Chapter 7

Environmental Stewardship in an Energy-Abundant Future: Considerations and Best Practices

Project Innerspace, with contributions from Augusta Grand and Lucy Cotton, Eden Geothermal Ltd

Geothermal energy combines low life cycle greenhouse gas emissions, round-the-clock reliability, and the smallest surface footprint of any renewable energy. Yet there are risks that must be managed. Taking steps to manage these risks will ensure geothermal remains a clean energy option for the United Kingdom.

As the UK looks to develop geothermal energy resources, it faces a challenge: Some stakeholders may be concerned that energy projects—even renewable ones such as geothermal—will affect natural environments. Protecting the natural landscape is important, and care must be taken to limit environmental risks. Most of the focus of this chapter is on deep geothermal electricity; geothermal heat projects present far fewer potential impacts.

Thankfully, it is possible to plan for potential environmental impacts of geothermal exploration and operation, as well as to mitigate harms before they happen. Careful coordination and communication with the public can enable geothermal energy development to proceed safely, with support from communities. As the UK works to move away from fossil fuels and towards more sustainable, domestic forms of energy production, geothermal offers major advantages. It provides clean, firm power and can help decarbonise industrial heat, as well as residential and commercial heating and cooling. Geothermal plants require much less land area for energy production than almost every other energy production source and produce far fewer air and carbon emissions than fossil fuels. Unlike nuclear power, geothermal has no radiation-related risks, and when properly managed and planned for, it can be built and run without significantly disrupting the natural environment.

This chapter identifies the environmental benefits and potential impacts of expanding geothermal energy use in the UK, starting with a summary of possible effects across the timeline of project development. The chapter also looks at two geothermal energy projects in the UK—the Eden Geothermal Project and United Downs—that offer examples for the future development of geothermal systems.

ENVIRONMENTAL BENEFITS OF GEOTHERMAL ENERGY

Reduced CO_2 Emissions

The most obvious environmental benefit of increasing geothermal energy for any nation is a significant decrease in carbon dioxide (CO_2) emissions. The UK's continued dependence on oil and gas for energy and heating needs and the industrial sector's heavy use of oil and gas are major causes of emissions. Greenhouse gas emissions in 2025 amounted to roughly 371 million tonnes of carbon dioxide equivalent.[1] Though emissions have decreased significantly over the past three decades, carbon dioxide still made up around 78% of all emissions in the UK in 2024.[2]

The nation's 2021 Net Zero Strategy set out a plan to reduce greenhouse gas emissions to that level by 2050. The subsequent 2023 Net Zero Growth Plan set a course for reducing emissions by 81% of 1990s levels by 2035.[3] Unfortunately, in July 2024, the UK's independent Climate Change Committee said the UK was not on track to achieve its 2030 targets, and despite significant progress in reducing emissions, only about one-third of the cuts the country would need to make to achieve its goal were backed up with a credible plan. The committee argued for action "across all sectors of the economy, with low-carbon technologies becoming the norm."[4]

The government currently has no targets for geothermal development; however, there are around 30 deep geothermal heating projects in development nationwide, a number of minewater heat and district heating projects underway, and more than a dozen companies that have secured private and public funding for geothermal projects.[5,6] An ambitious heat goal of 15 gigawatts and an electricity goal of between 1.5 gigawatts and 2 gigawatts—as referenced in Chapter 5, "Clearing the Runway: Policies and Regulations to Scale the United Kingdom's Geothermal Potential"—could yield great progress. The National Geothermal Centre has also suggested targets of 10 gigawatts of geothermal heat and 1.5 gigawatts of geothermal electricity by 2050. Achieving these goals would help the country potentially avoid 10 million tonnes of carbon emissions each year—about 3% of the UK's total 2024 emissions.[7,8] A 2023 meta-analysis of hundreds of studies comparing the climate change impacts of

