nature reviews earth & environment
https://doi.org/10.1038/s43017-025-00736-0

Review article

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Opportunities, benefits and impacts of shallow geothermal energy

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Abstract

Heat pumps, which transfer heat from one environment to another to provide heating and cooling, are considered a key technology for decarbonizing the building sector. However, geothermal heat pumps have been adopted slowly, owing to high investment costs and public distrust. In this Review, we discuss opportunities for sustainable and risk-conscious application of shallow geothermal energy (SGE) and identify suitable areas and outline the benefits and impacts of different SGE technologies. Globally, many regions have wide areas suitable for SGE, yet uptake rates remain low. For example, a third of Germany is hydrogeologically suitable for aquifer thermal energy storage systems, but only two systems were in operation in 2021. The environmental benefits of SGE are substantial, as greenhouse gas emissions can be reduced by up to 88% in European Union countries compared with conventional thermal energy systems. Environmental impacts on groundwater quality and ecosystem functions are minor as SGE-induced temperature increases are typically in the range of 5–10 K. However, owing to the limited number of assessments, benefits and impacts of subsurface cooling remain largely unknown. Widespread and sustainable operation of SGE will require subsurface management with particular focus on infrastructure, drinking water quality and thermal alterations.

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Key points

- There are suitable conditions for shallow geothermal applications across wide areas of Europe and Asia. However, direct geothermal use for residential heating and cooling is still a niche technology.
- Ground-source heat pumps have greater environmental advantages over air-source heat pumps, with 25% lower electricity consumption, 13–43% lower greenhouse gas emissions and reduced strain on the electricity grid.
- Shallow geothermal energy systems — with seasonal storage of heat — offer even greater environmental benefits, reducing greenhouse gas emissions and energy consumption by up to 74% and 70%, respectively, compared with conventional thermal energy systems, with payback times as low as 2 years.
- Shallow geothermal energy offers various site-specific, secondary benefits, such as reduced deforestation and noise levels, and improved air quality and economic growth; however, these benefits have been overlooked.
- Although the potential environmental impacts of shallow geothermal energy are generally minor, effects on locally specific groundwater fauna and corresponding ecosystem services might vary and deserve more attention in future research.

Introduction

Despite the global transition towards renewable power generation being in full swing, the share of renewables in the building sector increases slowly[1]. Utilizing environmental heat from air, surface water or the ground (the subsurface) via heat pumps is considered a key technology to achieve decarbonization of the building sector. Compared with air-source heat pump (ASHP) systems, shallow geothermal energy (SGE), including groundwater-source and ground-source systems, can provide higher efficiencies[2,3], lower environmental impacts[4], increase longevity of the heat pump[5,6] and balance seasonal mismatches in energy demand through thermal energy storage[7]. For example, ground-source heat pumps (GSHPs) consume roughly 25% less electricity than ASHPs and put less strain on electricity grids during severe weather conditions. Although GSHP systems have higher investment costs, they are advantageous against ASHPs in terms of relative payback times (2–20 years for ASHP versus GSHP)[5,6,8].

However, GSHPs only made up ~3.5% of global heat pump market in 2025. The heat pump boom during 2019–2023 that increased sales of heat pumps for buildings by 24% (ref. 9) is mainly driven by ASHPs[10]. The adoption of GSHP is often restrained by distrust, low consumer awareness, uncertainty in subsurface properties and a lack of skilled planners and installers[11,12]. As a result, direct utilization of deep and shallow geothermal heat is still a niche technology that provided only 0.9% of global heating demand for buildings in 2019 (ref. 13). More than 6.5 million geothermal heat pumps were in operation for heat generation[14] across 58 countries in 2021 (Fig. 1).

A diverse suite of SGE technologies allows for a flexible integration based on the local thermal, hydraulic and geological conditions and heating and cooling demands[15] (Box 1). SGE systems are classified by the installation of the ground loop into open-loop and closed-loop systems and separated from deep geothermal systems by lower depth (typically <400 m) and temperatures (typically <25 °C). Open-loop system, such as groundwater heat pump (GWHP) systems, use pumped groundwater as a heat source. Closed-loop systems pump a heat carrier fluid through tubes installed in a ground loop and are summarized as GSHP systems. Ground loops are often installed horizontally as heat collector (HC) systems, which are also termed very shallow geothermal systems[16], or vertically as borehole heat exchangers (BHEs). Open-loop systems that use groundwater for seasonal or short-term storage of heat are referred to as aquifer thermal energy storage (ATES) systems, whereas borehole thermal energy storage (BTES) systems use BHE for heat storage in closed-loop systems.

Hybrid systems (for example, GSHPs combined with solar thermal collectors or ASHPs) offer higher overall system efficiencies and greater opportunities for balanced local heating and cooling demands[17]. SGE is a key component in fifth-generation district heating and cooling networks, operating at low or ambient temperature level[18]. However, the lack of knowledge about benefits of SGE by the public is a barrier for expansion of these low-temperature technologies[19]. Although the city-scale potential of SGE[20], geothermal storage[21], modelling and optimization approaches for SGE systems[22] have been systematically investigated, global SGE potential and related environmental issues and benefits have not been reviewed.

In this Review, we present an overview of SGE installation worldwide and existing assessments of the suitability of the subsurface to host different SGE system types. First, we examine the shallow geothermal potential by compiling a global suitability map for closed-loop and open-loop SGE systems, including thermal storage. We then outline the environmental benefits of SGE reported from different regions and case studies and identify components and processes that need further assessment. Finally, we discuss the potential geotechnical risks and detrimental thermal, microbiological and ecological effects of different SGE systems. Future work should be focused on developing refined modelling approaches making best-possible use of the often-limited amount of available data and integrating these approaches into subsurface management strategies to minimize or avoid use conflicts.

Opportunities

To identify suitable areas for SGE, the so-called geothermal potential is often assessed using geospatial data on different scales[20]. The suitability or potential of SGE is mainly determined by geological and hydrogeological conditions, the accessibility of subsurface and surface space and the heating and cooling demand to be covered. On large scales, suitability assessments are mostly qualitative or semi-quantitative. On small scales, the availability of subsurface data and the applicability of modelling tools allow for a quantitative assessment of geothermal potential. The diverse facets of SGE can be transferred into several types of geothermal potential[20,23]: theoretical, technical, economic, acceptable or market potential and useful potential.

Depending on the target technology, shallow[20] (GSHP, GWHP, ATES and BTES; Box 1) and very shallow geothermal potentials for horizontal HCs[16] (Box 1) can be further distinguished. Potentials across different scales are now discussed.

Global potential

Assessments on a global scale address the suitability of SGE systems qualitatively, distinguishing very well to very poorly suited areas based on traffic-light approaches. Geographic information system (GIS)-based, multicriteria decision analysis is commonly used, combined with

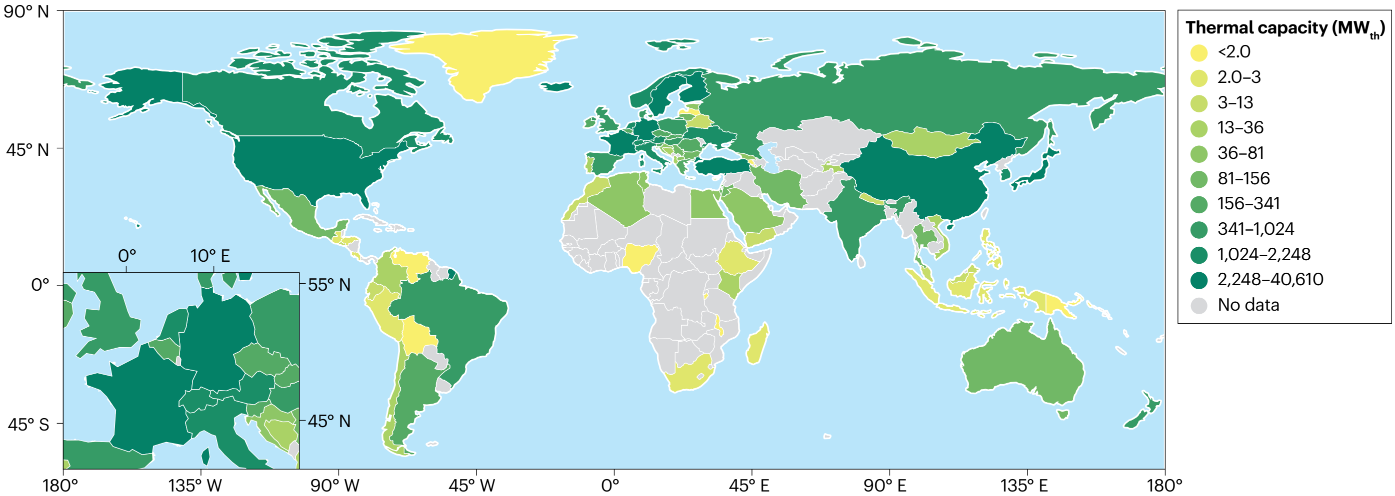


Fig. 1 | Worldwide application of shallow geothermal energy. Installed thermal capacity of direct geothermal energy utilization for different regions worldwide (data from Lund and Toth[199], excluding heat and cold storage through aquifer thermal energy storage and borehole thermal energy storage systems). Installed capacities vary widely across the world, with highest numbers in North America, Europe and East Asia.

geological and hydrogeological[24], as well as socioeconomic information, such as population density[25], gross domestic product per capita[25] or water poverty index[25]. As detailed thermal demand data are not available on a global scale, indicators, such as climate zones[24] or air temperatures[25], are often used as a proxy for thermal energy demands. So far, to our best knowledge, global assessments only exist for ATES[24,25].

