Accepted Manuscript

Geological Society, London, Special Publications

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DOI: https://doi.org/10.1144/gslspecpub2026-5

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Received 14 January 2026
Revised 13 April 2026
Accepted 15 April 2026

Assessing the Potential to Repurpose Hydrocarbon and Geothermal Exploration Wells as Closed-Loop Geothermal Systems

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Abstract

There are an abundant number of hydrocarbon wells worldwide which are approaching their end of life, along with a small number of unsuccessful geothermal exploration wells, that have the potential to be repurposed as closed-loop geothermal systems. The most suitable method for repurposing is as a deep borehole heat exchanger, which consists of a pipe inserted down the borehole to create two coaxial concentric flow conduits - the pipe itself and the annulus between the pipe and the borehole wall. This form of technology can provide low risk, predictable energy supply that can meet anchor loads in heat networks and reduce the initial capital expenditure associated to drilling when using repurposed wells. However, there are weaknesses of using this technology in repurposed wells: i) it produces significantly lower thermal power outputs than open-loop systems (wells which produce warm formation water, and which rely on advective processes), ii) many wells that have the potential to be repurposed will be drilled in locations which are not proximal to surface heat demand, iii) the potential for electrical power generation is usually not feasible due to low thermal capacity and production temperatures, and iv) there are several issues with ageing infrastructure, regulations and asset liabilities.

1. Introduction

To meet decarbonisation targets and strengthen global energy security, renewable energy resources must be developed. Past energy developments have focused on extraction or production of fossil fuels, including oil and gas. Yet, as these resources deplete and as cleaner sources of energy are sought there is a unique opportunity to reuse existing legacy infrastructure for clean, renewable energy development.

Existing hydrocarbon wells are typically drilled to depths in excess of 500 m and as a result can provide access to a significant amount of heat within the subsurface. This could in principle be exploited as a geothermal resource for both electrical power generation and heat production. Many countries are investigating the possibility of repurposing wells, due to their wide abundance around the world, including in the UK (Watson et al., 2020), China (Hu et al., 2017; Gao et al., 2024), U.S. (Meenakshishundaram et al., 2024), Italy (Soldo et al., 2020; Facci et al., 2024; Livani et al., 2025), Canada (Zolfagharroshan et al., 2024), among others. Theoretically, both open and closed-loop technologies could be adopted to exploit these resources, with open-loop solutions using traditional exploitation methods (i.e., a doublet or multi-well system) where fluid and heat is exchanged between the geological formation and wellbores (e.g., Hu et al., 2017). The production of hydrothermal fluids from hydrocarbon systems has risks such as, corrosion, scaling, subsidence, induced seismicity and dispersion of contaminants into shallower aquifers (Chen et al., 2020; Facci et al., 2024), as well as potential regulatory barriers associated to the co-production of hydrocarbons with geothermal fluid. In contrast, closed-loop systems are lower in risk, using an internally-circulating heat transfer fluid without direct hydraulic exchange with the geological formation. Closed-loop exploitation provides several advantages and is the focus of this study. Its benefits include: having lower geological risk/reliance on reservoir permeability as there is no hydraulic interaction between the borehole and subsurface, there should be no inadvertent production of fugitive hydrocarbons, and there will be predictable operation of the resource due to the main heat transfer mechanism of conduction through the borehole wall. It should also be noted however, local advection in an aquifer formation around a closed loop can improve system performance even if there is no direct hydraulic interaction (e.g., Brown et al., 2023a; Brown and Falcone, 2025).

Hydrocarbon wells can be repurposed using closed-loop geothermal technology. In its simplest form, this involves sealing the base of the borehole from perforated sections open to the hydrocarbon reservoir formation, with a packer or seal and inserting a thermally insulated central pipe concentrically within the wellbore. Heat transfer fluid (usually water) is circulated down the annular space warming with depth via conduction through the borehole wall, before being pumped to the surface through the central pipe. This type of configuration is referred to as a coaxial deep borehole heat exchanger (DBHE – see Figure 1); however, there are several other types of deep closed-loop system (also referred to as advanced geothermal systems – AGS) which an existing hydrocarbon well could be repurposed into (e.g., see Falcone et al., 2025a). These include more complex multi-lateral designs in the subsurface that may connect multiple wells.

Extensive work in the literature has focused on the modelling of closed-loop geothermal systems, typically aimed at exploring the operational performance of DBHEs. Operational and engineering parameters, such as flow rate, operational load, fluid inlet temperature, geometric configuration (i.e., U-tube versus coaxial), grout/cement and pipe thermal conductivity, heat transport fluid and borehole/pipe diameters, all play an important role in determining the thermal capacity of the system (e.g., Chen et al., 2019a; Ben et al., 2024; Brown et al., 2024; Wang et al., 2025; Wangen, 2025). Similarly, key geological parameters such as geothermal gradient, rock thermal conductivity and ground water advection can all impact system performance, largely due to their impact on overall energy in the system, or the regulation of heat transport (e.g., Le Lous et al., 2015; Brown et al., 2023a; Yang et al., 2024). Further work has investigated more complex geometrical DBHEs or AGS structures. This includes U-type systems where single (Figure 1), or multi-lateral components are connected between two vertical wellbores (e.g., Zhang et al., 2021; Brown and Falcone, 2025; Cai et al., 2025), among other complex radiator designs (e.g., Kelly and McDermott, 2022; Yuan et al., 2023). Several recent reviews have also summarised the key components of deep closed-loop systems with specific focus on DBHEs (Alimonti et al., 2018; Chen and Tomac, 2023; Kolo et al., 2024).

There is a paucity of data from real-world case studies, with few examples of closed-loop systems implemented in existing wells worldwide. For instance, Kirby Misperton gas field in the UK has recently had a well repurposed as a demonstration site, with independent modelling suggesting that the well could produce in excess of c.250 kW over a lifetime of 25 years (Falcone et al., 2025b); however, no details/data have been released from the tests. Further hydrocarbon wells have also been converted in Hungary (Santos et al., 2022). In addition, several ex-geothermal boreholes have been converted or have had plans to be converted to closed-loop systems, such as in Germany, Switzerland, the UK and North America (e.g., Collins and Law, n.d; Kohl et al., 2000; Falcone et al., 2018; Higgins et al., 2019; Santos et al., 2022; Abesser et al., 2023; Brown and Howell, 2023; Kolo et al., 2024; Brown et al., 2025a). Geothermal wells can hold different limitations to hydrocarbon wells for redevelopment as closed loop geothermal systems. This is due to the method of completion, with hydrocarbon wells typically narrowing in diameter with depth under different casing strings, whilst geothermal wells can be larger in diameter and often are completed using a liner.

Despite the vast interest in the field there are still gaps within the literature which this study aims to enlighten. Past closed-loop reviews have focused on DBHEs installed (Sapinska-Sliwa et al., 2016), DBHEs design and performance (Alimonti et al., 2018), and recent field developments, including numerical modelling and applications of thermal energy storage (Chen and Tomac, 2023; Kolo et al., 2024). Similarly, there are an increasing number of reviews bringing together the potential of past hydrocarbon wells to be developed as geothermal systems (Santos et al., 2022; Jello and Baser, 2023). Yet, few have investigated i) the differences in repurposing existing ex-geothermal and hydrocarbon wells, ii) methods of integration for heating, cooling and power generation, iii) the potential to repurpose wells as more complex AGS systems, and iv) the wide range of issues associated to repurposing wells from exchanging liabilities to locality problems (i.e., offshore versus onshore). Thus, this study aims to explore the potential of closed-loop repurposing in a range of settings and their potential to meet heating/cooling demand and also power generation.

2. Mechanisms of Repurposing

2.1 Deep Borehole Heat Exchanger

At present, the main conceptual method of repurposing wells as closed-loop geothermal systems is as coaxial DBHEs. These consist of inserting a coaxial pipe concentrically within the original borehole; the pipe should be highly insulated to prevent thermal short circuiting, with vacuum-insulated tubing being used to minimise heat losses (Śliwa et al., 2018). Vacuum insulated tubing minimises heat losses in comparison to high density polyethylene and steel tubes, maximising the thermal power and minimising operational costs through parasitic losses (Falcone et al., 2025b). However, the more efficient vacuum insulated tubing may be most costly to install. Cold fluid is then circulated down the annular space, warming with depth before being pumped to the surface through the central pipe. DBHE systems can be in vertical or deviated boreholes (Figure 1); although the insertion and centralisation of the central pipe becomes increasingly problematic with increasing deviation.

In theory, there is an option for the borehole to remain open to the reservoir formation at the base of the hole (either via an open hole section or perforated lining), allowing the possibility of some fluid exchange between the formation and the heat transfer fluid, and also allowing the possibility of ‘bleeding off’ a proportion of fluid flow from the circulation to improve the system’s thermal capacity (e.g., Westaway, 2018). However, a DBHE with a deep hydraulically open section raises issues of co-production of unwanted fugitive gas or petroleum, compatibility of deep saline water with the heat transfer fluid, and also corrosion and scaling issues. Thus, for existing hydrocarbon wells it is more likely that a packer or seal would be inserted below the base of the central coaxial pipe to prevent heat transfer fluid interaction with formation fluids and to keep the system fully closed. In contrast, repurposed geothermal wells will have the potential to be used in this quasi open- closed loop system, and in the UK boreholes have been trialled without sealing the base (e.g., Collins and Law, n.d.).

Some geothermal wells have been targeted for repurposing using alternative coaxial designs that rely on convection in an outer annulus section but retain a closed-loop in the central system. These use the pipe-in-pipe configuration which is similar to what was previously described; however, they have an additional annulus section. This outer annulus section can be open to the rock formations allowing advective contributions from formation fluids (and potentially from steam) which can then be transferred to the central closed-loop circuit (see Amaya et al., 2020). International examples of such systems are further described in section 5.2 with their potential for power generation.

There are also other methods of extracting heat in DBHEs. These include single and double U-tubes, which operate using the same principle as a coaxial system; however, fluid is circulated in a downward shank of a U-tube before being pumped back to the surface in the upward shank. U-tubes can either be left in the fluid column of the borehole or grouted. Heat transfers from the fluid to the cementitious grout, or fluid column in the borehole, to and from the subsurface formations. These types of configurations are conventionally used in shallow boreholes (<300 m depth) due to their ease of installation, whilst coaxial systems are used at depth, due to their lower hydraulic resistance (less parasitic power loss in circulation), lower borehole thermal resistances and larger cross-sectional area available for heat transfer (Brown et al., 2024). Suspended or grouted u-tubes have had minimal attention in literature when repurposing deeper wells, although they could pose relatively cheaper alternatives. There could however be issues with fluid migration within the well, particularly if there was uncertainty with well integrity posing potential for leakage of deep saline fluid or hydrocarbons to cause contamination at shallower intervals.