CARBON EMISSIONS OF DIFFERENT ENERGY TECHNOLOGIES

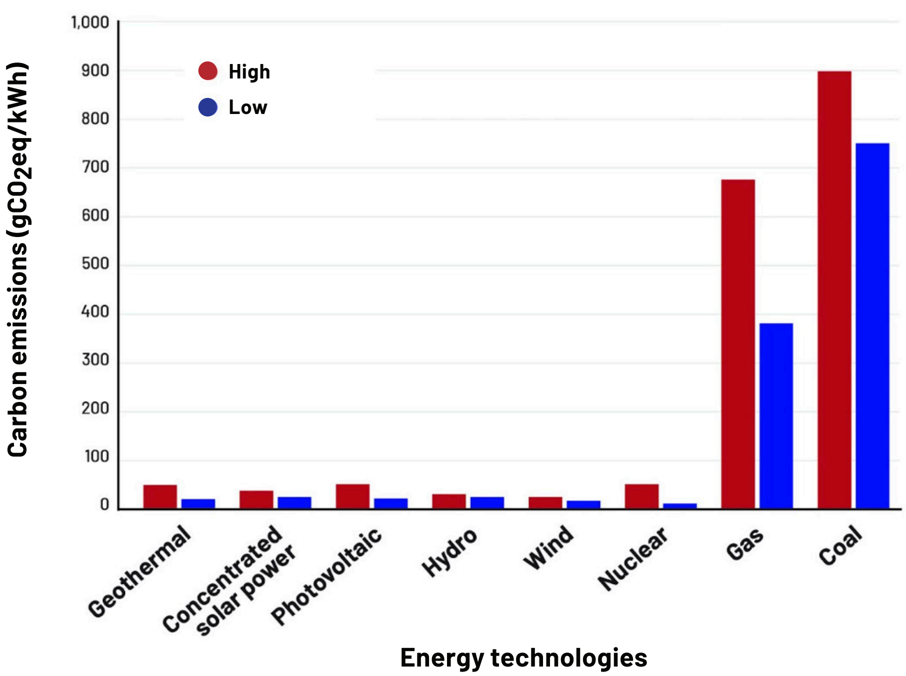
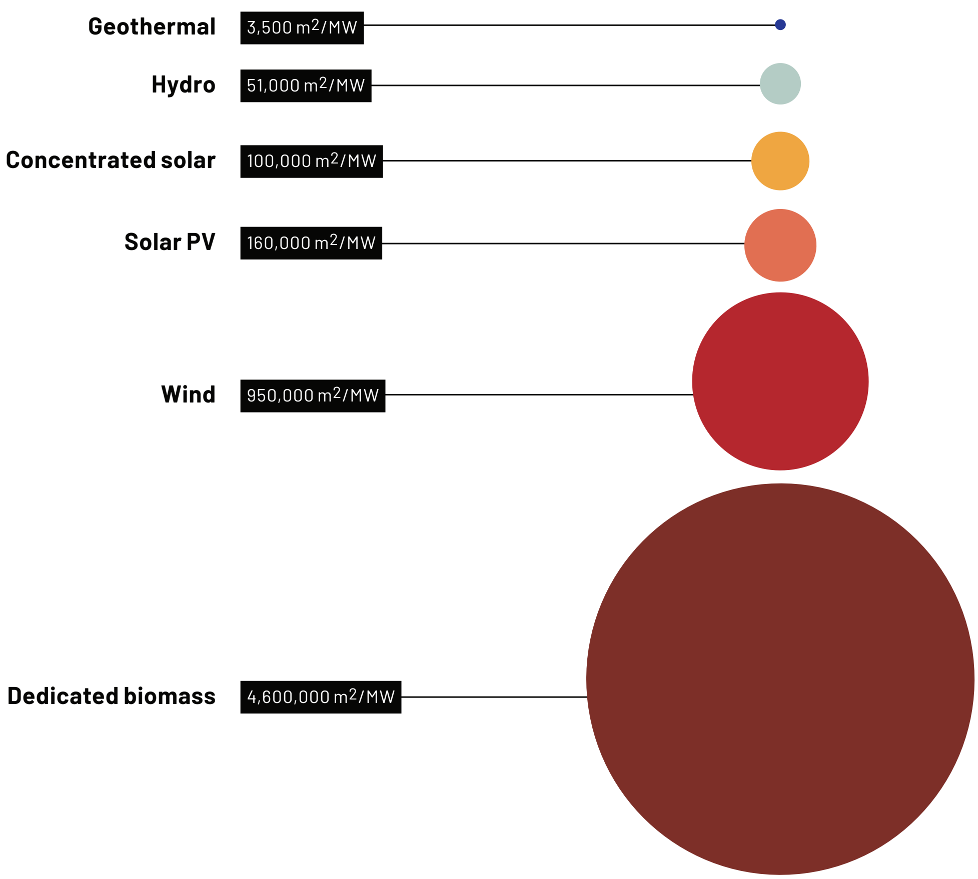


Figure 7.1: Climate impacts of various electricity-generating technologies. Source: Graphs created using figures Guidi, G., Violante, A. C., & De Iuliis, S. (2023). Environmental impact of electricity generation technologies: A comparison between conventional, nuclear, and renewable technologies. *Energies, 16*, 7847.

COMPARING SURFACE FOOTPRINT



Geothermal has the smallest footprint of any renewable energy source

Figure 7.2: The project surface footprint, acre for acre for 1 gigawatt of generating capacity, is smallest for geothermal compared with other renewables. m^2/MW = square metres per megawatt; PV = photovoltaic. Source: Lovering, J., Swain, M., Blomqvist, L., & Hernandez, R. R. (2022). Land-use intensity of electricity production and tomorrow's energy landscape. *PLOS ONE*, *17*(7), e0270155; National Renewable Energy Laboratory (NREL). (2022). *Land use by system technology*.

electricity-generating technologies shows how beneficial the development of geothermal energy can be for enabling the UK to reach its goals related to reducing carbon emissions.[9] The analysis finds that nuclear systems and wind are the technologies that produce the least emissions, followed closely by geothermal, hydropower, photovoltaics, and concentrated solar power. Geothermal performs almost identically with photovoltaics.

Though geothermal power plants have slightly higher CO_2 emissions than solar and wind facilities, they offer a critical advantage: Geothermal plants have a much higher capacity factor. Geothermal plants operate almost continuously, with capacity factors of between 70% and 90%, unlike wind and solar power plants, which generate electricity only when the wind blows or the sun shines. This capacity difference means a 100 megawatt geothermal plant will deliver far more electricity throughout a year than a wind or solar facility of the same size. Because this power is available at all times, its contribution to decarbonisation is more valuable.

Improved Air Quality

Since 1970, the UK has seen significant reductions in harmful emissions affecting air quality due to the end of coal as the dominant fuel for electricity production, ever-tightening regulations around the emissions from road transport, and a shift of some industries overseas.[10] Progress has been substantial, and it continues despite the UK leaving the European Union, where much of the regulation was initiated. Geothermal energy offers a clear advantage in this context due to its minimal emissions during operation. For direct-heat projects, geothermal produces zero emissions at the point of use—an important advantage for heat projects in urban areas and sensitive locations such as hospitals.

Limited Land Use

One of geothermal energy's major advantages over other energy sources is that it uses the smallest land area of any renewable energy source. Geothermal operations also use

WILDFLOWERS AT EDEN GEOTHERMAL PROJECT SITE

Figure 7.3: Wildflower mix planted over the heat main at the Eden Geothermal project site in Cornwall. Source: Image provided by Eden Geothermal, 2023.

the smallest land area of any renewable energy source. Geothermal electricity plants typically use only 2.25% of the land that solar requires, 0.38% of the land needed for onshore wind, and 0.078% of the land needed by electricity plants that burn biomass for fuel (see **Figure 7.2**).

Deep geothermal heat-only projects for industrial or institutional use are even more land efficient and can be retrofitted into urban areas. Many complexes large enough to warrant deep geothermal heating already have access to the land area needed for development and drilling right outside in car parks or brownfields. This is one clear benefit of the technology: Less land is disrupted and less habitat is disturbed than occurs with most other energy sources.