The suitability of open-loop and closed-loop systems is assessed by a multicriteria decision analysis approach[24]. The suitability analysis uses global data sets on local aquifer type[24,26], depth to groundwater table[27], near-surface (<100 m depth) permeability[28] and the absolute difference between heating and cooling degree days[29]; a balanced thermal demand is favourable for long-term operation (even if thermal storage is not intended[30]). For the suitability of closed-loop SGE systems, degree day data are also used, in addition to typical thermal conductivities per rock type[31] assigned to a global lithology map[32] and the aquifer type[26] to account for favourable heat transfer conditions in aquifers[33]. For suitability classification, five distinct categories are identified (Fig. 2) using the scheme of the ATES map of Germany[34]. More details on the methodology and data are provided in Supplementary Note 1.

SGE is well suited for areas with major groundwater basins owing to the high thermal conductivity of these basins (Fig. 2). The applicability of SGE in permafrost and low rainfall areas is limited, yet the extent of these areas is likely to decrease and increase, respectively, with future climate change. The same is true for future degree days, which will shift areas with a balanced thermal demand to higher latitudes[24,34].

Similar to previous assessments of ATES[24,25], open-loop systems highlight wide well-suited areas in Europe, South America and the Southeast of the USA (Fig. 2). However, many regions in lower latitudes, for example, Central America, India and China, are moderately suitable, which have previously been identified as poorly suited for ATES owing to diverging climatic and/or socioeconomic factors[24,25]. However, as the suitability rating is arbitrarily assigned, comparison with previous assessments is only limited to well and poorly suited areas.

Closed-loop systems show a similar spatial pattern to open-loop systems, yet also highlight well-suited areas in southern Europe, southern China and southern Brazil. Although the presented maps allow comparison of suitability for open-loop and closed-loop systems on a global scale, similar to other large-scale assessments they suffer from a lack of detail in local conditions, especially regarding thermal energy demand. Also, they do not differentiate over depth, although conditions at a specific site can vary substantially, as this information is not reflected in the data set on near-surface lithology and permeability[32,35]. Accordingly, global maps can inform higher-order political bodies and energy-related initiatives about large-scale areas with generally promising conditions and thus help to raise awareness of SGE; however, for actual decision-making, more precise information on smaller scales is required.

Continental and national potential

On continental and national scales, SGE assessments are much more diverse and detailed, covering some important aspects of SGE, such as drillability[36] and depth-dependent thermal conductivity[37]. However, existing assessments still suffer from a coarse spatial resolution[38–40] and are often restricted to densely populated areas[41] or primarily based on economic data[42] (Fig. 3).

Suitability maps have been developed for different areas, accounting for varying factors and processes with an increasing level of complexity. The first national suitability maps were developed in Japan[43], but they are now mainly found in Europe and often published by the national geological surveys (for example, Ireland[44], Great Britain[45] and Poland[37]) or universities (for example, Germany[34], Spain[46] and Europe[39]). They typically use traffic-light approaches to evaluate the technical feasibility of different SGE systems based on hydrogeological parameters[45], legal regulations[39], climate data[34,39] and economic factors[46]. Suitability maps for very shallow (<10 m below ground level) potential for HC systems were also developed for Switzerland[47] and Europe[38]. In the USA, feasibility maps are currently only available for deep geothermal reservoirs[48], but estimates based on economic data indicate that US energy consumption for space heating and cooling could be reduced by 46% by geothermal heat pumps[42]. Although thermal energy demand data are available for the USA[49] and Europe[50],

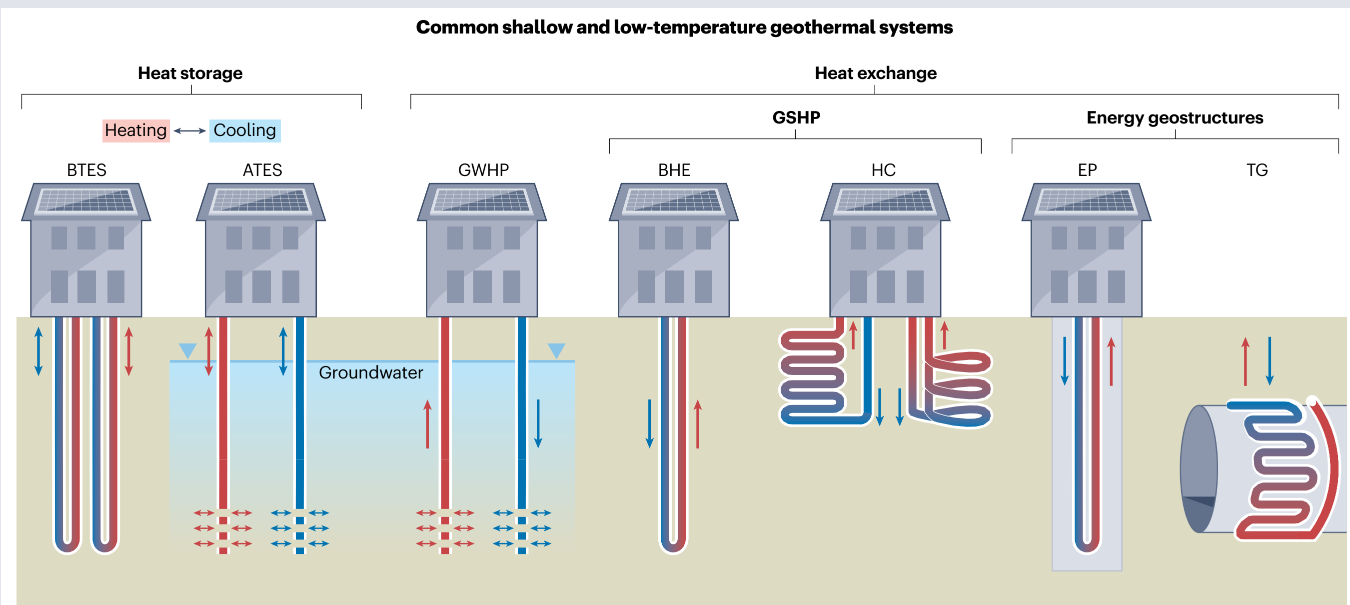
Box 1 | Types of shallow geothermal energy systems

Shallow geothermal energy systems are differentiated by the type of usage, the heat carrier and the way of heat exchange with the subsurface. Installations utilize either the natural replenishing energy in the ground or the slow energy transport in the ground for underground thermal energy storage, such as borehole thermal energy storage (BTES) and aquifer thermal energy storage (ATES)[7] (see the figure).

Open-loop systems, such as groundwater heat pump (GWHP) systems, use pumped groundwater from a well as heat carrier and reinject downstream after passing the heat pump. Such systems can extract a large amount of energy but are only suitable for productive aquifers with low groundwater flow velocities. Open-loop systems often require thorough planning and licensing, as they can use potential drinking water resources as heat source, and can also suffer from mineral precipitation and/or clogging. Depending on the hydrogeological and licensing situation, different well designs (doublet or mono well[7], standing column well) are commonly used.