2.2 Advanced Geothermal Systems and other Mechanisms of Repurposing

Alternative methods of repurposing wells are hypothesised; however, they will come with inherent difficulties associated to changing the subsurface structure of the borehole. This may lead to issues associated to wellbore integrity and difficulties with recompleting the well in a geometrically complex closed-loop. Several more complex systems exist which typically involve the interconnection between two or more vertical wells. Outside of coaxial DBHEs, U-type AGS or U-type DBHEs (terminology often utilised interchangeably), are considered one of the most promising technologies at extracting heat from new or repurposed wells. They consist of using two vertical wells (i.e., a past doublet system) connected by one or more lateral sections (e.g., see Facci et al., 2024; Hu et al., 2025). Fluid is circulated downwards in one vertical borehole, warming with depth, before being circulated through the lateral, and back to the surface through the other vertical well. They appear to have better performance with higher thermal power available than coaxial DBHEs as they maximise the surface area available for heat exchange (e.g., Chen et al., 2021; Zhang et al., 2021). However, others do note the specific thermal power (i.e., W/m) may be higher for coaxial DBHEs than U-type (Alimonti et al., 2023).

Presently, most indications of performance are attained through numerical modelling as there are few developed case studies limited to Germany, Canada and China (Toews and Holmes, 2021; Cai et al., 2025; Eavor, 2025), although none of these use repurposed infrastructure. In addition, there are also more complicated layouts that could be used including configurations such as the 'James Joyce design' which utlises folded multilateral sections (e.g., Kelly and McDermott, 2022); however, few have investigated the practical or economic potential of repurposing infrastructure with this level of complexity. Recently, power was generated from a first of a kind multi-lateral system in Geretsried, Germany in 2025. This consists of 6 horizontal wells (12 lateral wells) running a length of 16 km of continuous wellbore per pair (Eavor, 2025). Albeit, this was not a repurposed system, but it does highlight the potential of this technology. There are also further types of single well solutions proposed in literature as highlighted by Falcone et al. (2018) for geothermal systems at a range of temperatures and geological settings.

3. Status and Availability of Existing Wells for Repurposing

The repurposing of hydrocarbon wells to perform functions differing from their original design purpose is not uncommon within the oil and gas industry. For instance, exploration wells drilled during the discovery and appraisal phases of an onshore oil or gas field can be developed into production wells. Likewise, as the quantity of hydrocarbons decline in a reservoir, a production well may be repurposed to a water injection well (e.g., Wynn and Saundry, 2020). Once the well is no longer required, whether that be for its initial or repurposed function, it will be decommissioned (Johnson et al., 2021; NSTA, 2022; NSTA, 2025a). To decommission a well, permanent barriers, e.g., cement plugs, are installed in the well to prevent fluid movement between formations with different pressure regimes or loss of containment to the environment (Davies et al., 2014; Kang et al., 2021; Samano et al., 2022; Chukwuemeka et al., 2023). For fully decommissioned wells, the surface wellhead, valves, and upper sections of casing are removed so that the surface location is returned to its original condition (NSTA, 2022).

One opportunity present to prolong the use of a well, postpone decommissioning costs, and add value to the infrastructure present in the subsurface, is to repurpose an existing hydrocarbon well for geothermal energy production or storage.

There are several ways in which existing hydrocarbon wells could be used to harness their geothermal potential. For mature producing onshore fields, hydrocarbon operations could continue but with the inclusion of geothermal infrastructure, as studied at the Wytch Farm field in the UK (Lui et al., 2018; Watson et al., 2020), and the Trecate-Villafortuna, Gaggiano and Irminio fields in Italy

(Soldo et al., 2020). Depending on its temperature, the volume of co-produced water presents opportunities, including for electricity generation, direct use of heat by nearby users, district heating and cooling, industrial heating and cooling, and combined heat and power generation. Such use of the co-produced water has the potential for offsetting operational expenditure, extending the life of the hydrocarbon field, and delaying decommissioning liabilities. For abandoned exploration wells, or wells which have ceased economic hydrocarbon production, there are a variety of technological options available for repurposing. One option is to recomplete the well to implement a DBHE system (Westaway, 2018; Falcone et al., 2018; Alimonti et al., 2018; 2021). Application of this technology would remove the cost of drilling a new deep geothermal well. After a duration of use, if this technology is no longer economic, then the infrastructure might be easily repurposed for seasonal heat storage (Westaway, 2016; 2018). Alternatively, a well might be re-drilled or sidetracked to a deeper zone to enable conversion to a more complex AGS configuration, albeit this method of repurposing is untested.

Theoretically, any existing hydrocarbon well could be repurposed for geothermal energy use. However, there are a number of factors which make some wells more suitable for repurposing than others. Assessment of these factors, such as well integrity, well depth, operational status, age, orientation, estimated temperature yield, and proximity to heat demand, can be conducted to carry out screening exercises to broadly identify suitable wells for repurposing (e.g., Soldo et al., 2020; Watson et al., 2020; Environment Agency, 2022; Alimonti et al., 2023; Meenakshisundaram et al., 2024). Of course, whether an individual well is deemed suitable for repurposing is subject to detailed evaluation based on specific regulatory requirements, site-specific conditions, and project economics. In addition, hydrocarbon wells often narrow with depth to diameters of casing as small as 5 inches. This can prevent repurposing as it may be hydraulically inefficient for coaxial DBHE systems to operate, or there could be technical installation issues, such as difficulties inserting the central pipe within the narrow diameter.

3.1. Repurposing of Onshore Hydrocarbon Wells: A UK Perspective

The concept of repurposing existing hydrocarbon wells for geothermal utilisation in the UK has been investigated by several authors, with pre-feasibility studies carried out (Hirst et al., 2015; Westaway, 2016; Watson et al., 2020) and a demonstrator project announced in recent years (Third Energy, 2025).

Candidate onshore hydrocarbon wells which may be suitable for repurposing in the UK have been highlighted through nationwide screening surveys (e.g., Watson et al., 2020; Environment Agency, 2022). Within these studies, the operational status of onshore wells was considered as a key criterion to assessing the suitability, or not, for repurposing. In the UK, the operational status of hydrocarbon wells is defined by the North Sea Transition Authority (NSTA) Well Operations Notification System (WONS). Detailed in Table 1, wells are thus classified as: drilling, completed (operating), completed (shut in), plugged, or in abandonment phase 1, phase 2, or phase 3 (NSTA, 2025b).

Those wells which are most attractive for repurposing are those which are currently operational, and are thus future candidates for repurposing, and those which are presently approaching cessation of hydrocarbon production, for which repurposing would delay the onset of decommissioning operations and prolong the life of the well. In Table 1, wells described as Completed (Operating) and Completed (Shut-In) fall within this category. Furthermore, it is much more likely that the condition, with regard to well integrity, is known for an operational well, or a recently operational well, than it would be for a partially or fully decommissioned well. This would mean that there would be a reduced cost of proving that the well integrity is sufficient and would meet the need of the new function of the well. Wells with status plugged are likely to require investigation to prove they meet regulatory standards.

Correspondingly, those wells which are fully decommissioned (i.e., AB3) are extremely unlikely to be repurposed. Once a well has been fully decommissioned, the technical challenges to locate and use the well, combined with the uncertainty on the condition, make reuse an economically unattractive option. Partially decommissioned wells (i.e., AB1 or AB2), however, could be considered as suitable candidates to be sidetracked or deepened to a new target geological horizon. In this case, the part of the original well to be reused above the permanently isolated levels would require investigation to prove that it meets regulatory standards.

At the time of writing, there are 2115 wells included in the NSTA's database of onshore wells in England (NSTA, 2025c). Of these, 1395 are fully decommissioned, and 268 are partially decommissioned, and 427 are operational or recently operational. Based on operational status, it is these 427 wells which are most attractive for repurposing for geothermal energy production or storage.

Furthermore Nibbs et al. (2026) investigated the potential to repurpose onshore wells in the UK as coaxial DBHE systems. Screening was carried out based upon: well depth (>500 m true vertical depth), ease of installation (i.e., non-deviated boreholes only), status of the well (i.e., abandoned, plugged, operating), and the overall bottom-hole temperature. They identified the 10 wells with the highest potential to be Kirby Misperton 8, Malton 4, Gainsborough 2, Crosby Warren 1, Wytch Farm F1, Gainsborough 1, Stainton A1, Corringham 5, Fiskerton Airfield, and Reepham (see Figure 2). The study conducted numerical simulations in OpenGeoSys software, assuming a flow rate of 4 L/s and a 25-year operational lifetime for these wells if repurposed as DBHEs, predicting thermal power outputs ranging from 81.8 to 198.3 kW. The highest modelled average thermal power of 198.3 kW corresponded to Kirby Misperton 8.

The DBHEs capability to meet supply at KM8 has also been investigated by Third Energy (2025). The study highlighted that 147 properties in the adjacent village could require a peak demand of 984 kW (annual thermal demand of 2,278653 kWh), but there are limitations in the economic case for development 'without some form of grant funding for the initial network deployment' (Third Energy, 2025).

The top 10 DBHE candidates from Nibbs et al. (2026) are plotted in figure 3 against a selection of real-world examples (although these are not necessarily repurposed wells). Generally, the modelled potential attainable thermal power in UK DBHE candidates from Nibbs et al. (2026) is lower than current examples of international installations. This is largely due to the fact that the UK is subject to lower heat flow areas with the average national geothermal gradient recorded as 26 °C/km (Busby, 2014).

3.2 Offshore Repurposing

At the time of writing there are currently no operational geothermal energy developments located in offshore settings. The concept of producing geothermal energy from co-produced brines from offshore hydrocarbon wells, or converting offshore hydrocarbon wells for geothermal energy production, have however been investigated in previous studies. For example, the feasibility of generating electricity from co-produced brines via an on-platform Organic Rankine Cycle (ORC) has been investigated in mature hydrocarbon fields in the UK Continental Shelf (Auld et al., 2014), the potential of a DBHE to produce heat from the Magnus Field has been simulated (Kolo et al., 2023c) and evaluations of potential geothermal resources present in locations in the Norwegian North Sea and the Gulf of Mexico have also been investigated (Souza and Szklo, 2025).

The repurposing of offshore hydrocarbon wells for geothermal energy poses further challenges to that listed above for onshore wells. This includes consideration of the fact that 1) there is limited to no energy demand in offshore settings, apart from localised use of energy on the platform, 2) portions of the outer piping encountering cold sea temperatures would require further insulation, and 3) if there is potential for power generation, space and a connection to transmission systems would be required for a micro ORC generator.