Creation of Additional Wildlife Habitats

In some areas, geothermal power plants have created additional habitats for wildlife. At the Eden Project in Cornwall, project managers have made improvements in species-rich grassland and wildflowers, as trenches were sowed with a diverse seed mix. Ducks, geese, house martins, willow warblers, and grey wagtails all nest there, and foxes and deer are often present at the site.

Eden Geothermal staff also protected an oak and willow woodland area in the centre of the drilling site and retained hedge lines to support biodiversity. During installation of the heat pipeline, they created hibernacula for pollinators. Topsoil trenches were also reinstated and seeded with wildflower mix and topsoil bunds to provide suitable habitats for insects and burrowing bees. Natural stone gabions—rather than concrete pillars—were used to support the above-ground sections of pipe. During drilling, the site was monitored for noise, and the loudest sound recorded was the dawn chorus of birds in the hedge.

As this chapter makes clear, the potential benefits of geothermal energy are plentiful. But scaling geothermal across the UK will also present environmental and community concerns. Next, we consider some potential challenges.

ENVIRONMENTAL CONSIDERATIONS DURING GEOTHERMAL DEVELOPMENT AND CONSTRUCTION

Geothermal energy has numerous benefits, yet there are still some environmental considerations to account for in each stage of a plant's development: exploration to find and characterise the potential of the heat resources in the ground; construction when wells are drilled and cemented and the plant is built; and ongoing operations (addressed later in this chapter). These concerns can be properly mitigated with oversight and management.

When comparing geothermal to other energy technologies, life cycle assessments (LCAs) can provide an understanding of the benefits or trade-offs. An LCA quantifies the environmental impacts of technologies, products, and services throughout the life cycle of a power production plant, from cradle to grave. The standardised methodology enables decision-makers to compare technologies more clearly. The impacts are assessed across several dimensions, such as climate, toxicity, water resource depletion, land use, the creation of ionising radiation, and mineral and fossil resource depletion.

The first step when conducting an LCA is to consider all of the inputs into a system. These inputs are highly site specific, as the choices of well depth, drilling system, casing choice, and generation systems all influence the final inventory (see **Figure 7.4**).

In Cornwall, a preconstruction LCA was conducted at the United Downs Deep Geothermal Power project,[11] which is intended to become the UK's first geothermal electricity plant as of the writing of this report. Some of the takeaways from the study are discussed in further detail later in this chapter.

Geological Explorations

Many geothermal exploration techniques are mostly non-invasive and observational. For example, sampling methods occasionally involve the need to access sensitive areas, but environmental impacts from these activities are largely trivial. Some exploration methods, however, do have a larger effect.[12]

Most **exploration surveys** use existing road and infrastructure networks to save costs, resulting in little habitat loss or vegetation removal. When new infrastructure must be created, developers should take care to minimise environmental impacts.

During the exploration phase, **seismic exploration** involves generating seismic waves at the surface through rapid ground displacement. Active seismic surveys often compress soil or rock at the surface with an air gun or a seismic vibrator.[13] Though this method creates noise and disturbs soil and wildlife, it is temporary and usually does not require excavation or result in any lasting impacts.

For assessing **granite resources**, airborne geophysical surveys offer a non-intrusive exploration method that involves flying sensitive instruments over the ground to assess the subsurface without the need to disturb wildlife, clear vegetation, or build access roads. These surveys leave no permanent trace on the land and deliver high-resolution data for targeting granite-hosted geothermal resources. Because airborne campaigns rely almost entirely on the aircraft platform and leave no lasting footprint on the land, they offer an efficient, low-impact way to refine subsurface models and pinpoint the best drill targets in granite terrains.

There is, however, no replacement for **exploration boreholes** when obtaining the ultimate proof of concept

SAMPLE INVENTORY OF LCA INPUTS

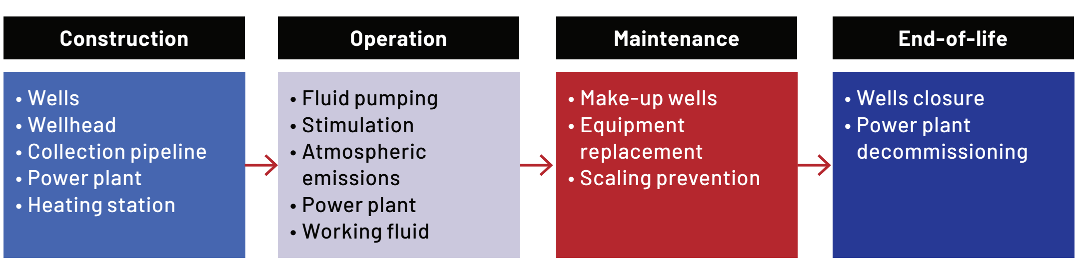


Figure 7.4: Sample inventory of LCA inputs. Source: authors.

and confirming the reservoir properties of a proposed geothermal project. Exploration boreholes require drilling small-diameter holes, much like those used in the exploration drilling that is typical in mining projects. In deep geothermal projects, these boreholes can range from hundreds of metres to a few thousand metres, and they are used to measure subsurface temperatures and collect rock cores to obtain permeability values (either porosity from the reservoir or permeability from fracture networks).

For boreholes, land disturbance is confined to a drill site (or pad) of a few hundred square metres, a space in which vegetation may be cleared and temporary access tracks constructed. As with development drilling, the process generates rock fragments and mud (on a much smaller scale) that are managed on-site or removed per environmental regulations. Although noise, vehicle traffic, and soil displacement occur during drilling, the level of sound generated is small and the duration short-lived, and sites can be reinstated once the borehole is complete. Any abandoned boreholes are safely decommissioned, capped, or repurposed for monitoring throughout the lifespan of the project, so there is minimal lasting impact on land use.

Exploration for new geothermal sites does not produce any other environmental disturbances. The only atmospheric emissions during this stage come from vehicles accessing the site. (In a typical geothermal power plant, any emissions associated with exploration account for only 1% of total life cycle emissions.[14]) Few, if any, issues with surface water contamination arise during this phase.