Closed-loop systems, which pump a heat carrier fluid through tubes installed in a ground loop, are applied more broadly and summarized as ground-source heat pump systems. These loops are often installed horizontally as heat collector (HC) systems (typically <5 m depth) or vertically as borehole heat exchangers (BHEs) (typically <100 m). Other possible designs include, for example, horizontal slinky and trench collectors, as well as vertical basket and helix collectors[16]. BHEs are commonly designed as single or double U-tubes (with or without grouting)[166], or coaxial BHEs[82]. Closed-loop systems can also be embedded in underground infrastructures such as tunnel geothermal (TG) systems and foundations, for example as energy piles (EP)[129]. This infrastructure utilizes both geothermal and anthropogenic (waste) heat.

ATES systems recover heat and cold by hybrid use for heating and cooling at high storage efficiencies (typical thermal recovery rates of 60–90%)[201] and typically operate in the natural temperature range of the shallow subsurface (<25 °C) except for a few systems («1%) that utilize waste heat[7]. Contrarily, BTES systems typically do not recover internal heat but store external waste, excess, or solar heat for heating in the cold season. They often perform at higher temperatures (>40 °C) and lower thermal recovery rates (typically 40–60%)[201].



it is so far rarely included in suitability assessments, likely due to low spatial resolution and inherent uncertainties. Thus, most suitability investigations at continental and national scales neglect the fact that heat in general, especially when provided by SGE, is a local resource that should be extracted close to the consumer.

In contrast to suitability assessments, the theoretical potential assessment provides quantitative information about the heat-in-place within a defined subsurface volume, which is often compared against local heating demands. Extensions to this approach include, for example, accounting for transient conditions (that is, replenishment of the reservoir through natural and anthropogenic heat fluxes[51]). This theoretical potential is often enormous. For example, the top 300 m of the Finnish subsurface could provide heat for the country for 3,500 years (ref. 52). In Central Europe, 14% of the studied area covering France, the Netherlands, Belgium (Flanders), Germany and Austria could sustainably cover more than a quarter of the annual heating demand just from anthropogenic waste heat and ground warming owing to climate change[51]. Vast theoretical potentials were also mapped in Canada, corresponding to 1.1×10^{21} J per heating season, and the potentials increase with global warming[40]. In China, the annually recoverable amount of heat in the top 200 m beneath 336 cities in the mid-eastern region hosts a vast potential, but the current uptake of SGE is concentrated in the northern regions of China[41].

Although factors such as the locally available space for drilling, market maturity of SGE systems or subsurface heterogeneities are typically not be considered on a national scale, certain aspects can be included in the technical and economic potential assessments[20]. For example, in Finland, 25–40% of the annually constructed residential buildings could be fully supported by GWHP systems, depending on subsurface properties and demand simulation[53]. For the UK and the Netherlands, potential maps that consider economic data such as installation and operational costs[54] and local subsidy schemes[55] were developed. These potential maps highlighted that subsidy schemes providing upfront cost reductions can increase the economic competitiveness of SGE compared with ASHP systems, also leading to an increase in areas where GHSPs are the economically preferred renewable alternative to gas boilers[55]. However, assessments of economic

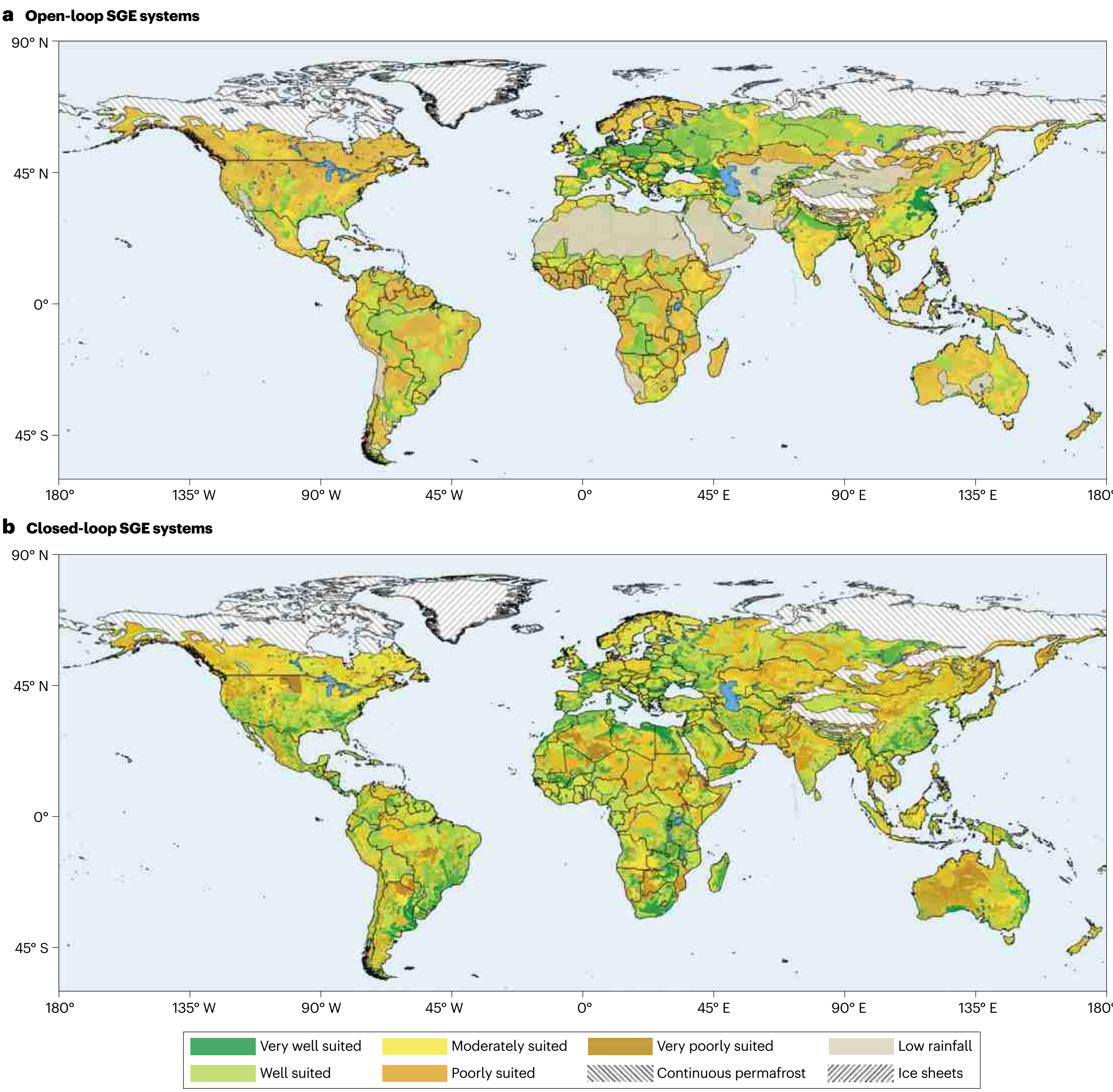


Fig. 2 | Global suitability of shallow geothermal energy. a, Suitability for open-loop shallow geothermal energy (SGE) systems excluding areas with low rainfall[26] and continuous permafrost areas[200]. **b**, As in part **a**, but for closed-loop SGE. Suitable areas for open-loop SGE are mainly found in Europe and Asia, whereas suitable areas for closed-loop SGE can be found in broad regions worldwide.