3.3 Repurposing Geothermal Exploration Wells

In addition to hydrocarbon wells, geothermal boreholes provide options for repurposing – particularly using open-loop boreholes that do not yield sufficient flow rates for production. For instance, in the UK setting multiple boreholes have been tested or repurposed as closed-loop DBHEs when not used for open-loop development. At the Eden Geothermal project, the deepest coaxial DBHE in the world was installed to 4.5 km vertical depth and connected to a heat network (Abesser et al., 2023), in Cornwall a 2.6 km field test was undertaken (Collins and Law, n.d) and there has been significant interest in repurposing the Newcastle Science Central Deep Geothermal Borehole (Brown et al., 2025a). There are further challenges in repurposing existing geothermal boreholes for closed-loop development. Geothermal boreholes can either be left open-hole for large parts (i.e., if the rock is a stable/competent granite), or have liners inserted rather than cased throughout. The former can create interactions between the heat transfer fluid and any subsurface fluid, whilst the latter liner can prevent the installation of the central pipe due to narrowing borehole diameter. Whilst these can pose technical challenges the idea of completing a borehole with some fluid interaction does appear to improve performance with the incorporation of some additional fluid into the system as 'bleed' (e.g., Collins and Law, n.d).

4. Key Parameters Impacting the Performance of Closed-Loop Geothermal Systems

4.1 Heat Extraction

Several studies have investigated the impact of geological and engineering parameters on the operation of DBHEs/AGSs in heat extraction mode (e.g., Brown et al., 2023b – see figure 4; Kolo et al., 2024; Gascuel at al., 2022). Key geological parameters that may impact performance include geothermal gradient, rock thermal conductivity, and groundwater flow. Engineering parameters include operational mass flow rate, size of the borehole and pipes as well as materials used for the grout and pipes. The following studies refer to coaxial DBHEs due to their better thermal performance resulting from lower thermal resistance (Brown et al., 2024).

Several geological factors impact the performance of DBHEs. The natural geothermal gradient means temperatures rise with depth, and a steeper gradient enhances heat extraction by supplying more thermal energy at depth (Holmberg et al., 2016) as illustrated in Figure 4(c). Similar results have been reported by Chen et al. (2019a). Figure 4 (a) also indicates that the heat extracted from the rock increases when the rock thermal conductivity increases. This is because a higher thermal conductivity results in a faster heat recovery in the rock around the DBHE (Chen et al., 2019a).

Studies have shown that groundwater flow will only have an impact on heat extraction for a Darcy velocity of 1×10^{-6} m/s or higher, positively influencing heat extraction by up to a 25-kW increase (Brown et al, 2023a, 2025b; Jiao et al., 2022). However, such high velocities are very unlikely to be encountered at depth across large portions of the borehole. Moreover, results have shown that where the aquifers only form a small portion of the DBHE, there is a very minor impact on thermal extraction (Chen et al., 2019a). When considering homogeneous versus heterogeneous lithology for the surrounding rock, some studies have shown that there is small difference between the approaches with a 1°C difference recorded for ~ 1 km DBHE. The difference depends on the difference in thermal properties of the lithological layers (Kolo et al., 2023a; Karabetoglu et al., 2021).

Further engineering and operational parameters also impact the thermal performance of the system. Borehole depth is a key parameter that affects the performance of DBHEs. As depth increases, heat extraction improves because the heat-transfer fluid experiences a larger contact surface and extended residence time within the DBHE (Deng et al., 2020). There is generally an exponential increase in thermal output with depth as shown in Figure 4(f) (Brown et al., 2023; Banks et al., 2024). The contact surface for heat transfer can also be increased by adding a horizontal section at the end of the DBHE. A demonstrated increase of 20 °C for a 2000 m horizontal section was reported by Wang et al. (2021); however, this comes with increased drilling complexities and cost (Beckers et al., 2022).

The mass flow rate of the circulating heat transfer fluid is key to the performance of the DBHE. The heat extraction increases with an increase in mass flow rate until a certain optimum point is reached beyond which there is no increase in thermal output (see Figure 4 (b)). It is noted that higher flow rates reduce the contact time between the inflow and outflow streams and hence minimise thermal short-circuiting within the borehole. Increasing the mass flow rate beyond the optimum point increases the cost of pumping without increasing the thermal output causing the coefficient of system performance to decrease (Kolo et al., 2023a). A trade-off between maximising the thermal power and reducing the pumping cost needs to the found. Several studies have also considered a configuration with the central pipe as inlet (CXC) in addition to the conventional configuration which the annulus as inlet (CXA). For extraction, the CXA configuration gives a slightly better thermal performance due to the heat-gaining fluid in the annular space moving in the direction of increasing temperature gradient (Banks, 2022; Brown et al., 2023).

The inlet temperature has linear inverse relationship with the heat extraction as shown in Figure 4 (g). As the inlet temperature increases, the temperature difference between the surrounding rock and the heat transfer fluid reduces thereby reducing the thermal output (Deng et al., 2020; Lund, 2019). Using a thermally enhanced grout also improves thermal performance (Figure 4 (d)). For a 2.5 km DBHE, increasing the thermal conductivity of the grout from 0.35 W/m/K to 2.1 W/m/K increased the outlet temperature by 12.6°C and the Coefficient of Performance (COP) by 1.05 (Chen et al., 2019a). This is because the heat transfer between the outer pipe and the surrounding formation is also improved.

The geometrical and thermal properties of the central pipe and borehole wall also affect the thermal performance of a DBHE. Increasing the outer borehole wall diameter enhances heat transfer and DBHE outflow temperature (Pan et al., 2020; Huang et al., 2020b). This is because of larger heat transfer surface with the rock and more residence time in the annular section. On the other hand, increasing the central pipe diameter reduces the outflow fluid velocity and increases residence time in the central pipe making it more susceptible to heat losses. Thus, heat extraction capacity and outlet temperature are reduced (Pan et al., 2020; Huang et al., 2020b). When the thermal conductivity of the outer pipe is increased, heat transfer between the fluid in the annulus and surrounding rock is increased leading to better heat extraction (Deng et al., 2020). However, no significant increase was observed beyond 10 W/mK (Deng et al., 2020), which can also be observed in Figure 4 (h). The lower the thermal conductivity of the inner pipe, the better the heat extraction performance (Deng et al., 2020). This is also illustrated in Figure 4 (e). This had led to the investigation of vacuum insulated tubes (VITs) for the inner pipe which can improve heat extraction; for example, a 22-kW increase in heat extraction was recorded between a VIT inner pipe and a HDPE inner pipe (Falcone et al., 2025b). It is however, noted that VITs are very expensive, and their performance does not appear to compensate for their cost (Gascuel et al., 2022).

Many factors are shown to impact DBHEs, however, when repurposing infrastructure, either hydrocarbon or exploration geothermal boreholes, many factors will be pre-determined. Thus, the performance and system potential should be thoroughly investigated prior to repurposing. Likely fixed factors include maximum depth, borehole diameter, cement grout and the geological properties of the surrounding rock formations.

While vertical DBHEs with coaxial design are more common, there is a rising interest in AGSs which make use of multi-lateral and/or U-type systems to enhance heat transfer by increasing contact surface area (Budiono et al., 2022). U-type systems have been developed in Canada (Eavor, 2023) and China (Li et al., 2018). Several other variations of these systems are being considered to optimise their output and analyse their cost (Malek et al., 2022; Doran et al., 2025; Chen et al., 2025). Advances in drilling technology and reduced cost are needed for these systems to be commercial and competitive (Malek et al., 2022). Therefore, it is less likely they would be used for repurposing existing wells, particularly given the complexity of the task. However, some have highlighted U-type systems could be used to retrofit existing boreholes with one or more multi-lateral sections. These studies showed sensitivities to the number of lateral components, the mode of operation and groundwater flow (Hu et al., 2021; Brown and Falcone, 2025). Newly developed AGS (i.e., without repurposing), highlight similar parametric influence to DBHEs, with sensitivities to flow rate, thermal properties, thermal conditions, modes of operation and geometrical configurations (e.g., Zhang et al., 2021; Huang et al., 2024a,b; White et al., 2024; Cai et al., 2025).

4.2 Borehole Thermal Energy Storage

Borehole thermal energy storage (BTES) is an approach typically used for shallow closed-loop systems with the aim of storing heat and efficiently recovering it. As a result, often the way arrays are designed differ from conventional ground source heat pump systems. For instance, spacing and array geometry may be designed to minimise the surface area to volume ratio, limiting thermal losses (Skarphagen et al., 2019), whereas for conventional borehole heat exchanger arrays the footprint may be larger to minimise thermal interference (e.g., Receveur et al., 2024). Few have successfully applied this method of heat storage to deep closed-loop systems in operating systems; however, many have considered the theoretical application through modelling studies. For deeper repurposed systems, it is most likely a single DBHE would be used, or if an array of existing wells were to be used they would be unlikely optimally developed for BTES. Nevertheless, there is still potential for deep BTES to help shift supply and demand, with the ground acting as a thermal battery (Westaway, 2016; Falcone et al., 2025a).

Both single and arrays of DBHEs have been modelled to understand how efficiently thermal energy can be stored and the impact on system performance. Thorough analysis has been undertaken on the potential for repurposed geothermal (e.g., Brown et al., 2023a,b), and hydrocarbon wells (e.g., Xie et al., 2018) to be used for BTES, with the most important parameters influencing performance including borehole depth, groundwater flow, geothermal gradient, flow rate, storage period and inlet temperature. This has been further corroborated by Huang et al. (2023), Ma et al. (2024), Meng et al. (2025), among others. These types of systems typically have much lower storage efficiency than conventional shallow BTES in arrays as for a single DBHE the surface area to volume ratio is increased, rather than minimised leading to increased thermal losses.

Many of the key parameters identified within the aforementioned single BTES studies are shared with deeper BTES arrays; however, the systems appear to be more efficient in an array design with higher recovery factors. It was shown by Welsch et al. (2015) that spacing also plays a role with larger inter-borehole spacing reducing the storage efficiency. Presumably, because the surface area to volume ratio is increased exacerbating thermal losses. It should also be noted, as highlighted by Kolo et al. (2024) the reported range in efficiency in deep BTES studies varies significantly, which largely comes down to the metric of reporting efficiency.

Whilst there is a paucity of data available for deep BTES systems some are being designed to test the concept. A pilot medium-deep BTES system is being installed at the Lichtwiese campus of the Technical University of Darmstadt in Germany for the research project SKEWS (Seasonal crystalline Medium Deep Borehole Energy Storage System), with four DBHEs to 750 m planned, with potential to scale the system to 19 and 37 DBHEs in new phases if successful (see Figure 5) (Seib et al., 2022). Only three boreholes were drilled for the 1st phase in 2022 to 750 m due to increased costs during drilling (Sass et al., 2024). During the drilling phases the boreholes were also subject to deviation which could impact the efficiency of BTES (Krusemark et al., 2025). Distributed thermal response testing was conducted in 2023 to determine varying thermal properties with depth (Seib et al., 2025).