ENVIRONMENTAL IMPACTS OF CONSTRUCTION

Much of the life cycle impact of geothermal plants occurs due to their construction, which is dominated by the use of diesel for drilling and steel for casing. In the UK, drilling activities are regulated under the Borehole Sites and Operations Regulations 1995, which provide a comprehensive framework for well control, emergency response, and operational safety. Health and safety standards are non-negotiable, drawing on decades of experience from the UK's oil and gas industry, which sets a high bar for safe operations.

Lessons Learned: The Eden Project

The Eden site is a large, flat brownfield that had been used to dispose of building waste in the 1980s. The site is surrounded by farmland on three sides. There is a public bridleway along the fourth edge where people walk their dogs and ride horses. In the middle of the site is an area of willow woodland with several fine veteran oaks. Eden preserved this part of the site, which has become an oasis with deer, foxes, ducks, geese, grey wagtails, green woodpeckers, and blackcaps. The rich mix of wildflowers planted also helped create a welcome environment for insects.

As is standard in the UK, several environmental assessments were conducted before developers applied for planning permission. The assessments included a study of seismic risk and ecological surveys for vegetation, invertebrates, bryophytes, ferns, birds, bats, amphibians, reptiles, mammals, and dormice; they also surveyed for possible noise impact and water resources impact (including flood risk assessment). Other requirements included a heritage statement, a transport statement, landscape and visual assessments, an air quality assessment, ground conditions and hydrogeology impact assessments, tree surveys, and an arboricultural statement.

The ecological surveys showed that a single male dormouse (named Norman by the team) had made his home at the development site. Dormice are protected under UK legislation, so the habitat was cleared under a license and a "precautionary working method statement." Dormice hibernate in root balls at ground level, so the trees and shrubs were cut carefully during winter to avoid disturbing Norman. When dormice wake in spring, they leave to find a new home more to their liking. As the site clearance had to be carried out during winter anyway to avoid the bird nesting season, this task only added a few days to the project.

As part of the regulatory process for the Eden project, the Environment Agency (EA) was consulted ahead of drilling activities and provided with detailed information on the proposed drilling programme and methodology. Early and ongoing engagement with the EA helped the project team identify and manage environmental risks.

A formal letter of agreement was issued following this consultation to confirm that the proposed works aligned with environmental safeguards.

Drilling for a new deep geothermal project can be completed within a few months, making disruption fairly minimal. Even so, along with wells, geothermal operators must install pipelines, transmission lines, heat exchangers, turbines, and more. Work must be done with careful consideration of the environment at each site—with the understanding that each site can have different sensitivities. The drilling phase requires particular vigilance to mitigate possible environmental effects, including seismicity. The LCA of the United Downs geothermal project in Cornwall revealed that 88% of the environmental impacts occurred during the construction phase.[15] The assessment also showed that steel (primarily that used for well casings) and diesel used during the drilling process were dominant contributors to all impact categories. Disposal of drilling waste, or cuttings, made up between 10% and 20% of the toxicity categories. The drilling mud, concrete, and spacers used during well drilling, wellhead, and well closure and the steel used for the downhole pump yielded negligible impacts.[16]

Lessons Learned

1. Analysis of the United Downs project found that the use of electricity for drilling, rather than diesel generator sets, can reduce construction impacts. One study reported a close to 15% improvement in climate impact by using grid electricity rather than diesel.[17] At the moment, unfortunately, grid constraints and electricity prices in the UK mean it is not often possible to use electricity. However, certified hydrogenated vegetable oil is now available as a cost-competitive alternative to diesel, which results in as much as 90% lower greenhouse gas emissions and lower emissions of volatile organic compounds and nitrogen oxide.[18]
2. Although steel consumption cannot be reduced without impairing the normal functioning of a geothermal well, it is worth considering whether recycled content within the steel could be increased to offset ore extraction and processing.

Solid Waste Generation

Geothermal drilling produces solid waste through multiple streams. If not properly handled, waste such as maintenance and construction debris, dried drilling-mud residue, obsolete machinery, damaged piping and flow elements, and drilling cement waste could end up in nearby landfills or sit idle at the geothermal site.[19] When handled correctly, this waste does not pose a threat to the environment. Some waste, however—including drilling circulation chemicals, fuels, lubricants, asbestos, and other hazardous materials—must be handled properly and disposed of through more regulated waste streams involving chemical treatment. In the case of the Eden Project, naturally occurring radioactive material was a particular concern. For that reason, no waste left the site without being tested with a Geiger counter, and all cuttings were tested before disposal.

Careful Use of Water

Water use in geothermal projects is typically carefully managed to minimise environmental impact and make the most of available resources. Although drilling fluids are a necessary part of well development, UK projects use water-based and recyclable materials rather than oil-based ones. Shallow exploration and monitoring wells—typically no deeper than 450 metres—require between 50 kilolitres and 85 kilolitres of water (between 13,000 gallons and 22,000 gallons), while deeper engineered geothermal system wells can require more. However, the geothermal industry in the UK is adopting innovative approaches to keep this footprint as small as possible.

A common practice to use water wisely is the reuse and recycling of drilling fluids, which substantially reduces freshwater demand for future drilling operations and also helps ensure the reservoir's longevity. In fact, most plants reinject geothermal fluid back into the reservoir; this approach both limits consumptive use and sustains the resource. Field experience indicates that roughly 90% of injected water is recovered via reinjection, and a best practice is to avoid potable supplies by using nonpotable (brackish or high total dissolved solids) sources instead.[20] When fluid disposal must occur, responsible management ensures that waste is minimised and environmental risks are mitigated.

The Eden Project offers one strong example. The team reduced water use through novel drilling fluid management practices and selected environmentally friendly ingredients such as barite, bentonite, and xanthan gum—substances more commonly found in medicine, cat litter, and food products than in heavy industry. These water-based fluids lower the risk of pollution and simplify cleanup and reuse.