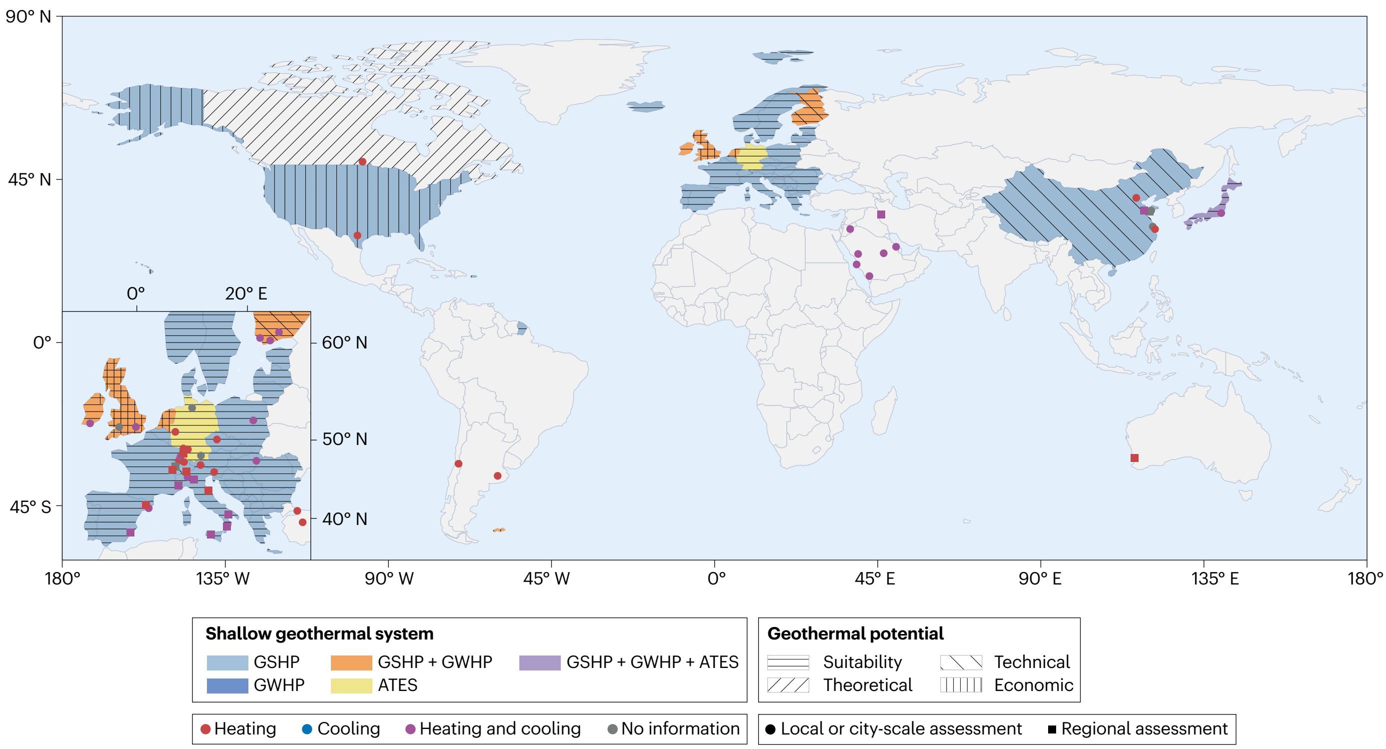


Fig. 3 | Existing shallow geothermal energy potential assessments. Global overview of geothermal potentials (according to the classification in ref. 20) that have been analysed for different regions and different shallow geothermal system types and purposes. References used for data generating the figure are provided in Supplementary Note 2. Assessments that cover more than one shallow geothermal energy technology, heating as well as cooling, and encompass areas outside Europe and North America are still rare. ATES, aquifer thermal energy storage; GSHP, ground-source heat pump; GWHP, groundwater heat pump.

potential on a large scale are still rare, as well as potential assessments for underground thermal energy storage systems, such as ATES or BTES (Fig. 3).

Machine learning was used for SGE potential assessment to overcome the lack of continuous spatial data. Random forest and ensemble learning algorithms were mainly used to predict subsurface temperatures[56], thermal conductivity[56,57] and diffusivity[47], as well as the technical potential of BHE fields[58]. Such machine-learning approaches are of particular interest for areas with little or no assessment of SGE potential, particularly in Asia (outside China) and Australia (Fig. 3). For the Indian subcontinent, a massive increase in space cooling demand was forecasted; however, SGE has barely been considered so far[59], and the geothermal potential for cooling has not been assessed yet. The same applies to the Middle East, where an under-representation of geothermal energy was recognized[60], yet subsurface assessments are currently limited to analysing subsurface temperatures in Saudi Arabia[61].

National assessments differ widely in their methodological approaches and consequently their results because of various conditions for (subsurface) data sets, groundwater monitoring directives and legal frameworks for SGE. Also, the size of a country and federal and state legislations influences the applicability of assessment schemes. For instance, assessment concepts developed for the Netherlands are difficult to transfer to countries on larger scales such as the USA or China, or to countries where geodata collection and management are performed at the state level, for example, in Germany and France.

Regional and local potentials

Assessment on regional scales is again dominated by GIS-based approaches, yet often with added quantification of the heat-in-place[62] or combined with analytical modelling of subsurface heat transport[63,64]. Local factors, such as available space for system installation[65], long-term efficiency[64] and groundwater drawdown (and rising), are often considered in the assessments at such scales[33], but quantitative comparison to heating demands is still rare. Spatial comparison of available thermal energy through GSHPs and heat demand reveals great potentials, for example, coverage of the thermal demand of 44–93% of residential buildings in the German state of Baden-Württemberg (depending on refurbishment)[65], almost full supply of thermal demand in the Po Plain, Italy[63] and coverage of 63% of the cooling and 55% of the heating demand in western Switzerland for the year 2050 (ref. 23).

As more local information is considered, limitations to installing SGE emerge, for example, when the highest potentials are found in areas where drilling is not permitted[34,66] or restricted to a certain depth[67]. Furthermore, local effects of groundwater extraction and reinjection[33] and potential consequences for groundwater quality and quantity[63] are considered in the so-called acceptable potential[20], which is a fraction of the technical potential. However, issues such as public concern (for example, distrust in technology and/or fear of drilling damages), market maturity and availability of companies that can install SGE systems and perform drilling have so far not been well integrated into regional assessments. Also, technological options to distribute the extracted heat effectively are mostly neglected, although distribution via district heating and cooling networks can substantially increase the SGE potential compared with decentralized usage[23].

Urban areas are often the focus of SGE potential assessments[20] owing to high thermal energy demands. These assessments include qualitative suitability assessment (for example, in Tokyo[68]) to coupled numerical modelling of SGE use on city scale[69,70]. City-scale SGE potential assessments are rare outside Europe (Fig. 3). However, notable assessments revealed that heating of Saudi Arabian cities can be fully satisfied by SGE, whereas cooling supply rates are between 20% and 100% (ref. 61), similar to heating supply rates in Europe. Assessments for urban areas require consideration of additional aspects such as subsurface temperatures change[71] and thermal interactions with existing subsurface infrastructure, such as building basements[72] and tunnels[73]. These aspects can be incorporated either by considering local heat fluxes in GIS-based approaches[74] or by implementing numerical heat transport models[70,75]. Heated basements were found to increase the SGE potential by 9–11% in the city of Cardiff (Wales, the UK), leading to cost savings in BHE length and drilling[76].

As surface and subsurface construction in urban areas is highly dynamic, the SGE potential of built-up areas is likely varying over time. Factors that change SGE potentials include the changes in energy demands, for example, owing to building refurbishment[74] or climate change[23], land use[70], subsidy schemes[55] and implementation of SGE systems[51]. Potential impacts of decreasing groundwater levels, which are forecast for many areas[77], have not yet been considered in SGE potential assessments. Although urban subsurface thermal management was suggested in many potential assessments based on analytical and/or numerical tools[78,79], their implementation is not straightforward and hindered by missing validation of SGE potential. However, the heat accumulation rate in the shallow aquifer in the city of Cologne (Germany) was found to be only about 1% of the annual residential heating demand[80]. Management concepts that can deal with open-loop and closed-loop SGE systems[78] and simultaneous heating and cooling[23] exist; yet so far they neither allow for integration of thermal energy storage in the subsurface nor for identification of synergies with other renewable energy sources.

Benefits

The use of SGE systems has environmental benefits in comparison to conventional and other renewable heating and cooling systems, which are typically expressed in greenhouse gas (GHG) savings (expressed in CO_2-eq.)[81–83]. Additional benefits of SGE include reductions in local air pollution and deforestation, potential synergies of subsurface heat storage with groundwater remediation and socioeconomic aspects, such as economic growth and creating local jobs. These environmental and socioeconomic benefits are now discussed in detail.

Global environmental relevance

Despite unavoidable environmental impacts during construction, SGE systems are counted among renewables that do not consume substantial primary resources during operation[84]. The full environmental performance of SGE systems should ideally be calculated by life-cycle assessment that offers various standardized impact categories, with global warming potential expressed by GHG emissions as the most relevant[81–83].

Accounting for all materials and processes and their embedded emissions for the technical lifetime of SGE systems (typically assumed between 15 and 100 years (refs. 4,81,82)), the GHG emissions per produced unit of thermal energy can be estimated. Depending on climatic and hydrogeological conditions, system-specific GHG emissions vary widely, for example, 83 g CO_2-eq. kWh^{-1} for generic ATES in Germany[85], 98 g CO_2-eq. kWh^{-1} for heating and cooling in a research centre in Italy[4] and 33–76 g CO_2-eq. kWh^{-1} for different BHE types of a typical residential building in China[86]. Most life-cycle assessments identify the operational phase as the dominant source of GHG emissions, accounting for 42–87% of total emissions[81,87], because of the large embedded emissions in the electricity used for the heat pumps[4,82,85,88]. Accordingly, estimating GHG savings from SGE is often simplified from full life-cycle assessment to electricity use (or savings)[15,89,90].