In addition to vertical DBHEs, U-type DBHEs or AGS have been modelled to explore their viability for thermal energy storage. Modelling has highlighted that inlet temperature, flow rate, storage duration, flow direction, and rock thermophysical properties all impact performance (Huang et al., 2024a,b; Yu et al., 2025), while other types of complex AGS have seldom been investigated for storage. This is probably due to the fact they require far higher fluid inlet temperatures due to the increasing temperatures at depth under the natural geothermal gradient.

Whilst much of the investigation of the potential for thermal energy storage in deep closed-loop geothermal systems has been linked to modelling studies, there has been limited analysis on the impacts at depth and interactions of heat with hydrocarbons within the system. Thus, further investigation should be undertaken on how system performance may change, and any potential environmental impacts which may be associated to fluid mobilisation by heat.

5. Integration to Meet Surface Demand

5.1 Heat Demand

Cost-effective solutions for decarbonising heat are essential to complete the energy transition in the thermal sector. In 2024 heating for domestic, industrial, and commercial purposes accounted for almost half of the final global energy consumption and 37% of energy-related CO_2 emissions (IEA, 2025), with cooling demands to play an additionally critical role as they are expected to triple due to climate change impacts (IEA, 2023). Repurposed hydrocarbon and geothermal exploration wells can provide cost effective solutions to provide thermal energy from closed-loop systems, predominantly through baseload supply.

Thermal networks are at the forefront of these decarbonisation efforts as they can flexibly combine different thermal sources, storage options, and energy transformation units at various levels of centralisation (flat/building/district) to manage heat and cooling demands efficiently (IEA, 2025). Geothermal energy is ideal for thermal networks, offering a renewable heat source or sink, that can act as a baseload, storage, or balancing unit (Tester et al., 2016; Falcone et al., 2025c). Deep closed-loop geothermal systems may be more suited for providing anchor loads due to the low thermal capacity of the systems limiting the ability to meet peak loads (Ben et al., 2024). Utilisation of geothermal energy for thermal networks can be in the form of direct-use in district heating systems and power production, or as an input for Ground Source Heat Pumps (GSHPs), upgrading the geothermal heat to the required levels (of temperature) (e.g., Farghali et al., 2023). Specifically, thermal networks can decouple the direct connection of heat extraction from end-users, allowing multiple demands to be met through a single point of heat supply. For geothermal energy, a centralised heat extraction means that the high capital costs and technical and environmental complexities linked with it are concentrated at one optimal location, enhancing efficiency and reducing risks (Chen et al., 2019b). Moreover, geothermal wells can also provide a thermal sink for district cooling networks, resulting in greater efficiency and lower energy costs for large installations. There are limitations however when linking repurposed infrastructure, with hydrocarbon wells seldom proximal to heat networks or high energy density areas.

To identify what is the best use of heat extraction, the heat network's characteristics need to be evaluated. Different generations of district heating can utilise geothermal energy in various ways, depending on their temperature profile and overall operational structure. These are captured clearly in Figure 6. For example, newer generations of district heating networks operate at lower temperatures, allowing the use of lower temperature geothermal energy with a direct heat exchanger, avoiding the use of an energy transformation unit requiring input power/fuel (heat pump, boiler etc.) (Lund et al., 2018). This approach minimises electricity use and fuel expenditure for energy transformation, potentially countering the large capital costs associated with the complex installation and infrastructure requirements of geothermal systems (Madurai Elavarasan et al., 2022). Furthermore, this direct heat exchanger approach broadens the feasibility of extracting heat from more geothermal wells, thus reducing high capital costs and associated risks with higher temperature wells that are often located deeper underground (Tester et al., 2016).

As mentioned, when geothermal temperatures aren't sufficient for the network, GSHPs are needed to upscale the temperature, which is likely to be the case for many repurposed wells unless in high heat flow areas. Sweden, Germany, and France are the frontrunners of GSHP implementation (Rybach and Sanner, 2017), with over 2 million GHSPs installed in Europe in 2019 (Madurai Elavarasan et al., 2022).

Despite requiring an energy transformation unit, GSHPs offer several advantages over conventional Air Source Heat Pumps (ASHPs). GSHPs generally achieve higher COP because they utilise consistent geothermal temperatures year-round, unlike ASHPs which are affected by variable ambient air temperatures. This results in higher Seasonal COP (SCOPs) for GSHPs, enhancing stable operation without risks of freezing (Maddah et al., 2020), supporting their use for long term baseload consumption.

Deep closed-loop geothermal systems can supply a single GSHP in an energy centre or multiple GSHPs at the property level through an ambient temperature thermal network. Such an ambient network with decentralised heat pumps, which is referred to as 5th Generation District Heating and Cooling, can supply both heating and cooling to individual properties or district thermal networks (Zeh et al., 2021). However, the boundaries of beneficial operation are limiting it to cases of high co-occurrence of heating and cooling demands, with a 30% overlap of heating and cooling needed to make it economically comparable to 4th Generation District Heating and Cooling (Angelidis, 2025; Wirtz et al., 2020). In Europe only 0.1% of the building stock offers such a demand overlap (Zhang et al., 2023).

Moreover, geothermal wells can facilitate sector coupling between the thermal and electricity networks since they can be "charged" with heat during low-heat demand periods

(Angelidis, 2025). This charged heat can then improve the COP in times of GSHP operation and thus enable smarter operation of the entire energy system. This concept can be expanded with utilisation of GSHPs during times of low electricity prices further increasing efficiency. For example, reversing GSHPs to charge geothermal wells during periods of curtailed wind or excess electricity generation enables synergies between the heating and electricity sectors, reducing costs (Brown et al., 2023c). Furthermore, such synergies can alleviate grid pressures, performing voltage control regulation, particularly during high PV generation in the summer (Fischer and Madani, 2017). However, it is essential to analysis the geological characteristics of the well to identify the techno-economic feasibility of it acting as a storage unit (daily or seasonal) (Loredo et al., 2017). Although it should be noted for single DBHEs BTES is less efficient than shallower arrays due to greater heat losses and has greater performance in shorter storage periods (Brown et al., 2023a,b).

In conclusion, geothermal energy offers multiple uses for heating and cooling decarbonisation, making it a versatile and essential component in achieving sustainable energy goals. In the case of deep closed-loop systems, it is likely they would be best used as anchor loads for heat supply. Past work has showed they operate most efficiently with near constant loads of extraction as they do not have flexibility to meet varying load profiles due to the limited heat transfer potential of conduction through the borehole wall (Ben et al., 2025). Whilst they also have potential to be used for thermal energy storage, past work has shown individual DBHEs will generally have inefficient recovery factors, so should only be used for BTES if there is significant surplus waste heat or low-to-negative electricity prices enabling charging via heat pumps (Brown et al., 2023a,b,c).

5.2 Power Generation

There is the potential to couple deep closed-loop systems with generators to create electricity to supply the grid. However, the plausibility of consistently delivering high temperature and high-power output has been questioned in literature in areas outside those which do not naturally have high heat flows or geothermal gradients. For instance, recently Tangirala and Vilarrasa

(2025) suggested that these types of systems are unlikely to recover costs over their lifetimes and AGS are not scalable purely for electricity generation. They suggest costly multi-lateral systems are required to slow flow rate in horizontal sections, whilst maintaining high flow rates in the vertical boreholes to increase the power generation. Thus, they conclude 'claims of universal geographical scalability of closed loop geothermal systems in power generation (not coupled with direct use application) at competitive prices are not supported by simulation results, which demonstrate a rapid temperature drop at the production well caused by limited heat conduction from the rock to the flowing water within the well to be a limitation of this technology'. Although it should be noted that the study acknowledges the simplified set up of using two decoupled 2-D axisymmetric models which could impact results. The study also wasn't designed to evaluate the feasibility of repurposing existing wells. When considering repurposing wells, it may be even more problematic for development for power generation as these would not necessarily be drilled in high heat flow areas, unless repurposing a failed (i.e., dry) conventional geothermal well.

Although AGS systems are often classified based on well architecture (e.g., coaxial DBHE, U-type, and multilateral designs), alternative classification frameworks also exist. An alternative approach is based on the dominant heat transfer mechanism. Most studies emphasise conductive heat transfer through the borehole wall to a pressurised heat transfer fluid. However, other system designs exploit advective processes and may incorporate phase-change mechanisms, which have the potential to further enhance thermal performance and scalability potential (Amaya et al., 2024). Such technologies aiming to exploit high heat flow areas are undergoing field testing to explore the potential for power generation. As reported by Van Horn et al. and Amaya et al. (2020), field trials in an unproductive geothermal well in a high heat flow area in Coso, California allowed efficient operation of a 1000 ft (approximately 305 m) closed loop for power generation. A vacuum insulated tubing was inserted within a plugged liner, with natural fluid circulating around the outside. Testing highlighted it could produce an estimated 1 MW_e of net power from low flow rates with temperatures of ~175 °C (Higgins et al., 2019). Thus, it appears this technology could have potential to be used for repurposing, although when repurposing hydrocarbon wells developments should be targeted in high heat flow areas.

There are further issues when coupling deep closed-loop systems to power plants generally. In contrast to open-loop systems, deep closed loop systems produce lower outlet-fluid temperatures at lower flow rates, resulting in lower efficiencies during power generation. Or, to produce higher temperatures at higher flow rates they require more complex multi-lateral systems. Alimonti et al. (2021) studied different applications of a DBHE including district heating (DH), adsorption cooling (ABS_CHILL), Organic Rankine Cycle or ORC power production (ORC) and a thermal cascade system combining district heating with either ORC power production (ORC + DH) or adsorption cooling (ABS_CHILL + DH). Adsorption cooling results in the lowest exergy efficiency. The ORC gives exergy efficiencies between 20 – 30 %, comparable to existing binary power plants. It works best when combined with district heating for bottom hole temperatures above 300 °C, however, realistic bottom hole temperatures for most places will fall between 100 °C and 300 °C. For these temperatures, combining adsorption cooling with district heating and then district heating alone, give the best exergy efficiencies.

Several works have looked at the potential of generating electricity from DBHEs. Akhmadullin and Tyagi (2014) compared different working fluids for power generation in a DBHE using a geo-pressured reservoir in Vermilion Parish, United States as case study. The working fluid with the maximum efficiency of 14.85% was n-Pentane resulting in an electrical power of 321.23 kW_e. The optimal length of the DBHE was determined to be 304.8 m for brine produced at 126 °C. Wang et al. (2007) used isopentane as working fluid. They reported thermal powers above 150 kW which can be significantly increased to 500 kW when the DBHE is connected to a reservoir fracture. However, the net electrical power was still very low (< 80 kW_e). Similar values were reported by Nalla et al. (2005) who state that it is unlikely that a DBHE can produce more than 50 kW_e electrical power after reaching pseudo steady-state conditions. Noorollahi et al. (2015) investigated a 4.4 km well in Iran and found a thermal power of 1842 kW with a net electrical power of 364 kW_e. Wight and Bennett (2015) studied power generation from abandoned hydrocarbon wells in Texas using DBHEs. For well depths between 4.2 km and 6.8 km, net electrical power recorded ranged between 108.59 kW_e and 629.74 kW_e.