Eden also demonstrated the value of local partnerships. Community groups and small businesses helped collect and repurpose drilling-related materials, transforming plastic waste into new products such as kayaks. This circular approach shows how geothermal developers in the United Kingdom can conserve water, prevent contamination, and foster community innovation—all while advancing a secure, low-carbon energy future.

Atmospheric Pollution

As mentioned, when building a geothermal operation, nearly 90% of the emissions generally come from the construction phase. The drilling process can release gases into the atmosphere, including carbon dioxide, methane, and hydrogen sulfide, among others. In the UK, geothermal drilling operations fall under the same robust environmental and health and safety framework that governs the oil and gas sector, which ensures that any naturally occurring greenhouse gases, such as carbon dioxide or hydrogen sulfide, are managed to the highest standards of environmental protection and worker safety.

Before any drilling begins, the EA is consulted as part of the planning process, and an Environmental Impact Assessment may be considered, depending on the project's scope. Gas monitoring and mitigation are implemented through a layered set of measures.

Liquid Pollution

A recent wide-ranging literature review in the United States found no instances of groundwater contamination caused by geothermal wellbore failures. In fact, no instances of groundwater contamination resulting from geothermal operations were found in general.[21] However, groundwater contamination still remains a significant concern for some stakeholders, so developers should adhere to regulations to mitigate any spills of fuels, additives, and lubricants. The UK regulations around drilling make sure that proper care is taken to prevent spills from happening in the first place, making them an unlikely occurrence. Liquid emissions from the drilling process can be minimal if drilling fluids that circulate in the wellbore are reused. In geothermal operations in the UK and other parts of the world, significant effort is invested to limit spills during drilling.[22] If spills do occur, however, heavy metals from geothermal brine, including carcinogenic arsenic, could cause some pollution,[23] though such incidents are extremely rare around the world.

Lessons Learned

1. Eden Project staff implemented measures to ensure environmental protection and prevent thermal pollution, or damage caused by inadvertent heating of groundwater, during both the construction and drilling phases. During the construction phase, the entire working area was bounded to prevent any harmful or hazardous substances from entering the environment. Further, a 3,000 square metre lagoon was installed to help manage thermal pollution.
2. Downhole, the casing was designed to provide multiple layers of protection to the surrounding environment and any ecosystems that may be present. The casing consisted of three layers of casing down to 300 metres, two layers of casing down to 1,700 metres, and one layer of casing down to 4,000 metres.

Noise Management

Noise typically is not a long-term issue in geothermal activities. That said, it does occur during drilling and operations, so addressing it is important. Noise levels can be as high as 120 dBA—akin to an emergency vehicle siren or jet takeoff—when field workers are perforating a well during deep drilling.[24] This noise is only temporary, and from 900 metres away, it decreases to match ambient noise levels in urban areas (71 dBA–83 dBA). During normal operations, noise levels drop to between 15 dBA and 28 dBA, which matches the average background noise in wilderness areas (20 dBA–30 dBA).[25] If necessary, geothermal operations can employ muffling techniques such as noise shields, exhaust mufflers, and acoustic insulation to reduce noise by up to 40%.[26] **Figure 7.5** shows reported values for various noise sources for comparison.