Environmental benefits mainly arise from the replacement of conventional heating and cooling technologies with SGE. These benefits are most evident when substituting oil and gas with closed-loop[90] or open-loop systems[91] (also reducing dependence on primary energy resources[92]), yet also when comparing with other renewables or different types of SGE. In rare cases, for example, when substituting gas heating by a GSHP driven by coal-based electricity, GHG savings can be negative (indicating an increase of GHG emissions), as shown in 2010 for Greece, Macedonia, Poland and Serbia[81]. Most locations, however, offer considerable savings when replacing fossil-based heating, which vary widely, depending on the carbon intensity of electricity[81,89] and SGE performance[89]. For EU countries, GHG savings range between −31% and +88%, compared with gas and oil heating in 2009 (ref. 81), and between −4,825 t CO_2 and 1.82 million t CO_2, compared with national heat mixes in 2012 (ref. 89).

Compared with ASHPs, GSHPs are environmentally more beneficial in the long term, because they need less electricity in the operating phase owing to a more stable thermal source temperature[4]. According to a Europe-wide assessment, GSHPs showed 13–43% lower global warming potential in six out of seven countries, even when used in low-energy residential buildings with system capacities of 9–15 kW (ref. 87). However, when comparing the cumulative energy demand, GSHPs are shown to be preferable to AHSPs only for system capacities >100 kW (ref. 93). For a range of system efficiencies (coefficient of performance of 4–5.5) and thermal recovery factors (0.2–1.0) in the UK, ATES systems were shown to potentially save on average 41% GHG emissions for heating (94% for cooling) against ASHPs and 13% for heating (70% for cooling) against GWHPs, owing to high system efficiencies[94] by seasonal heat storage. BTES systems appear to offer lower potential GHG savings (23%) than ATES systems (40%) when compared with natural gas in the Netherlands[88]. However, BTES system still offers large GHG savings, for example, 144 t CO_2 over 10 years compared with district heating in Sweden[95].

Upscaling the potential savings reveals that for 19 European countries, GSHPs alone could potentially save 3.7 million t CO_2 annually[89]. Although this saving was equivalent to less than 1% of GHG emissions from residential space heating in 2008, it has increased rapidly[89]. In 2015, GSHPs accounted for 3.5% (157 million t CO_2) of the targeted GHG savings of 80% in 2050 by the EU[96]. For China, potential CO_2 savings of more than 35% were predicted in the case of a broad transition from conventional heating to GSHPs[83]. Wide deployment in the USA of 5 million GSHPs per year along with weatherization measures, such as reducing outdoor air ventilation and ductwork leakage, could jointly result in potential savings of 5 billion MJ of fossil fuels, 400 TWh of electricity and thus 342 t for each year of CO_2 (ref. 97).

On a global scale, geothermal energy technologies (including SGE) are estimated to save about 600 million barrels of oil annually, corresponding to about 250 million t CO_2 (ref. 14). If fully exploited, the potential for CO_2-emission reductions from geothermal heat pumps was estimated to be 1.2 billion t per year, corresponding to 6% of global CO_2 emissions[98]. Considering the installed SGE capacity in 2020 (ref. 14), the saved GHG emissions amount up to 27.6 million t CO_2 globally (sum of diamond symbols, Fig. 4), when assuming replacement of gas (80%) and oil (20%) heating, an average coefficient of performance of geothermal heat pumps of 3.5 and typical GHG emission factors[99] (Supplementary Note 3). These savings correspond to 0.08% of global GHG emissions from fossil fuels and industry (35 billion t CO_2 in 2020 (ref. 100)).

Applying linear regression to the reported use numbers of geothermal energy for heating in the past[14,101–104] allows projections of growth rates and the corresponding increase in potential GHG savings (Fig. 4), with the same assumptions as for GHG savings in 2020. The projected GHG savings in the future can even be larger by using less carbon-intense electricity for the heat pumps, either through a high share of renewable electricity in the grid[89,90] or by direct coupling to photovoltaics[4,105,106]. On the basis of current and projected electricity mixes, GHG savings can be up to 97% for switching from heating oil to ATES in 2050 (compared with 74% in 2020) in Germany[85], and up to 95% for heating by ATES compared with ASHP in 2030 in the UK, which also come with a 41% lower grid demand[94].

There are different options to increase the environmental performance of SGE technologies that should be further investigated. Besides the transition to lower-carbon electricity, environmental performance of SGE will also benefit from improved efficiency of heat pumps[85,96] and the use of more climate-friendly refrigerants[89,107]. In addition, replacing carbon-based fuels in excavation and drilling[4,86] and using more environmentally friendly materials for the BHE tubes and backfilling[82,83,106] can enhance the environmental performance. As system layout has a key role in the operation of SGE[20], other optimization strategies focus on the geometry of BHE fields[82,86] and well arrangement in ATES[108] and GWHPs[109].

Local and social benefits

Apart from global environmental benefits of GHG savings, there are local benefits from substituting conventional heating fuels, such as coal

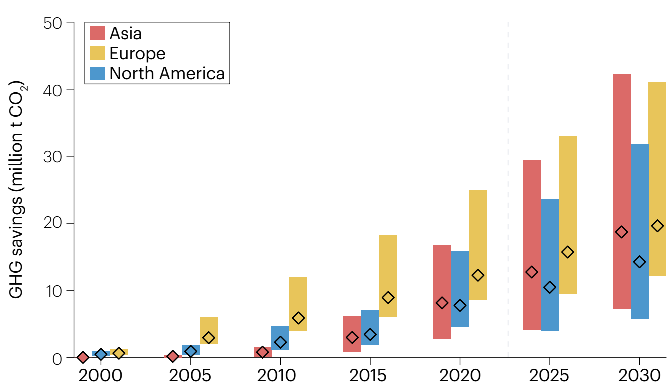


Fig. 4 | Greenhouse gas savings of shallow geothermal energy systems from 2000 to 2030. Historical, present and future greenhouse gas (GHG) savings of shallow geothermal energy in different continents are estimated using data from refs. 14,101–104. Savings are calculated for a coefficient of performance ranging from 3 to 4 (with an average of 3.5) for substituting a conventional heat mix (80% gas and 20% oil) with electric energy emissions[99]. The diamond symbols indicate the derived mean values of GHG savings. GHG savings have substantially increased and have the potential to increase further in the future with larger shares of renewable electricity to operate geothermal heat pumps.

and wood, by SGE. For example, exploiting only 1% of the theoretical SGE potential in Tianjin, China would not only reduce local CO_2 emissions by 117.4×10^4 t but also reduce emissions of coal ash (particulate matter) and nitrogen oxides by 0.3×10^4 t each and sulfur oxides by 0.4×10^4 t, greatly improving local air quality. Similar considerations were reported as additional motivation to replace wood and coal-based heating systems in Serbia[110]. Also, SGE can help to preserve woodlands and prevent deforestation in areas that otherwise use wood as primary heating fuel, such as Patagonia[111]. These local benefits, despite being rarely quantified, can be augmented by locally produced renewable energy (for example, from hydro or solar power) for operating the heat pumps[112], or combined with seasonal heat storage, for example, from industrial waste heat.

As degradation of many organic contaminants in the subsurface is mainly driven by microbial activity, which increases with temperature, thermal energy storage in the urban subsurface offers synergies with in situ bioremediation[113]. For a Dutch ATES system, a 1,000-fold increase in the concentration of mesophilic dechlorinating bacteria was observed, along with a decrease in chlorinated hydrocarbon concentrations[114]. In batch experiments that mimic ATES operation at 25 °C, removal of dichloroethane was shown to be 13 times more efficient than under natural conditions[115], which would greatly reduce remediation duration[116].

With increased temperatures (>35 °C), adsorption of organic compounds decreases, whereas solubility and diffusivity increase. This effect raises the bioavailable amount of contaminants for biodegradation[113] and hence the risk for spreading contaminants[117]. However, comprehensive long-term field investigations that could shed light on the effects of natural aquifer heterogeneity remain a key challenge. Moreover, frequently occurring mixed contaminants[118], as well as other organic compounds of emerging concern, such as pharmaceuticals and pesticides[119], have been rarely studied in the context of thermally enhanced bioremediation. Therefore, successful implementation of SGE will have to balance the optimal temperature for microbial biodegradation and energy storage for heating and cooling purposes[118]. Besides the synergies of heat injection, heat extraction through SGE can also counteract the subsurface urban heat island effect[71].