Several authors have studied the potential of electricity generation from a 6 km deep DBHE (Kolo et al., 2023b). Cheng et al. (2012) reported a maximum net electrical power of 134 kW_e while Alimonti and Soldo (2016) reported a thermal power of 1.5 MW with net electrical power of 134 kW_e. Davis and Michaelides (2009) reported a very high net electrical power of 3 MW_e from a 3 km abandoned oil well in South Texas. Their study does not seem to mention simulation times and thermal drawdown that occurs with time when extracting from a DBHE.

Further work by Facci et al. (2024) investigated the potential of repurposed hydrocarbon wells in Italy as U-type AGS for power generation. They showed that the potential from power generation for this type of technology is low at 50 to 143 kW_e, with the reference case a 3 x 2 km U-type system. Similarly, Higgins and Pratson (2026) investigated the potential of repurposed horizontal hydrocarbon wells as coaxial DBHEs in the U.S, highlighting they can produce 36 kW_e of electricity from a binary organic Rankine cycle generator from a DBHE with 3 km vertical and 2 km lateral with competitive levelised cost of electricity.

6. Discussion

Deep closed-loop systems have strong potential to supply heat, providing there is nearby demand, thanks to their predictable performance and low inherent geological risk due to their lack of hydraulic interaction within the subsurface. When using repurposed infrastructure, they also have limited initial capital expenditure, as costly drilling has already been completed. However, several barriers and limitations remain in place which may prevent installation of closed-loop systems in repurposed wells. These challenges are associated to technological barriers associated to system installation, physical nature of the system and mechanism of heat transfer limiting the power potential, geographical restrictions, regulatory factors and liabilities. Furthermore, subsurface temperature data sets are essential to development to provide accurate thermal profiles for the well and allow accurate prediction of the systems thermal capacity. In the UK, there are many open data sets available both on- and off-shore to allow access to not only thermal profiles but wellbore completion data (e.g., Rollin et al., 1997).

6.1 Closed-loop Thermal Power Potential

The most feasible way of repurposing existing boreholes, that has been demonstrated in test sites is the DBHE concept. Whilst this is an effective mechanism for repurposing, typically these types of systems have low thermal power outputs in the order of hundreds of kilowatts, unless in high heat flow areas – such as the system in Coso, California (Amaya et al. 2020; Van Horn et al. 2020). For instance, Banks et al. (2024) demonstrated varying power outputs up to 3 km in depth for a range of rock thermal conductivities (Figure 7). The study highlighted thermal output increases non-linearly with depth and increases with thermal conductivity. From this, and other studies outlined in this review, it highlights the potential thermal capacity of such systems is orders of magnitude lower than open-loop systems as the dominant mechanism of heat transfer is conduction, rather than advection.

However, for more complex geometry AGSs, the power output can be significantly increased with greater surface contact areas between rock and wellbore for heat transfer. While this does enhance the thermal capacity of the systems, it is likely to increase costs to connect multiple vertical wellbores and create lateral pathways in U-type systems. It also remains a question on the feasibility of connecting two existing wells, given they would be initially designed to narrow with depth towards a reservoir in the typical telescopic configuration of hydrocarbon wells. It may be more possible in failed geothermal wells which have slightly different completion configurations, often including liners which have the potential to be removed. Nevertheless, avoiding drilling of new wells through repurposing will lower capital expenditure and improve the levelized costs of heat and electricity (Beckers et al., 2022).

6.2 Well Integrity

One of the principal technical challenges of repurposing hydrocarbon wells for geothermal use is ensuring the mechanical integrity of the well.

Well integrity is generally defined as maintaining full control of fluids within a well at all times by employing and maintaining one or more well barriers to prevent unintended fluid movement between formations with different pressure regimes or loss of containment to the environment (Environment Agency, 2022; Santos et al., 2022). Maintaining the integrity of the well is therefore critical to prevent environmental contamination and methane emissions, which may occur if the well is not sufficiently sealed and monitored (Lebel et al., 2020).

The integrity of wells hinge upon their construction materials and method of construction (Meenakshisundaram et al., 2024). The older the well, the less likely it will have been constructed with the latest technology required for current performance standards and commissioning criteria, which can make their repurposing less likely (Environment Agency, 2021; Meenakshisundaram et al., 2024). In addition to aging wells, examples of wells that are more likely to have long term well integrity issues include wells drilled in years of abnormally high drilling activity and wells that are deviated (Environment Agency, 2021). As a result, well integrity is a key issue when considering the potential to repurpose wells.

6.3 Proximity to Demand for Heat

One critical aspect to consider when repurposing wells for closed-loop geothermal heat extraction is the proximity to the actual demand for heat. While the cost of extraction is significant, the distance between the geothermal source and the heat demand plays a crucial role in evaluating the feasibility and efficiency of such projects. Aside from industrial high-temperature heat demand, most heat demands exist in densely populated urban areas, which introduces technical challenges related to underground installations. Beyond drilling costs, proximity considerations must address interactions with other utilities, such as water, electricity, and telecommunications infrastructure. Proper planning and coordination are necessary to avoid disruptions and ensure seamless integration. In addition, there are also potential issues with land use and ownership.

Proximity allows for reduced capital expenditure on heat network infrastructure (trenching and pipework), lower utility relocation costs, minimised thermal losses, and decreased operational expenses (pumping and ancillary controls). If the source is too far from the energy centre, the system's efficiency drops and costs escalate due to these factors. This is particularly an issue when repurposing existing wells as closed-loop geothermal systems, which are usually drilled outside of densely populated areas.

Moreover, offshore wells are likely to prove too costly for practical implementation due to the immense infrastructure required to transport heat over long distances, and inefficiencies of doing so. Therefore, optimising the proximity to demand is vital to achieve a cost-effective and efficient geothermal heating solution in repurposed wells. Moreso, it may be more practical to develop new industrial to domestic sites around repurposed wells. For example, Watson et al. (2020) considered using heat from Wytch Farm on the south coast of England for newly developed greenhouses and swimming pools.

6.4 Regulatory factors

The development of deep closed loop geothermal systems will likely be subject to a range of regulatory requirements, which will differ strongly from nation to nation. Depending on country, the repurposing of hydrocarbon wells as geothermal wells may involve satisfying hydrocarbon licensing authorities, health and safety bodies, planning authorities, environmental and water resources regulators or mining regulators.

In the UK, for example, the exploration for and development of hydrocarbon resources will require a so-called PEDL (Petroleum Exploration and Development Licence) from the government for the exploration area (NTSA, 2018). No such regional licensing exists for exploration and development of geothermal resources. Hence, the possession of a PEDL licence for hydrocarbons conveys no automatic right to develop geothermal resources, nor any exclusivity of access to geothermal resources within the PEDL area. In many other nations, the situation may be very different, and a system of regional geothermal exploration licences may exist (Fraser, 2013).

In the UK, penetrative exploration for both petroleum and geothermal resources below a footprint of land can only be carried out with the explicit permission of the landowner down to 300 m depth. Below 300 m depth, there are more widespread rights to explore beyond the surface footprint (Infrastructure Act, 2015).

The safe and responsible development, operation, decommissioning and abandonment of hydrocarbon wells in the UK is overseen by the Health and Safety Executive (HSE – Bradley and Norman, 2017). The operator will also typically require a series of licences or permits for specific activities from the Environment Agency (EA, 2020) in England (or their national counterparts in the other UK nations) and from the NSTA (2018, 2022). Planning permission will also be contingent on consultation with a range of regulatory bodies, including Mineral Planning Authorities.

The development of a closed loop geothermal borehole in England will primarily involve interaction with the Environment Agency (or national counterparts elsewhere in the UK). Until c. 2023, the regulation of closed loop geothermal systems in England was minimal, although there now exists a specific set of guidelines for the environmental permitting of such activities (EA, 2025). Many deep closed loop developments may not satisfy the “exemption” criteria specified in the guidelines and may thus require a bespoke Environmental Permit.

In rare cases where a hydrocarbon well might be repurposed as a hydrothermal well (i.e., extraction of hot groundwater / formation water), then it seems likely that the development would also require an abstraction licence to be acquired, as well as an environmental permit covering discharge or reinjection of the thermally spent water. Guidelines issued by the Environment Agency on this can be found at EA (2023).

The regulatory system in England and the UK is not typical of other nations, and the consultation, licensing and permitting system is likely to be significantly different elsewhere. Irrespective of location, among the environmental and engineering risks that will need to be considered in the repurposing of a hydrocarbon wells as a geothermal well are:

- Will the geothermal well be a true closed loop installation – i.e. will the well bore be completely hydraulically isolated from any downhole reservoir or formation? Or will there still be a section of borehole open to the reservoir (directly or via perforated casing or screen)? Is there any risk of artesian flow at surface?
- Will the circulating fluid be a formation water or an artificial fluid of controlled composition? If the latter, has the density contrast between the circulating fluid and any external dense formation brine been considered?
- Have galvanic and corrosion risks been adequately considered, especially in deep, saline, reducing environments?
- Is there any risk of fugitive emissions of hydrocarbons (e.g., methane) during operation, which could not only be dangerous but also elevate the climate risk potential of the operation?
- Is there an odour risk from fugitive emissions of hydrogen sulphide or other noxious gases?

- Have the thermal stresses been considered of circulating a chilled fluid to considerable depth (in a closed loop system) or in a reinjection well (open loop system)? How will these thermal stresses affect casing and grout integrity?
- If the geothermal well is not a true closed loop, have the risks of scaling and accumulation of naturally occurring radioactive materials, due to extreme hydrochemical conditions been considered? Have disposal routes been identified for NORM and scaling products?
- Has a monitoring and maintenance plan been developed to ensure that any decline in well performance or well integrity is identified at an early stage?
- What is the lifetime of the geothermal well?
- Is there a plan and financial resources for responsible decommissioning, plugging and abandonment?

Furthermore, in the UK geothermal energy is 'not recognised as a natural resource in UK legislation and there is no regulatory authority in the UK', and whilst aspects of geothermal are covered by existing regulations there is a significant need for further review of UK legislation (Abesser et al., 2023).

6.5 Asset Liabilities

As seen in Section 6.4, geothermal wells and hydrocarbon wells may be subject to very different sets of regulations, overseen by different regulatory bodies. The question thus arises, when a hydrocarbon well is converted to a geothermal well, does it suddenly cease to be a hydrocarbon well? Most importantly, if it is no longer a hydrocarbon well, is it no longer obliged to follow the rigorous decommissioning, plugging and abandonment procedure required for hydrocarbon wells in most advanced regulatory regimes? Is converting a hydrocarbon well to a geothermal well a route to avoiding the costly liabilities associated with a spent hydrocarbon well? Moving forward hydrocarbon, geothermal and environmental regulators must have a streamlined process to ensure that a legitimate pathway is developed to allow repurposing of hydrocarbon wells without diluting the obligation for responsible operation, maintenance, decommissioning and abandonment at end-of life.