NOISE LEVELS ACROSS GEOTHERMAL DEVELOPMENT PHASES COMPARED TO ANTHROPOGENIC SOURCES

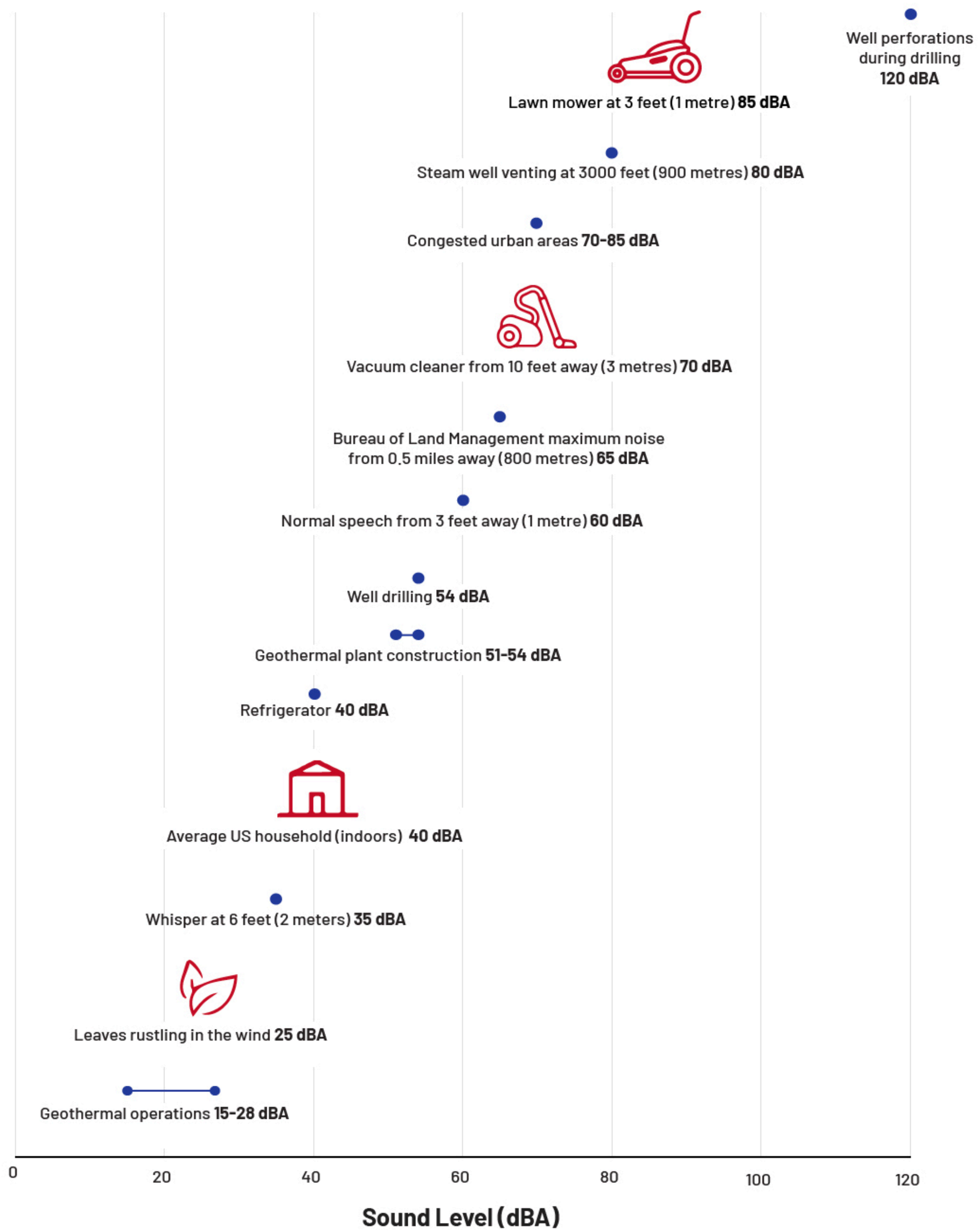


Figure 7.5: Noise levels in geothermal phases comparedwith U.S. anthropogenic sources. Sources: Kagel, A., Bates, D., & Gawell, K. (2005). *A guide to geothermal energy and the environment.* Geothermal Energy Association; Massachusetts Institute of Technology (MIT). (2006). Environmental impacts, attributes, and feasibility criteria. In MIT (Ed.), *The future of geothermal energy: Impact of enhanced geothermal systems (EGS) on the United States in the 21st century* (pp. 8-1–8-20). Massachusetts Institute of Technology; Bryant, M., Starkey, A. H., & Dick-Peddie, W. A. (1980). *Environmental overview for the development of geothermal resources in the State of New Mexico*. New Mexico Department of Energy; Birkle, P., & Merkel, B. (2000). Environmental impact by spill of geothermal fluids at the geothermal field of Los Azufres, Michoacán, Mexico. *Water, Air, and Soil Pollution*, *124*, 371–410.

At Eden, noise monitors were installed around the site prior to enabling works, and strict management procedures were put in place in accordance with daytime and nighttime limits.

ENVIRONMENTAL IMPACTS OF OPERATING GEOTHERMAL ENERGY PLANTS

Land Use

As mentioned, geothermal facilities mostly require far less infrastructure than other energy sources, with a typical geothermal energy power plant occupying just 1,500 square metres per megawatt-hour (0.37 acres per megawatt-hour) compared with 40,000 square metres per megawatt-hour (9.9 acres per megawatt-hour) for a coal-fired power plant. (See **Figure 7.2**.) Emerging next-generation geothermal technologies require even less space, such as a single, shallow groundwater circulation well for direct use or a geothermal doublet well for electricity production.

Geothermal facilities require far less infrastructure than other energy sources. A typical geothermal energy power plant uses just 1,500 square metres per megawatt-hour (0.37 acres per megawatt-hour) compared with 40,000 square metres per megawatt-hour (9.9 acres per megawatt-hour) for a coal-fired power plant.

The infrastructure of these geothermal plants includes pipelines, transmission lines, heat exchangers, and turbines, among others. After the drilling rig has gone, periodic access is needed to service equipment and wells using a crane or small workover rig, but again, the footprint of the plant is minimal. (At the Eden Project site, the well pump controller and heat exchanger fit easily into two shipping containers.)

Subsidence

In a geothermal operation, a developer must consider land subsidence, or the possibility that the developed land could sink over time. When pore fluid is removed from the subsurface without reinjection, the stress between soil and rock grains is decreased and the overlying mass compresses deeper layers.

Subsidence often takes place over decades, but it has been seen in multiple geothermal projects around the world, most commonly in porous or pyroclastic reservoirs.[27] Subsidence as high as 6.8 inches per year (17 centimetres) has been seen at Ohaaki in New Zealand; another site in New Zealand, Wairaki, has seen 46 feet (15 metres) of total subsidence over 50 years of operations.[28,29] Subsidence can be mitigated or eliminated by reinjecting fluid into the reservoir.[30] The good news is that nearly all geothermal power plants use reinjection, resulting in very few cases of *extreme* subsidence.[31] This is much less of an issue for geothermal heat projects.

To date, extreme subsidence has not been an issue in the UK, and many projects have been built in granite, which does not suffer from subsidence. (It may be unlikely that a project could get planning permission or an EA agreement for a system that does not reinject fluids.)

Solid Waste Generation

As with drilling, geothermal operations produce solid waste through multiple waste streams. Maintenance debris, obsolete machinery, and other waste can end up in landfills or sit idle at a geothermal site,[32] but when properly disposed of, this waste poses little threat to the environment. As mentioned earlier, some waste must be handled properly and disposed of through more regulated waste streams.

Another form of solid waste generated by geothermal operations is geothermal scale, a solid substance that forms from cooling or depressurising a geothermal fluid. In some geologies, scale formed from fluids with high total dissolved solids can be on the order of several metric tonnes per hour. This scale can be used for other purposes. One study showed that scale, when mostly silica, can be used as an additive in construction when combined with cement, asphalt, lime, and other common building materials.[33] Some sites can extract valuable lithium from geothermal scale for use in the battery industry—another benefit of geothermal development in the race to electrify transport and space heating and cooling.[34] Cornish Lithium, a UK-based geothermal company, is already exploring lithium extraction from geothermal brines in Cornwall, and United Downs is likewise looking to extract lithium at its site. When not used in other applications, solid scale must be transported and disposed of properly.

Water Use

Water use during geothermal operations can vary depending on the type of plant and technology used. As mentioned, engineered geothermal system technology requires the most water (1,900 liters per megawatt-hour) to maintain reservoir pressure and keep fractures open amid losses to the reservoir rock.[35,36,37] Geothermal for electricity generation uses similar amounts of water to natural gas—and far less than coal, nuclear, and concentrated solar power (**Figure 7.6**).