Although the environmental and technological benefits of SGE have been widely discussed, social benefits are rarely investigated[12,120]. For example, the vast theoretical SGE potentials in Canada offer opportunities for local thermal energy supply for remote indigenous communities[121]. Social acceptance of SGE was investigated in various aspects, such as spillover effects of seismic risks from deep geothermal energy[122], or how to improve the public perception[123]. However, direct social benefits from SGE, such as creation of local jobs with increased wages and improved living conditions through noise reduction compared with conventional air-conditioning[124], are rarely reported. Thus, the call for urgently needed research on combined social and engineering aspects for deep geothermal energy[125] can be transferred to SGE. Geothermal energy also has an overall positive effect on economic growth[126], although the individual motivation for installing SGE is often related to reducing environmental emissions[12], increasing energy self-sufficiency[127] or simply being an agent of change[111].

Other benefits of SGE, for example, financial aspects[12], primary energy savings[7] or reducing peak electricity grid loads[94], are not elaborated here in detail. Indeed, very few assessments of economic geothermal potential provide specific estimates for cost savings[55]. Some exiting assessments highlight small spatial variability in costs, especially for drilling[42]. For example, variation in near-surface geology can lead to differences in installation costs, ranging from 2,600k€ to 3,900k€ per installed kilowatt (ref. 66). ATES systems are particularly cost-efficient, with payback times between 2 and 10 years[7] and energy costs of 4.2€-ct kWh_{th}^{-1} for heating and 0.6€-ct kWh_{th}^{-1} for cooling, respectively[128].

Risk, impacts and challenges

Besides the benefits, SGE has potential geotechnical risks and environmental impacts during construction and operation. Geotechnical risks of SGE are mainly associated with energy geostructures, which integrate heat exchange pipes into underground structures, enabling them to function as heat exchangers in GSHP systems[129]. Drilling of geothermal wells or boreholes for installation of BHEs in complex hydrogeological settings can pose major challenges and damages, such as land subsidence and ground uplifts[130]. Once in operation, SGE systems naturally alter the local thermal conditions with potentially detrimental effects on local ecosystems and/or groundwater quality.

Geotechnical risks

The dual role of energy geostructures as structural elements and heat exchangers, such as energy piles[129,131,132], offers cost-effective solutions but at the same time, it introduces design complexities and poses thermally induced challenges that can affect the stability and longevity of structures.

Energy piles remain the most extensively investigated energy geostructures[133]. Soil stiffness and thermal expansion potential are crucial factors that affect axial thermal stresses and thermal displacements, particularly in fixed-head piles, with boundary conditions further influencing these stresses during heating and cooling[134]. Energy piles display reversible thermal contraction and expansion without cracking[135]; however, shaft-bearing piles can accumulate plastic displacements during thermal cycles, although their ultimate load capacity remains stable[136].

Thermal loading primarily increases axial strains while inducing minor radial strains[137]. However, in stiff soils, neglecting radial strain effects can lead to overestimated axial deformations[138], which are often highly non-uniform across the cross-section of the pile[139]. Although axial stresses rise under thermal loading, stress redistribution occurs over thermal cycles, gradually transferring load from the pile to the surrounding soil[140]. Temperature variations greatly impact soil–pile interactions, particularly in clay, where high temperatures increase friction whereas cooling reduces it. These stresses near the heat exchanger necessitate careful design to prevent potential concrete issues[141] such as cracking or deformation. Thermally induced axial stresses can reach up to 100% of theoretical limits, although actual effects vary with ground conditions, end restraint and thermal loading, underscoring the need for refined design models[142].

Energy tunnels are among the least investigated types of energy geostructures; however, they hold great potential in meeting the growing demand for clean and renewable energy solutions[143,144]. Several pilot and testing energy tunnels have been built worldwide, with a few in operation[145–147]. Research on the thermo-hydro-mechanical behaviour of energy tunnels highlights their performance under various soil conditions. In coarse, highly permeable soils, high groundwater flow rates, for example, 1.5 m per day, amplify short-term thermal stresses in the tunnel lining owing to enhanced convective heat transfer. Simultaneously, residual postoperational stresses are reduced through rapid heat dissipation. Conversely, static groundwater conditions lead to greater residual stresses when compared with flowing groundwater conditions as natural convection creates sustained thermal imbalances. Conversely, dry soil conditions demonstrate minimal residual stresses, making alternating heating and cooling cycles particularly advantageous for long-term structural integrity[148].

The coefficient of thermal expansion dominates ground settlement in energy tunnels, whereas elastic modulus controls soil-lining stress changes. Low-permeability soils develop excess pore pressures that double the settlement, whereas thermal conductivity greatly affects settlement but not lining deformation. Shallow tunnels require special consideration owing to amplified mechanical responses, with alternating thermal cycles mitigating risks in low-permeability conditions[149]. Managing heat transfer and pore water pressure is crucial in energy tunnels for accurate settlement prediction. Permeable tunnel linings help to dissipate pore water pressures, which however also suggests that cooling-induced contraction of tunnel linings and surrounding soil can lead to ground surface settlements comparable to those from tunnel construction[150]. Although the majority of energy tunnels are located within fully saturated soils, tunnels in unsaturated soils need fully coupled thermo-hydro-mechanical modelling to avoid underestimating mechanical effects, especially in clay, in which errors exceed 50% owing to suction and thermal effects[151].

There have now been a number of energy walls constructed around the world[152–155]. The thermal effects in energy wall systems can lead to additional displacements and alter internal actions such as axial forces and bending moments. Therefore, precise modelling is important during the design phase to manage potential overstress conditions[156]. The presence of an asymmetric pipe layout induces bending, leading to uneven stress and strain responses on the wall's sides[157]. In thermally activated walls, thermally induced pore pressures dominate short-term behaviour, whereas soil swelling from dissipation controls long-term response. Although soil thermal expansion reduces restraint on the wall, lowering axial forces compared with non-thermal cases, impermeable walls lead to high residual pore pressures and large long-term deformations[158]. For example, at Crossrail's Tottenham Court Road Station in London, the thermo-hydro-mechanical behaviour of a diaphragm wall shows that GSHP operation induces seasonal cyclic movements and pore pressure fluctuations, with thermal expansion being the primary factor influencing seasonal stress and bending strain variations[159].

Geothermal pavement systems utilize mostly asphalt or concrete to transfer heat with the shallow ground, delivering both thermal energy and structural support. Despite their potential for widespread application in urban areas, geothermal pavements have been largely neglected in previous investigations[160]. The mechanical properties of the asphalt are highly sensitive to temperature changes, with large reductions in compressive and flexural strengths at temperatures >60 °C and slightly improved strength at low temperatures[161]. By reducing the pavement temperature during summer, geothermal pavement systems can contribute to extension in pavement life and urban heat island mitigation[162].

Drilling practices for BHEs face key challenges and can cause severe damages. For example, damage costs associated with the drilling for BHE amount to more than 50 million euros[130]. Drilling challenges include but are not limited to difficult geology (hard rocks or unstable soils), groundwater risks (collapses and poor grouting), slow and costly drilling methods, limited site data and inconsistent regulations[36]. In Germany, vertical GSHP drilling has encountered substantial problems owing to incomplete or leaky backfilling (or grouting), particularly

