi.org/10.1016/j.enbuild.2015.04.034, https://www.sciencedirect.com/science/article/pii/S0378778815003333.

[176] J.B. Singh, G. Foster, Advantages of using the hybrid geothermal option, in: The Second Stockton International Geothermal Conference, the Richard Stockton College of New Jersey, 1998, http://styx.geo-phys.stockton.edu/proceedings/hybri/singh/singh.PDF, https://citeseerx.ist.psu.edu/doc/10.1.1.504.2695.

[177] M. Ramamoorthy, H. Jin, A.D. Chaisson, J.D. Spitler, Optimal sizing of hybrid ground-source heat pump systems that use a cooling pond as a supplemental heat rejecter-A system simulation approach, ASHRAE Trans. 107 (2001) 26–38, https://scholar.google.de/scholar?hl=de&as_sdt=0, Ramamoorthy M., Jin H., Chiasson A.D., Spitler J.D., Optimal sizing of hybrid ground-source heat pump systems that use a cooling pond.

[178] Y. Man, H. Yang, J.D. Spitler, Z. Fang, Feasibility study on novel hybrid ground coupled heat pump system with nocturnal cooling radiator for cooling load dominated buildings, Appl. Energy 88 (2011) 4160–4171, https://doi.org/10.1016/j.apenergy.2011.04.035, https://www.sciencedirect.com/science/article/pii/S0306261911002571.

[179] Y. Man, H. Yang, Z. Fang, Study on hybrid ground-coupled heat pump systems, Energy Build. 40 (2008) 2028–2036, https://doi.org/10.1016/j.enbuild.2008.05.010, https://www.sciencedirect.com/science/article/pii/S037877880800128X.

[180] Z. Liu, Y. Li, W. Xu, H. Yin, J. Gao, G. Jin, L. Lun, G. Jin, Performance and feasibility study of hybrid ground source heat pump system assisted with cooling tower for one office building based on one Shanghai case, Energy 173 (2019) 28–37, https://doi.org/10.1016/j.energy.2019.02.061, https://www.sciencedirect.com/science/article/pii/S0360544219302567.

[181] P. Bayer, D. Saner, S. Bolay, L. Rybach, P. Blum, Greenhouse gas emission savings of ground source heat pump systems in Europe: a review, Renew. Sustain. Energy Rev. 16 (2012) 1256–1267, https://doi.org/10.1016/j.rser.2011.09.027, https://www.sciencedirect.com/science/article/pii/S1364032111004771.

[182] J.W. Lund, A.N. Toth, Direct utilization of geothermal energy 2020 worldwide review, Geothermics 90 (2021) 101915, https://doi.org/10.1016/j.geothermics.2020.101915, https://www.sciencedirect.com/science/article/pii/S0375650520302078.

[183] S. Gehlin, J.D. Spitler, Final Report Annex 52: Long-term performance monitoring of GSHP systems for commercial, institutional, and multi-family buildings, Technical Report, Heat Pump Centre, Borås, Sweden, 2022, https://heatpumpingtechnologies.org/publications/final-report-annex-52-long-term-performancemonitoring-of-gshp-systems-for-commercial-institutional-and-multi-family-buildings/.

[184] F. Bockelmann, M.N. Fisch, It works—long-term performance measurement and optimization of six ground source heat pump systems in Germany, Energies 12 (2019) 4691, https://doi.org/10.3390/en12244691, https://www.mdpi.com/1996-1073/12/24/4691, Publisher: Multidisciplinary Digital Publishing Institute.

[185] P. Pärisch, O. Mercker, P. Oberdorfer, E. Bertram, R. Tepe, G. Rockendorf, Short-term experiments with borehole heat exchangers and model validation in TRNSYS, Renew. Energy 74 (2015) 471–477, https://doi.org/10.1016/j.renene.2014.07.052, https://www.sciencedirect.com/science/article/pii/S0960148114004509.

[186] C. Zhang, Y. Wang, Y. Liu, X. Kong, Q. Wang, Computational methods for ground thermal response of multiple borehole heat exchangers: a review, Renew. Energy 127 (2018) 461–473, https://doi.org/10.1016/j.renene.2018.04.083, https://www.webofscience.com/api/gateway?GWVersion=2&SrcAuth=DOISource&SrcApp=WOS&KeyAID=10.1016, wOS:000437077300041.

[187] A. Huber, O. Schuler, Berechnungsmodul für erdwärmesonden, BFE Projekt, 1997.

[188] L. Rybach, R.J. Hopkirk, Shallow and deep borehole heat exchangers - achievements and prospects, in: Pro. World Geothermal Congress, vol. 1995, 1995, pp. 2133–2139.