Geothermal for electricity generation uses similar amounts of water to natural gas—and far less than coal, nuclear, and concentrated solar power.

Atmospheric Emissions

In the UK, with its subsurface heat resources between 140°C and 200°C, binary systems with Organic Rankine Cycle generation will be the order of the day. These systems are cooled by air, so they use little water and have no plumes of steam escaping from chimneys. The emissions are dominated by the choice of working fluid: Many are water-glycol hydraulic fluids, so careful consideration is needed to make sure potential impacts are quantified and equipment is regularly maintained to reduce losses.

Deep geothermal systems in the UK—including direct-heat use applications and deep engineered geothermal systems for electricity generation—can be designed as closed systems, keeping the working fluid (whether natural or introduced) entirely contained. Therefore, any potential reservoir-derived gases (such as carbon dioxide, hydrogen sulfide, and methane) remain dissolved or trapped in the closed circuit and do not vent to the surface under normal operations.

Noncondensable gases (NCGs) such as carbon dioxide, hydrogen sulfide, and methane can be present in geothermal fluids and are monitored during drilling operations, but in the UK's hydrothermal and granitic reservoirs, these gases typically amount to less than 1% of the fluid by weight. Field data from UK pilot sites (United Downs and Eden) confirm that trace CO_2 concentrations fall below detection thresholds, and hydrogen sulfide and methane are virtually undetected in surface vents, reflecting the low natural gas content of British subsurface formations.[38]

A recent whole-life carbon assessment for UK deep geothermal schemes found operational greenhouse gas emissions as low as between 5 kilograms and 15 kilograms of carbon dioxide equivalent per megawatt-

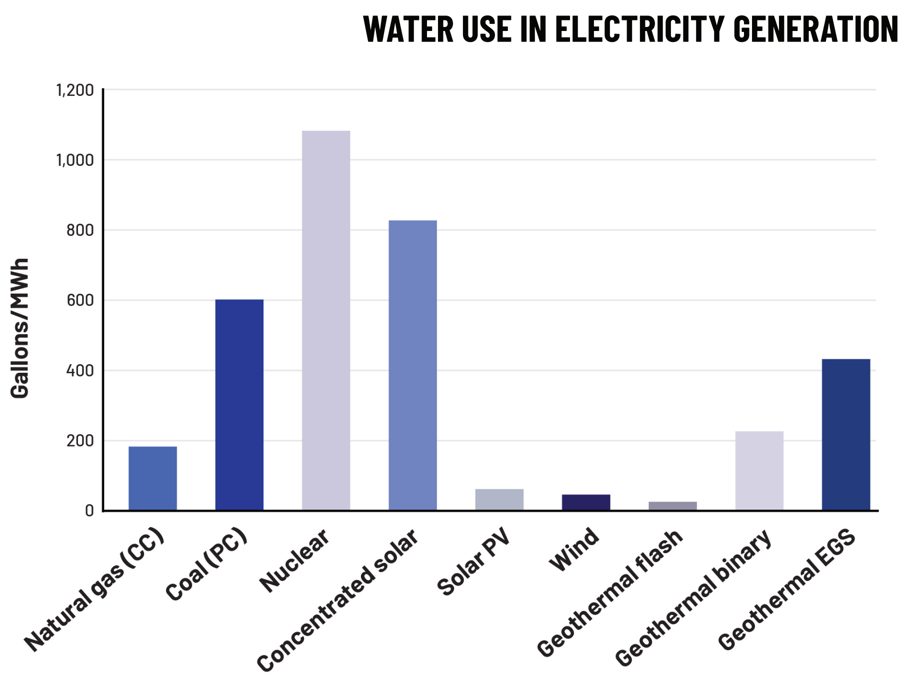


Figure 7.6: Water use in electricity generation by power plant type. CC = combined cycle; EGS = engineered geothermal system; MWh = megawatt-hour; PC = pulverized coal; PV = photovoltaics. Source: Meldrum, J., Nettles-Anderson, S., Heath, G., & Macknick, J. (2013). Life cycle water use for electricity generation: A review and harmonization of literature estimates. *Environmental Research Letters, 8*, 015031.

GEOTHERMAL DEVELOPMENT IN THE UK: WHAT ABOUT HYDRAULIC FRACTURING AND INDUCED SEISMICITY?

The vast majority of geothermal projects in the UK will use low- to medium-enthalpy resources for direct-heating applications—ground source heat pumps or closed-loop geothermal installations, for example—which do not require hydraulic fracturing (the application of pressure exceeding that of the subsurface to create or expand cracks in the rock underground). This technique has been successfully used to produce gas and can also be used to increase the efficiency of geothermal energy production. For a small number of projects that extract heat from hard granite, water-based hydraulic fracturing may be employed. These projects carry some known risks, including induced seismicity and fluid migration, but such risks are being well managed through careful site selection, conservative injection pressures, continuous seismic monitoring, well integrity standards, and transparent reporting. UK environmental regulations require multiple layers of well casing and careful fluid management to protect against groundwater contamination. (See Chapter 5, "Clearing the Runway: Policies and Regulations to Scale the United Kingdom's Geothermal Potential," for more.)

By applying science-led planning and monitoring, geothermal projects can safely provide clean heat and electricity while minimising environmental impacts. Continuous community engagement, clear communication of safety measures, and real-time monitoring of injection and production ensure that risks remain low and manageable.

Spotlight on Eden Geothermal, Cornwall

During development, Eden Geothermal implemented conservative seismic protocols, monitoring peak ground velocity to ensure community safety. More than 300 micro-seismic events were recorded during drilling, with only two felt at the surface. The team used water-based drilling fluids composed of barite, bentonite, and xanthan gum, as well as multiple containment measures to protect groundwater and minimise waste. They also reused drilling fluids where possible, managed thermal discharge through a dedicated lagoon, and engaged local communities in waste minimisation initiatives, including recycling programs. These measures helped demonstrate that deep geothermal development in the UK can be carried out safely, with minimal environmental impact and transparent communication to the public.