7. Conclusions

This study assessed the potential for both hydrocarbon and geothermal exploration wells to be repurposed as closed-loop geothermal systems, turning an expiring asset and liability into a useful resource in the energy transition to net zero. The mechanisms of repurposing, status of wells, key factors influencing closed-loop performance, and connections to heat networks/ generators for electricity production were all examined, highlighting the potential strengths and limitations of repurposing wells.

Different types of mechanisms for repurposing wells as closed-loop systems exist; however, the simplest and most likely method to repurpose would be as a coaxial DBHE. More complex AGS structures are conceived, but have only been deployed as new AGS in Germany, China and Canada, and not via repurposed wells which could provide further technical limitations.

It is not uncommon for hydrocarbon wells to be repurposed during their lifetimes, particularly for other production related processes. Following cessation of production in hydrocarbon fields, wells are often decommissioned with permanent barriers such as cement plugs to prevent fluid migration; however, recompleting the well as a closed-loop DBHE can remove costs such as drilling and allow the delay of costly decommissioning. To test the viability thorough assessment must be undertaken to ensure no well integrity issues which may lead to interaction between the heat transfer fluid and surrounding rock. Furthermore, in the UK, 427 wells are identified at the time of writing as being suitable for repurposing as the status currently falls as operational and recently operational. In addition to hydrocarbon wells, failed or ex-geothermal wells for open-loop developments hold potential to be repurposed; however, they can have different barriers to hydrocarbon wells such as the incorporation of liners when completing the system which would either need to be removed or isolated below a packer as they can cause installation and operational issues due to the narrowing of borehole diameter.

Both geological and engineering factors impact the performance of closed-loop systems. The key geological features that influence performance impact the ability to either transmit heat, or the total heat within the system prior to operation, including ground thermal conductivity, natural geothermal gradient, groundwater flow and free- or forced- convection. Engineering parameters also effect performance. These include the thermal properties of wellbore material and geometry, which are unlikely to be designed to optimise performance of closed-loop geothermal systems. This could lead to poorer thermal gain from surrounding rocks with lower thermal conductivity casing, or higher pressure drop in the heat transfer fluid in narrower portions of the borehole, leading to greater requirements from the circulation pump. These narrower portions of the borehole will also have lower contact areas with surrounding formations for heat transfer, may prevent installation of greater diameter more insulated central vacuum insulating tubing and increase thermal short circuiting.

Closed-loop systems also have potential to produce anchor loads for heat networks and limited potential in high heat flow areas for power generation. As conduction is the main method of heat transfer in a closed loop geothermal system, the potential to meet fluctuations in demand is limited (Ben et al., 2024). Thus, they are best operated using a constant load. There is also potential to utilise them for BTES; however, low efficiencies of single DBHEs means BTES should only be considered when there is no other user of waste heat, or when there are negative/low electricity prices which can be used to power heat pumps to charge the system. Application for electrical power generation is limited to high heat flow areas, where temperature gradients are sufficiently high that production temperatures are possible for electricity generation. Although this is likely to be significantly less than open-loop geothermal systems, in the order of hundreds of kilowatts.

Future work should focus on the technical possibility to connect vertical boreholes as AGSs with more complex geometrical configurations and the potential economic benefits of doing this in contrast to drilling a new system. In addition, more case studies and test facilities are required with open data to allow the assessment of system performance.

Acknowledgements

The authors would like to thank Andres Gonzalez Quiros and Mylene Receveur for their constructive comments during an internal review at BGS. The authors would also like to thank the editor and two anonymous reviewers which have helped to improve this paper. This work was supported by the British Geological Survey via NERC national capability and for the purpose of open access, the author has applied a Creative Commons Attribution (CC BY) licence to any Author Accepted Manuscript version arising.

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Figure Captions

Figure 1. Examples of closed-loop geothermal configurations, highlighting a) U-type DBHE, and b) inclined DBHE. Figure from White et al. (2024).

Figure 2. a) Estimated thermal gradient and existing onshore hydrocarbon wells locations in the UK, and b) north-east England candidates and c) Wytch Farm candidates. Taken from Nibbs et al. (2026), see references therein for data sources and details.

Figure 3. Depth plotted against thermal power for a range of DBHEs across the world. Compiled from Nibbs et al. (2026), Morita et al. (1992), Kohl et al. (2002), Kohl and Rybach (2003), Sapinska-Sliwa et al. (2016), Cai et al. (2019), Bu et al. (2019), Huang et al. (2020a), Pokhrel et al. (2022), Yishuo et al. (2022), Huang et al. (2025), Chen et al. (2023) and Liu et al. (2024).

Figure 4. Impact of different parameters on average heat transfer rate (in kW) after 6-month extraction from a 920 m DBHE with a flow rate of 8.33 L/s and an inlet temperature of 10°C (after Brown et al., 2023b).

Figure 5. Location and design of the phases of the SKEWS research project (taken from Seib et al., 2022).

Figure 6. Progression of district heating—1st–4th generation (from Thorsen et al., 2018).

Figure 7. Constant thermal power output over a 25-year simulation, without allowing the entry temperature of the DBHE to fall below 5 °C, after Banks et al. (2024) using a model from Beier (2020).

Table Captions

Table 1. Summary of the various states of active, suspended and partly and fully decommissioned wells, according to the NSTA's well operation notification systems (WONS) definition (NSTA, 2025b). NSTA data and information is for non-commercial use only. The NSTA Open User Licence is available here: https://www.nstauthority.co.uk/footer/terms-and-conditions/

Table 2. Operational status of onshore hydrocarbon wells in England, from NSTA (2025c) data. NSTA data and information is for non-commercial use only. The NSTA Open User Licence is available here: https://www.nstauthority.co.uk/footer/terms-and-conditions/

WONS Completion Status	Definition
Completed (Operating)	Completed wellbore that is currently active
Completed (Shut In)	A wellbore that is shut-in either at the tree valves or subsurface safety valve, (usually only applied if the wellbore is intended to be shut-in for 90 days or more).
Plugged	A wellbore that has been plugged with a plug rather than an abandonment barrier.
Abandoned Phase 1 (AB1) (Partly decommissioned)	Reservoir has been permanently isolated. Tubing may be left in place, fully or partly retrieved.
Abandoned Phase 2 (AB2) (Partly decommissioned)	All intermediate zones with flow potential have been permanently isolated.
Abandoned Phase 3 (AB3) – can be considered fully decommissioned	Wellhead and conductor are removed. Well origin at surface is removed. The well will never be used or re-entered again.

Table 1

Operational Status	Number
Abandonment Phase 1	220
Abandonment Phase 2	48
Abandonment Phase 3	1395
Completed (Operating)	300
Completed (Shut In)	127
Plugged	25