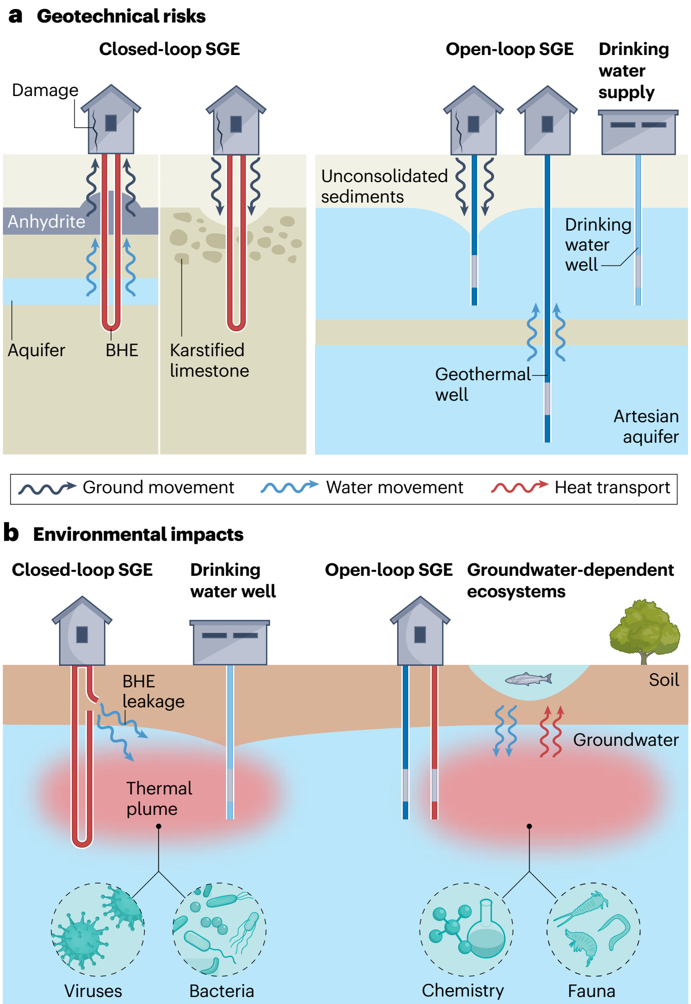


Fig. 5 | Potential geotechnical risks and environmental impacts of shallow geothermal energy systems. a, Potential building damages due to ground uplift caused by anhydrite swelling in the subsurface (left) and sinkholes in areas with karstified limestone (middle), as well as potential impacts on drinking water supply by upwelling of deep groundwater through hydraulic shortcuts (right). **b**, Potential environmental impacts on groundwater quality and/or groundwater-dependent ecosystems through thermal and/or hydraulic alteration caused by SGE. SGE can pose geotechnical risks, which are reported to be manageable, as well as have only minor impacts on environmental processes as temperature increases are typically in the range of 5–10 K. BHE, borehole heat exchanger; SGE, shallow geothermal energy.

in sensitive geological conditions such as anhydrite layers, karstified limestone and artesian aquifers (Fig. 5). Approximately 12% of documented BHE failures in Germany was attributed to incomplete grouting in sandy aquifers, leading to hydraulic shortcuts and borehole instability[130]. Furthermore, defective grouting in BHEs can reduce thermal efficiency by 15–30% and elevate contamination risks from glycol leakage by 40% in permeable formations[163].

These issues have led to severe ground uplift, land subsidence, flooding as well as hydraulic short circuits between layered aquifers[130]. In Ontario, Canada, SGE drilling unexpectedly encountered volumes of pressurized natural gas in depths of 120 m below ground level, leading to adapted governmental approval procedures with specific safety regulations[164,165]. In Finland, BHEs face challenges such as borehole collapses and excessive water yields, along with environmental risks from hazardous fluids and improper sealing[166].

Accordingly, drilling activities for BHEs and energy piles should be carefully planned and executed, in particular with respect to monitoring the drilling progress and testing of grouting. Implementation of corresponding legislation and policies (as, for example, introduced in 2011 in the German state of Baden-Württemberg[130]) can help to safeguard and further develop good drilling practice for SGE. Optimized BHE design was tested through modelling[167], but there is still a need for long-term field experiments and subsurface monitoring, especially for sites with clay-rich soils that can exhibit gradual ground settlement owing to cyclic consolidation. Given the role of grouting in some of the reported damage events[130], attention should be paid to its durability, especially for low-permeability grouting, which is particularly vulnerable to damage from freezing[168].

Environmental impacts

Operating SGE systems can alter physical, chemical, microbiological and other ecological processes in the subsurface and adjacent water bodies, causing direct and indirect environmental impacts (Fig. 5b). Direct environmental impact on groundwater quality can occur in case of leakage of heat carrier fluid of a BHE, which typically consists of water and organic compounds for freezing and corrosion protection[169,170]. The ecological impacts of some additives, such as benzotriazoles, can be severe[169]. However, to date, there is only one reported case, in which leaked fluid reached an observation well[163]. Although the number of undetected leakages is probably higher[130] than reported, the amount of additive is relatively low (typically <2 l per BHE). Nevertheless, their use in BHE heat carrier fluids should be avoided or restricted, as is already the case in the Netherlands[171].

Indirect impacts such as thermal alteration of the subsurface through the operation of SGE systems potentially negatively affect soil and groundwater[114]. However, overall, when temperature is less than 45 °C, impacts on pH, electric conductivity, total inorganic carbon, oxygen, redox conditions and reactions, anions and cations are minor, with no direct impact on groundwater quality[172,173]. Temperature dependency of redox reactions is of particular interest with respect to drinking water protection, as temperature increase can lead to reduction of metal oxides and an according release of heavy metals from sediment (for example, for iron(III) at >25 °C)[172]. Arsenic, manganese and lithium are released from sediment at temperatures >40 °C, but this effect is partially reversible (30–95% element-specific)[174] according to laboratory and modelling experiments. With increasing groundwater temperatures, the solubility of contaminations, such as dense non-aqueous phase liquid, can increase, leading to more contaminants being released from the source. However, increased groundwater temperature also raises microbial metabolic rates, resulting in higher tetrachloroethylene degradation rates and therefore higher biodegradation by reductive dechlorination[175]. Chemical effects of decreasing temperatures, for example, for cold storage with temperatures <10 °C, are rarely investigated[173].

Temperature increase can induce alterations in microbial communities[176,177]. Yet, no major effect on microbial functions has been observed below 45 °C. The long-term effects and reversibility, especially at temperatures >45 °C, are still insufficiently investigated and understood[177]. Virus particles showed a faster collapse at higher temperatures (20–45 °C), whereas at lower temperatures

(4–15 °C) prolonged conservation was observed by experiments and simulations[178,179]. Abundance of pathogens and bacteria in monitoring wells that are thermally impacted by SGE was found to be lower than the abundance in thermally non-impacted wells in an urban aquifer[179]. No substantial impact on bacterial productivity was observed in an operating open-loop system[179]. Faunal invertebrate abundance, sampled from a thermal plume at 9–18 °C, showed no threat to groundwater (drinking water) quality[180]. The temperature sensitivity of five groundwater species with lethal temperature values (LT_{50}) ranging between 17 °C and 28 °C showed that these specific species are also sensitive towards compounds such as salt, ammonium and metals, whose concentrations can increase with higher groundwater temperatures[181].

However, so far only few investigations into the potential SGE impact on groundwater quality were carried out at fully operating sites[180,182]. Furthermore, these investigations are geographically biased towards a few countries (The Netherlands[183], Belgium[182], Spain[184] and Germany[172]). According to the European Union Water Framework Directive, the release of heat into groundwater is defined as a type of pollution, but the cooling of groundwater for heating purposes is not explicitly mentioned[185]. Besides SGE, other heat sources such as climate change[186] and subsurface infrastructures[187] thermally impact groundwater. In general, ecological assessment of SGE-affected aquifers (particularly in urban areas) is challenging owing to superimposing anthropogenic influences on groundwater fauna and the lack of generally accepted ecological assessment schemes.

Overall, the environmental impact of locally increasing groundwater temperatures owing to SGE systems can be considered low. Typical temperature alterations of 5–10 K cause only minor alterations in groundwater chemistry and microbial activity[188]. However, for some groundwater fauna species, for example, from the order Amphipoda, small temperature changes might still be relevant[188]. Hence, for large SGE systems, a site-specific environmental and ecological assessment is recommended[120,185]. To minimize any environmental impact and optimize the environmental benefits of SGE systems, they should be sustainably operated and comprehensively monitored to fully understand their environmental impacts. Also, local laws and regulations on permissible temperature levels for SGE operation should reflect the environmental impacts described earlier. In 2010, an overwhelming majority of countries (38 out of 46 investigated) had no regulation for open-loop and closed-loop systems at all[189], posing potential risks to drinking water resources and corresponding ecosystems. By contrast, restrictive temperature limits, such as ±6 K temperature change in Germany and Austria and ±3 K in Switzerland for open-loop systems[189], respectively, hinder large-scale implementation of SGE technologies.