EXAMPLE OF CONTINUOUS SEISMIC MONITORING SYSTEM

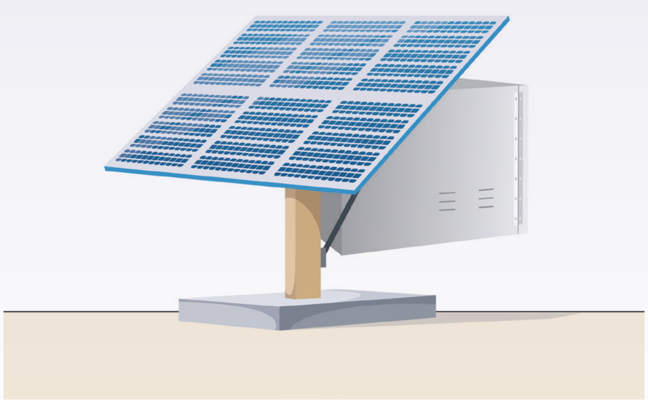


Figure 7.7: Image of a continuous monitoring system. Source: Project InnerSpace.

EXAMPLE OF ENGINEERED GEOTHERMAL SYSTEM (EGS)

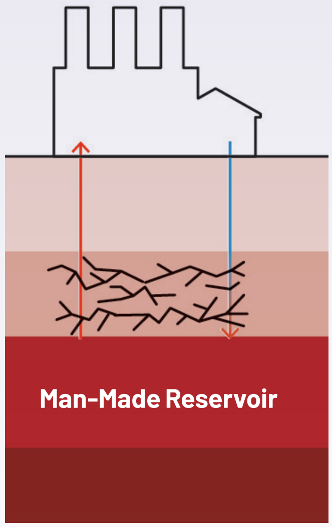


Figure 7.8: Example of engineered geothermal system (EGS). Source: Adapted from D'avack, F., & Omar, M. (2024). Infographic: Next-generation technologies set the scene for accelerated geothermal growth. S&P Global.

hour of thermal output over a 30-year plant life.[39] When reinjection of fluids (and dissolved NCGs) is included, net emissions over centennial time scales effectively match natural background fluxes that would occur in the absence of development.

Residual emissions in UK projects arise only from ancillary equipment: gas-powered pumps, standby generators, drilling rig maintenance, and occasional heavy vehicles. These sources are regulated under the EA in England and corresponding bodies in Scotland, Wales, and Northern Ireland; they must operate within permitted emission limits, with regular monitoring and reporting requirements set by Department for Energy Security and Net Zero guidance.

Liquid Emissions

Liquid emissions during operations can include minor spills of fuels, lubricants, and accessory chemicals. These emissions can generally be prevented through proper employee training and operational practices, but in rare instances, larger accidental spills can occur due to a mechanical failure of the plumbing infrastructure transporting the geothermal fluid. In the UK, the primary use of closed-loop geothermal systems means the risk of accidental spills is extremely low.

Lesson Learned

The management and choice of working fluid in an Organic Rankine Cycle plant can make a big difference. One LCA for a binary geothermal plant in Germany found the greenhouse gas emission estimate was 38.2 grams of carbon dioxide equivalent per kilowatt-hour. The main contributor—at 64%—was the choice of working fluid. Yet another LCA, for a binary power geothermal plant, found that changing to a low-pressure refrigerant as a working fluid resulted in a reduction of the climate impact value from 78 grams to 13.2 grams of carbon dioxide equivalent per kilowatt-hour.

CONCLUSION AND RECOMMENDATIONS

The benefits of geothermal heat use and electricity generation far outweigh the potential impacts. There are a number of examples in the UK and around the world that can help guide developers in establishing geothermal energy plants and systems in a responsible way.

Geothermal does, however, still present risks that need to be minimised. During the planning process of any geothermal project, developers must address any potential significant environmental risks that could occur throughout the lifespan of the development. Although regulations around geothermal are in their infancy in the UK, the following issues must be addressed to gain planning consent.

- **Waste disposal:** The disposal of waste products from the deep drilling operations is an environmental concern. Specialist contractors are brought in to handle disposal, following all regulatory and guideline procedures.
- **Groundwater impact:** Drilling regulations in the UK mean the risk of groundwater contamination is negligible, but operators must take care to follow best practices. Local developers and authorities should ensure that the data are well understood and part of a local communications strategy to reassure the public about the low risks.
- **Traffic and transportation:** The impact on the local network for the transportation of heavy goods vehicles and drilling rigs is always a concern for the surrounding community and must be carefully managed, as all developments are required to do under UK planning laws.
- **Site restoration:** Once a project has reached the end of its life, the developer must restore the site to its former condition.
- **Noise pollution:** Noise can be a concern during various phases of the project. Specific conditions related to noise during enabling works, drilling, and operations need to be managed throughout the development and operational phases. However, drilling and construction phases are short-lived, and noise is generally not an issue over decades of operation.
- **Seismic activity (when relevant):** Any developer dealing with the subsurface has a duty of care to monitor any changes and to mitigate risks that may occur. As a minimum, each project must include the installation of a micro-seismic monitoring network to monitor and control seismicity if hydraulic fracturing is necessary.

Implementing careful environmental protections and mitigating damage will help maximise the benefits of geothermal energy development while avoiding the risks associated with waste disposal, water use, and induced seismicity. By taking necessary steps, the UK can ensure that geothermal—a low-carbon, homegrown energy source—fulfills its potential to be transformative for the nation.

Lesson Learned

At Eden Geothermal, potential environmental risks were addressed publicly. Simple solutions such as sharing an FAQ page on a project's website, providing a contact number for people to call if they were concerned, holding regular meetings with a community liaison group, and having a publicly accessible viewing area helped facilitate communication and build trust with the local residents most affected by the operation. All members of the Eden team were encouraged to engage with the public throughout the duration of the project, and if anyone was at the viewing area, their questions would always be answered by personnel.

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