Table 2

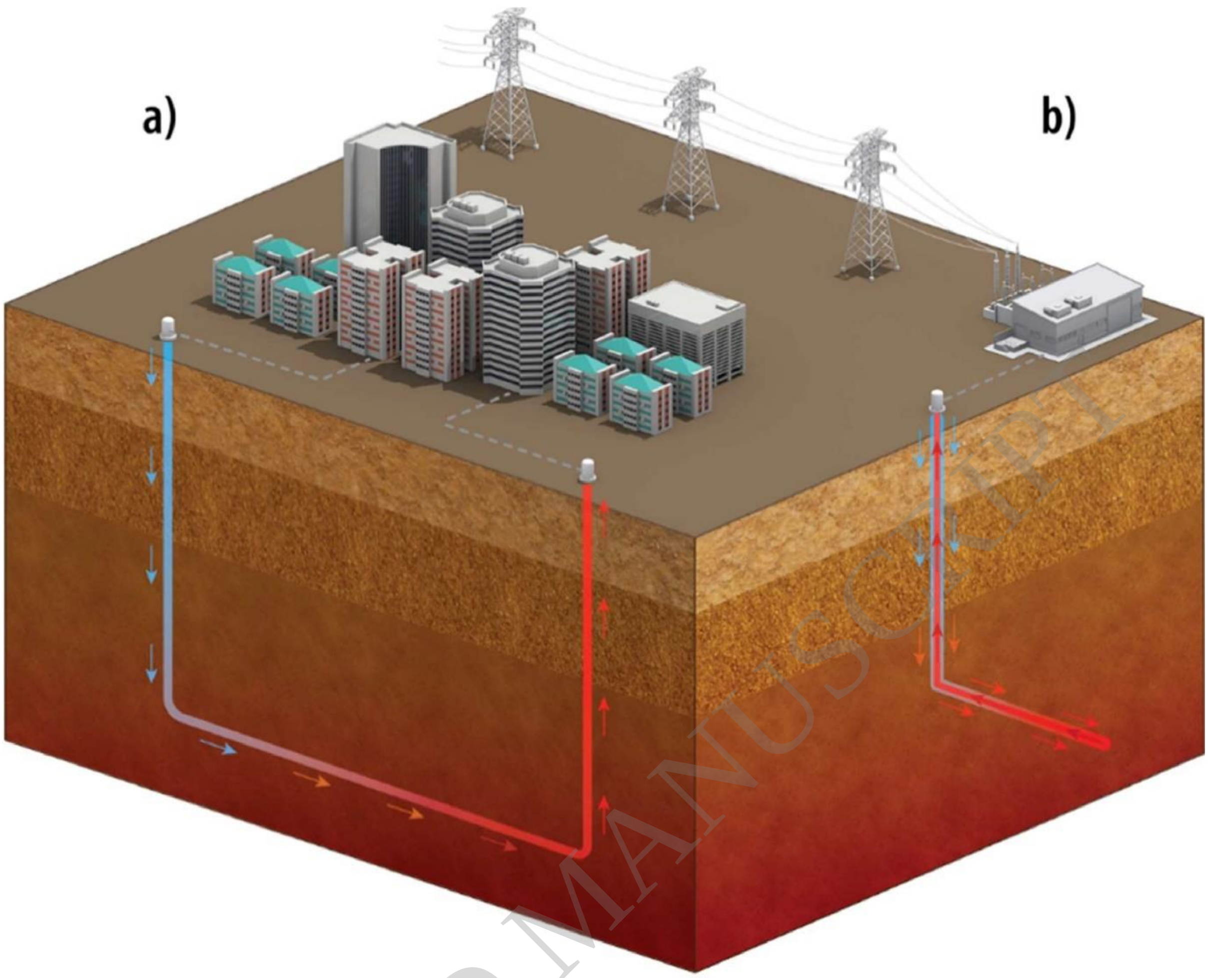
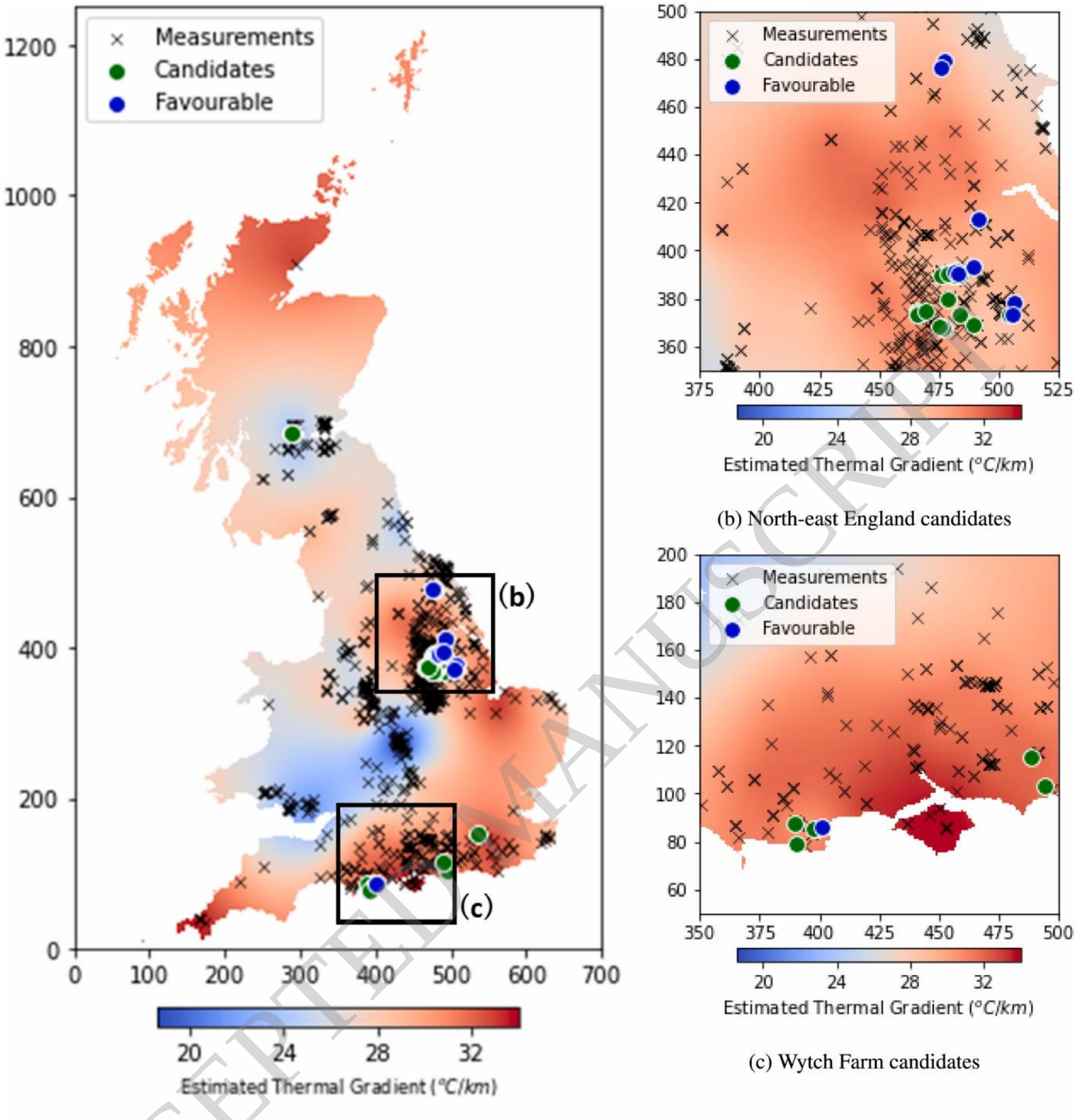


Figure 1



(a) UK thermal gradient estimates

(b) North-east England candidates

(c) Wytch Farm candidates

Figure 2

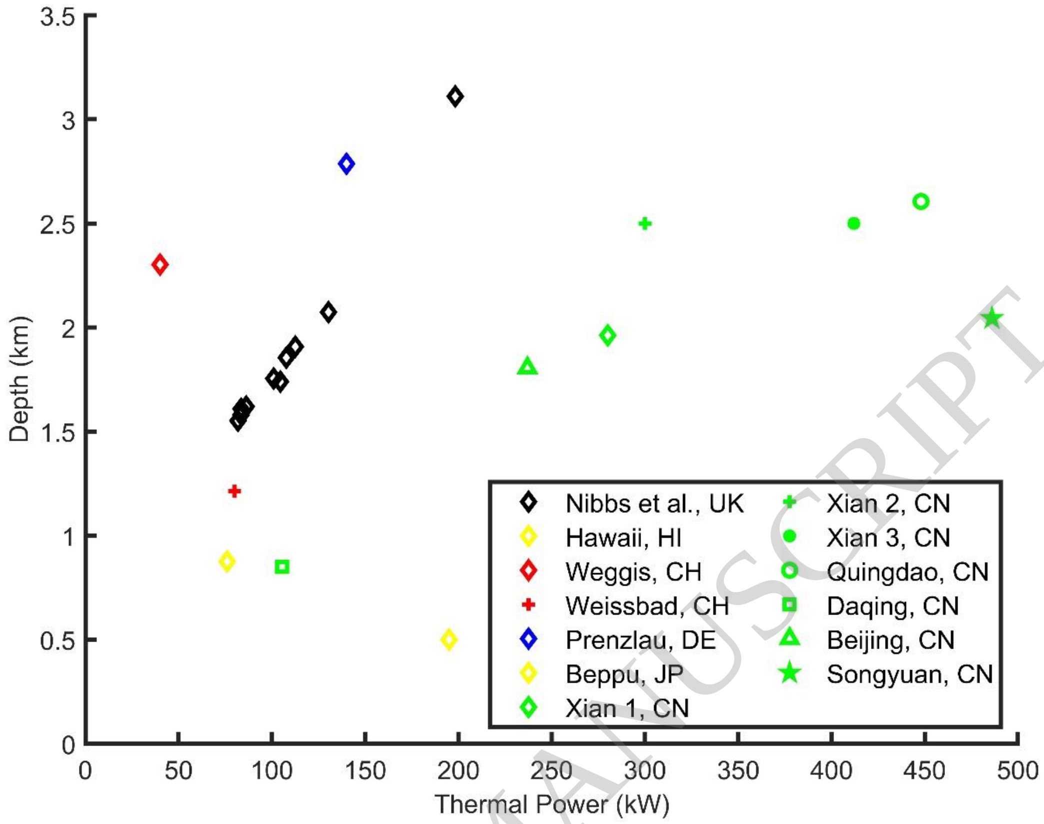

3.5
3
2.5
2
1.5
1
0.5
0
Depth (km)
0
50
100
150
200
250
300
350
400
450
500
Thermal Power (kW)
Nibbs et al., UK
Hawaii, HI
Weggis, CH
Weissbad, CH
Prenzlau, DE
Beppu, JP
Xian 1, CN
Xian 2, CN
Xian 3, CN
Quingdao, CN
Daqing, CN
Beijing, CN
Songyuan, CN

Figure 3

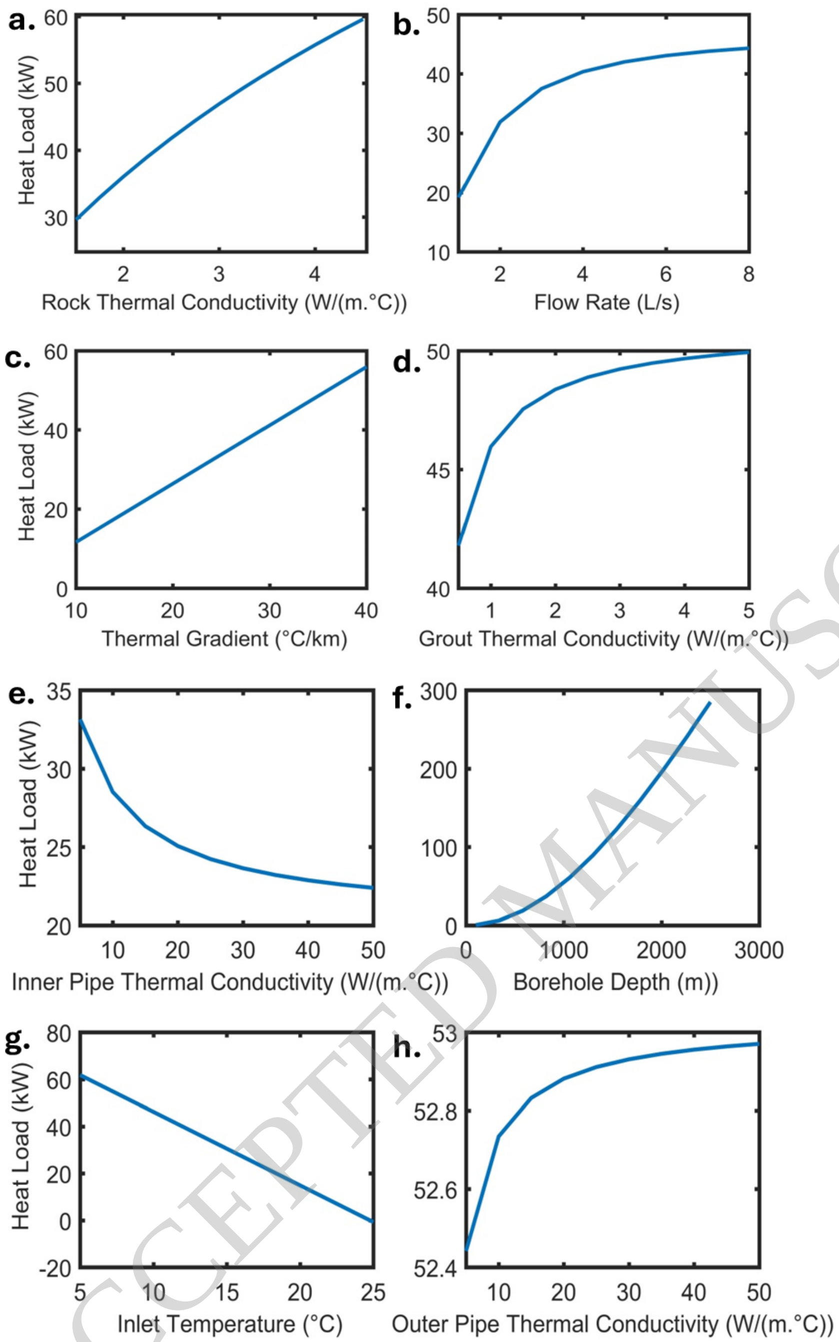

a.
Heat Load (kW)
Rock Thermal Conductivity (W/(m.°C))
b.
Flow Rate (L/s)
c.
Heat Load (kW)
Thermal Gradient (°C/km)
d.
Grout Thermal Conductivity (W/(m.°C))
e.
Heat Load (kW)
Inner Pipe Thermal Conductivity (W/(m.°C))
f.
Borehole Depth (m))
g.
Heat Load (kW)
Inlet Temperature (°C)
h.
Outer Pipe Thermal Conductivity (W/(m.°C))