Summary and future perspectives

The number of SGE applications is on a continuous rise, with large capacities installed already in Europe, North America and China. These regions also stand out by having publicly available information on the geothermal potentials at different scales. However, the current assessments are mainly focused on heating. Given the cooling-dominated climates as well as to promote thermal storage with SGE, the aspect of cooling needs to be addressed in future potential assessments. Although many areas around the world are identified as particularly suitable for heating with SGE, installation rates often lag behind the areas' potential. For example, a third of Germany is hydrogeologically suitable for ATES systems[34], yet only two ATES systems were in operation in 2021 (ref. 190). Conducting interviews with geological surveys and practitioners in the field of SGE could help identify the reasons behind this mismatch. For example, legislative and regulatory frameworks as well as technical standards are found to be important for the ATES market development[191]. Non-technical risks such as legal, social and organizational risks of HT-ATES are perceivably higher than technical issues[192]. These concerns highlight the need for stringent regulations and reliable long-term incentive programmes to promote a widespread uptake of HT-ATES and SGE technologies in general. Online tools, for example, those available in Austria and the Netherlands, which provide subsurface SGE potential and thermal demand assessment, can raise awareness as well as promote implementation of SGE technologies.

These online platforms also host a huge potential for integrating data-driven machine-learning approaches, for example, by building upon a random forest approach to estimate the technical geothermal potential for closed-loop systems[58]. Machine-learning approaches have yet to be used to predict applicability and performance of open-loop systems that strongly depend on site-specific hydrogeological conditions. The present lack of data on local hydraulic parameters, such as hydraulic gradient and conductivity, hinders the application of commonly used neural network approaches, as these are particularly data-hungry. The substantial impact of groundwater flow conditions on thermal interactions of open-loop systems and the thermal recovery factor of ATES system highlight the need for a joint effort from research and authorities to create such data sets and ensure public access to it.

In the absence of sufficient information on subsurface conditions, alternative computational methods, such as Bayesian approaches that can handle sparse data, offer possibilities to obtain reliable predictions about SGE system performance. For example, a Bayesian modelling framework was shown to accurately predict temperature alterations in a BHE field in complex hydrogeological settings[193]. Bayesian approaches also allow incorporating uncertainty about hydrogeological parameters and operational conditions, which is often substantial as there is still a lack of experience with SGE operation in many areas. Another promising direction for predicting subsurface conditions and SGE performance is explainable artificial intelligence approach, which has so far been only applied in the context of deep geothermal, for example, for predicting reservoir temperatures[194]. Of particular interest in the context of SGE are explainable AI approaches that use white box models (for example, regression models and decision trees), which can help to communicate findings with stakeholders and the public to build trust in computational tools for SGE and the technology in general.

In mature SGE markets, operational data from SGE systems can be used to update corresponding training data for computational frameworks and online SGE information platforms to provide detailed insights into long-term system performance, support optimization of systems and promote sustainable thermal use of the subsurface. Such frameworks and tools will accelerate implementation of SGE, especially when combined with building demand data for heating and cooling. Thermal energy demand data are already available on different spatial levels (for example, building, district and so on) across different scales (city, global), based on aerial images and convolutional neural networks[195] or regression modelling using global climate data[196]. Bridging the gap between large-scale potential assessments, such as the maps shown in Fig. 2, which are often built upon coarse data of a limited set of parameters, and detailed local SGE assessments using site-specific information in a consistent manner is paramount for developing realistic future SGE strategies on national or continental scale. The so-called platform-based design approaches that formally define different levels of abstractions (for example, spatial scales or

Glossary

Axial thermal stresses
Stresses that develop along the longitudinal (axial) direction of a structural element owing to temperature changes, when thermal expansion or contraction is restrained.

CO_2-eq.
Standard unit used to express the impact of different greenhouse gases in terms of the amount of carbon dioxide (CO_2) that would have the same global warming potential over a specific time period.

Degree days
Measure of how much and for how long the outside air temperature deviates from a given base temperature, typically used to estimate heating or cooling energy requirements.

Energy geostructures
Geotechnical structural elements, for example, piles, retaining walls, slabs, tunnel linings or shallow foundations, that are thermally activated to function as ground-coupled heat exchangers.

Energy piles
Foundation elements, typically concrete piles, that are thermally activated by embedding absorber pipes or heat exchangers to function as geothermal heat exchangers.

Energy tunnels
Underground infrastructure tunnels, for example, used for transportation, that are thermally activated to harness geothermal or aerothermal energy for heating, cooling and other energy applications.

Geographic information system (GIS)
Computer-based tool used to capture, store, analyse, manage and visualize spatial or geographic data.

Ground settlement
Downward movement of the ground surface owing to changes in the underlying soil structure.

Grouting
Process of filling the space between the heat exchanger pipes and the borehole wall with a specially formulated material, called grout, to ensure thermal contact, structural stability and environmental protection.

Heat-in-place
Volumetric estimate of the thermal energy stored in a geothermal reservoir, based on the physical properties of the rock and fluid, reservoir volume and temperature difference relative to a reference.

Lethal temperature values (LT_{50})
Specific temperature threshold at which 50% of the test population of organisms dies.

Radial strains
Deformation of a material (for example, soil or rock) in the radial direction, that is perpendicular to the axis of loading or symmetry.

Relative payback times
A comparative metric expressing the difference in payback durations between two technologies, indicating how much faster or slower one technology recovers its initial cost compared with another.

Shaft-bearing piles
Deep foundation elements that transfer structural loads to the surrounding soil or rock primarily through skin friction along the surface of the pile shaft.

Traffic-light approaches
Decision-making frameworks that use the colours of a traffic light (green, yellow, and red) to indicate different levels of geothermal potential on a qualitative or semi-quantitative scale.

Thermal displacements
Physical movement or deformation of a structural element, for example, an energy pile, wall or tunnel lining, caused by temperature changes owing to heat exchange with the ground.

system design stages), as well as specific modelling tools or computational framework for each level of abstraction, offer a great potential to increase spatial scalability, technological flexibility and long-term reliability of SGE planning[197].

Mature SGE markets will expand when opportunities of multiple use forms (for example, heating and cooling) and thermal storage are considered together, when SGE systems are integrated as elementary components in fifth-generation district energy systems and when SGE can realize sector coupling of subsurface systems. This integration requires novel co-simulation approaches for energy systems and the urban subsurface, including modelling thermal interactions between different subsurface infrastructures, which are computationally efficient enough to be applied in practice[198]. One key challenge is the shortage of trained personnel and experts to design, build, manage and integrate large-scale SGE. Addressing this skill gap, for example, by transfer of drilling knowledge from the oil and gas sector, is essential for expanding SGE and maximizing its role in renewable energy growth.

The global benefits of SGE depend on the amount and source of primary energy used for heat pump operation. They have been assessed primarily in terms of GHG emissions, with few investigations looking at other environmental impacts. Generally, there is a need for more case-specific life-cycle assessments and more comprehensive functional and operational assessments that include heating, cooling and thermal energy storage and consider the temporal variability of environmental impacts over a standardized lifetime. Geotechnical risks associated with SGE are often related to site-specific geological conditions and are largely manageable. Energy geostructures that combine structural support with geothermal energy exchange are promising, but include further geotechnical challenges when compared with SGE systems with stand-alone heat exchangers such as BHE.

So far, only minor impacts on microbiology, groundwater fauna and groundwater-dependent ecosystems have been observed, especially for low-temperature SGE. However, these findings have yet to be corroborated by long-term field investigations covering various hydrogeological settings. Potential conflicts with other subsurface uses, such as drinking water supply, remain a major concern that requires development of 4D management strategies accounting for the subsurface as a 3D space that behaves dynamically over time and incorporating cross-disciplinary research and cooperation. Local environmental effects, particularly thermal impacts, require approaches that are tailored to site-specific conditions, such as groundwater flow conditions and the ecological status, for in situ, real-time monitoring and management of SGE systems and the subsurface, especially in densely populated areas with multiple installations and groundwater uses. Finally, full market penetration of SGE systems strongly depends on national decisions and policies, science-informed technical standards and stringent regulations as well as reliable long-term national incentive programmes.

Published online: 18 November 2025

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Acknowledgements

The authors thank the Ministry for Science and Art (MWK) Baden-Württemberg for the financial support for K.M. via the Margarete von Wrangell programme. Further financial support for K.M. and H.H. was provided by the German Federal Ministry for Education and Research (BMBF) through the project CHARMANT (FZK: 02WGW1666A, 02WGW1666D).

Author contributions

K.M. and P. Blum developed the concept and structure of the manuscript. K.M., C.B. and H.H. collected and analysed the data. All authors contributed to the scientific input, writing and editing of the manuscript.

Competing interests

The authors declare no competing interests.

Additional information

Supplementary information The online version contains supplementary material available at https://doi.org/10.1038/s43017-025-00736-0.

Peer review information *Nature Reviews Earth & Environment* thanks Jatin Nathwani, Hamidreza M. Nick and the other, anonymous, reviewer(s) for their contribution to the peer review of this work.

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