Figure 4

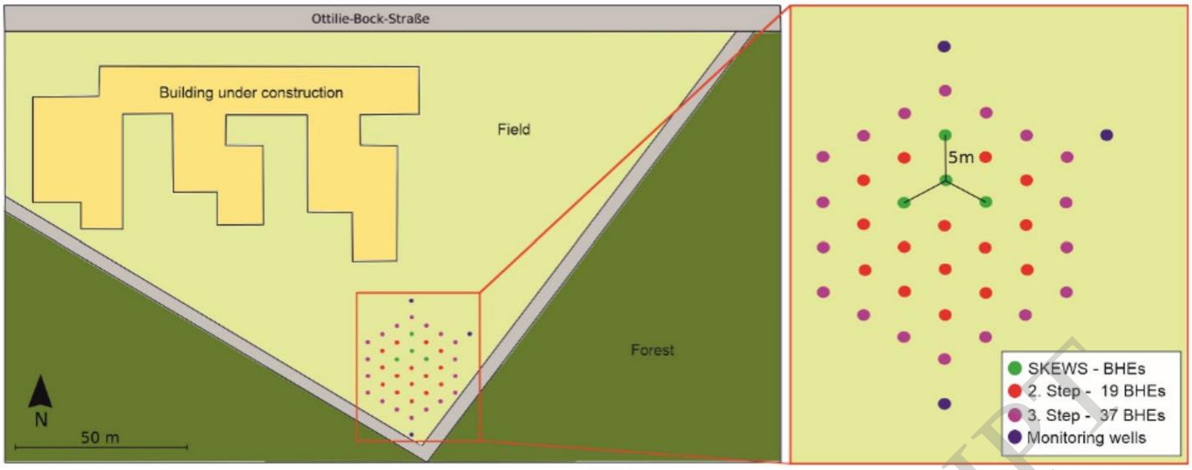

Ottilie-Bock-Straße
Building under construction
Field
Forest
N
50 m
5m
SKEWS - BHEs
2. Step - 19 BHEs
3. Step - 37 BHEs
Monitoring wells

Figure 5

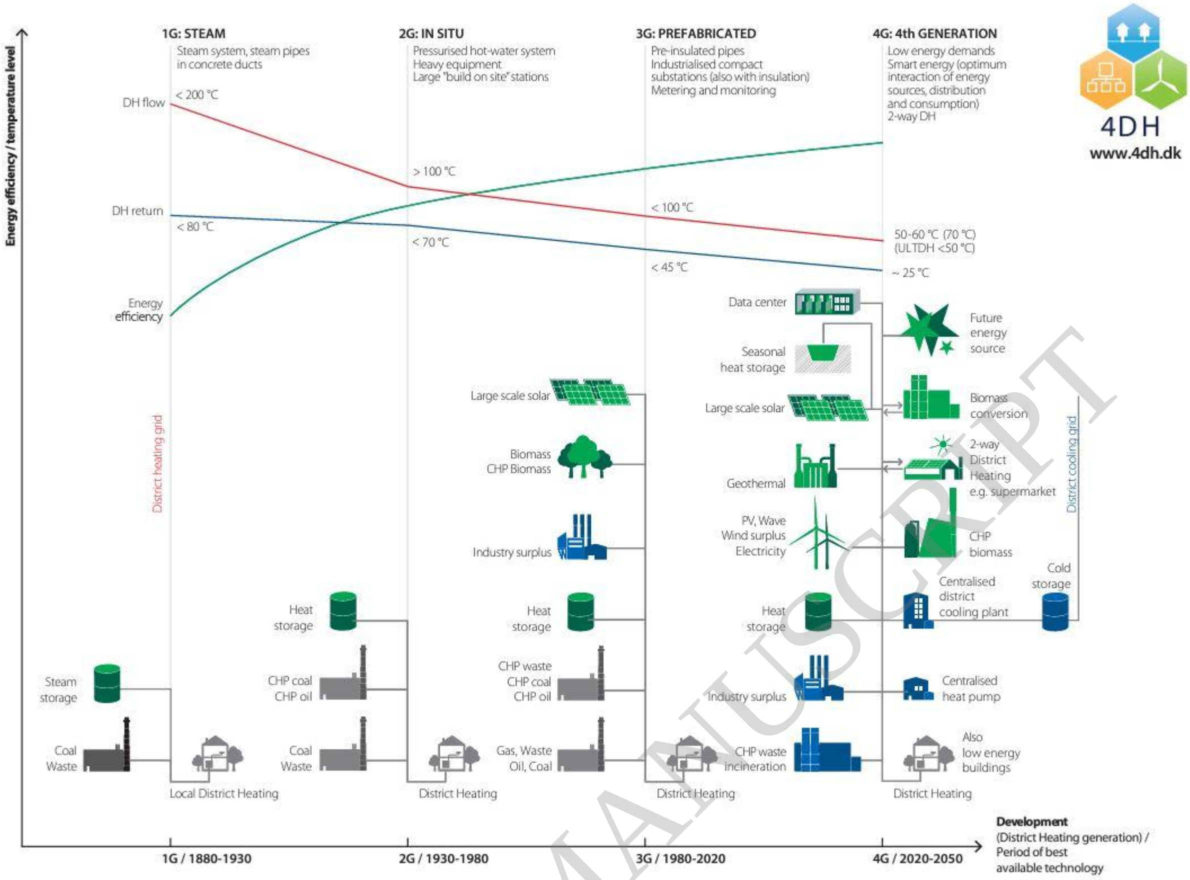

1G: STEAM
Steam system, steam pipes in concrete ducts
2G: IN SITU
Pressurised hot-water system
Heavy equipment
Large "build on site" stations
3G: PREFABRICATED
Pre-insulated pipes
Industrialised compact substations (also with insulation)
Metering and monitoring
4G: 4th GENERATION
Low energy demands
Smart energy (optimum interaction of energy sources, distribution and consumption)
2-way DH
4DH
www.4dh.dk
Energy efficiency / temperature level
DH flow
< 200 °C
> 100 °C
< 100 °C
50-60 °C (70 °C)
(ULTDH <50 °C)
DH return
< 80 °C
< 70 °C
< 45 °C
~ 25 °C
Energy efficiency
District heating grid
District cooling grid
Data center
Future energy source
Seasonal heat storage
Large scale solar
Biomass conversion
Biomass CHP Biomass
Geothermal
2-way District Heating e.g. supermarket
Industry surplus
PV, Wave Wind surplus Electricity
CHP biomass
Cold storage
Centralised district cooling plant
Heat storage
Steam storage
CHP coal CHP oil
CHP waste CHP coal CHP oil
Centralised heat pump
Coal Waste
Gas, Waste Oil, Coal
CHP waste incineration
Also low energy buildings
Local District Heating
District Heating
1G / 1880-1930
2G / 1930-1980
3G / 1980-2020
4G / 2020-2050
Development (District Heating generation) / Period of best available technology

Figure 6

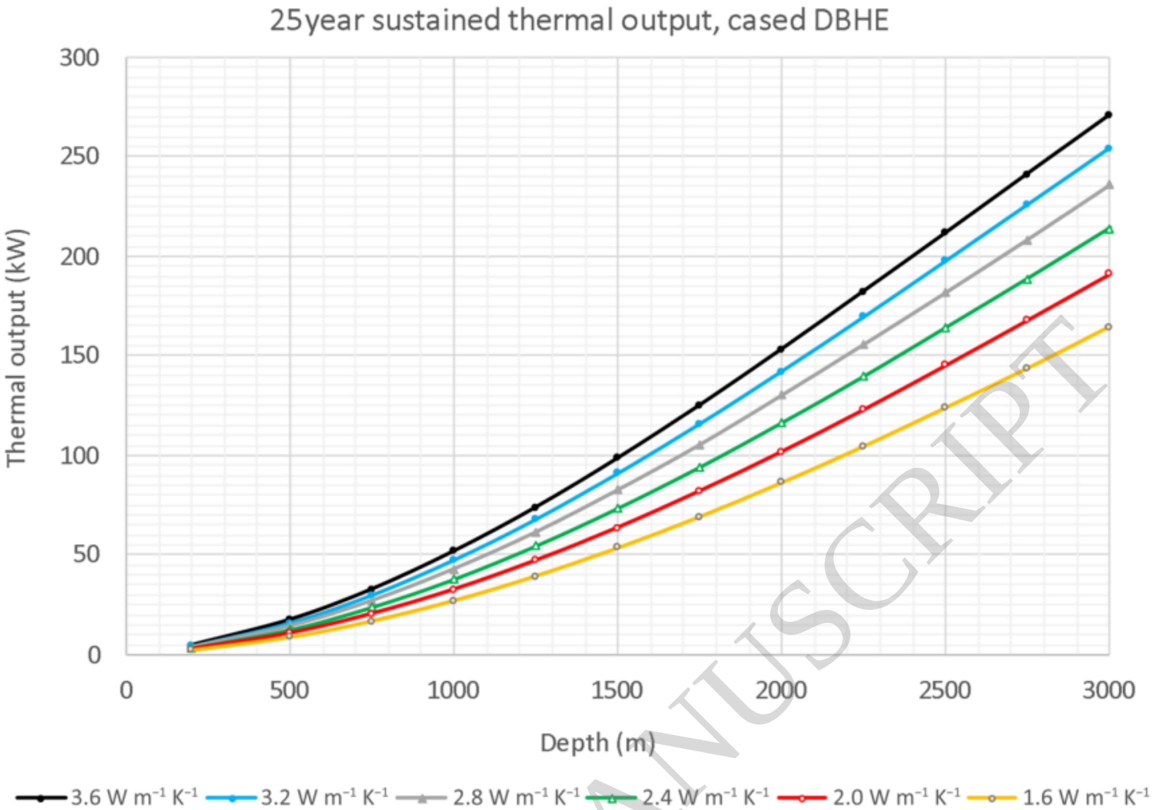

25year sustained thermal output, cased DBHE
Thermal output (kW)
300
250
200
150
100
50
0
0
500
1000
1500
2000
2500
3000
Depth (m)
3.6 W m⁻¹ K⁻¹
3.2 W m⁻¹ K⁻¹
2.8 W m⁻¹ K⁻¹
2.4 W m⁻¹ K⁻¹
2.0 W m⁻¹ K⁻¹
1.6 W m⁻¹ K⁻¹

Figure 7