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REVIEW

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A comprehensive review of deep borehole heat exchangers (DBHEs): subsurface modelling studies and applications

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Abstract

Deep borehole heat exchangers (DBHEs) with depths exceeding 500 m have been researched comprehensively in the literature, focusing on both applications and subsurface modelling. This review focuses on conventional (vertical) DBHEs and provides a critical literature survey to analyse (i) methodologies for modelling; (ii) results from heat extraction modelling; (iii) results from modelling deep borehole thermal energy storage; (iv) results from heating and cooling models; and (v) real case studies. Numerical models generally compare well to analytical models whilst maintaining more flexibility, but often with increased computational resources. Whilst in-situ geological parameters cannot be readily modified without resorting to well stimulation techniques (e.g. hydraulic or chemical stimulation), engineering system parameters (such as mass flow rate of the heat transfer fluid) can be optimised to increase thermal yield and overall system performance, and minimise pressure drops. In this active research area, gaps remain, such as limited detailed studies into the effects of geological heterogeneity on heat extraction. Other less studied areas include: DBHE arrays, boundary conditions and modes of operation. A small number of studies have been conducted to investigate the potential for deep borehole thermal energy storage (BTES) and an overview of storage efficiency metrics is provided herein to bring consistency to the reporting of thermal energy storage performance of such systems. The modifications required to accommodate cooling loads are also presented. Finally, the active field of DBHE research is generating a growing number of case studies, particularly in areas with low-cost drilling supply chains or abandoned hydrocarbon or geothermal wells suitable for repurposing. Existing and planned projects are thus presented for conventional (vertical) DBHEs. Despite growing interest in this area of research, further work is needed to explore DBHE systems for cooling and thermal energy storage.

Keywords: Deep borehole heat exchanger (DBHE), DBHE array projects, Closed-loop geothermal system, Deep borehole thermal energy storage (DBTES), Advanced geothermal systems, Numerical modelling, Analytical modelling

Introduction

Decarbonising heating and cooling is fundamental to realising a net-zero carbon emissions energy system (Carmichael 2019; Goldstein et al. 2020). Yet, space heating in the residential and public sectors continues to be sourced by natural gas (Goldstein et al. 2020), despite the availability of sustainable alternative heat sources. Geothermal energy has been demonstrated as one such feasible alternative to fossil-dominated heating and cooling (Durga et al. 2021; Gluyas et al. 2018). The geothermal energy sector has the potential to deliver baseload electricity generation, direct heating/cooling or by means of a heat pump, and thermal energy storage, independent of weather conditions. Conventional open-loop systems, for example, generate electricity using the heated fluid extracted from the reservoir via production wells. Heat transfer at surface subsequently drives power-producing generators, before the extracted fluid is then reinjected into the subsurface or disposed of at surface. To enhance subsurface flow pathways and well productivity, hydraulic and chemical stimulation of the reservoir can become necessary, thereby exposing such systems to risks such as induced seismicity (Pasqualetti 1980; Bayer et al. 2013). The high initial drilling cost coupled with high geological risk is seen as a further barrier to the adoption of hydrothermal geothermal systems, particularly Enhanced Geothermal Systems (EGS), at scale (Soltani et al. 2021).

Closed-loop systems provide an alternative to open-loop systems by removing direct hydraulic interactions with the reservoir. By operating using a single closed well design, conductive heat transfer between a heat transfer fluid and the surrounding geological formations is achieved through the borehole walls. Hence, the risk profile of closed-loop systems is considerably lower as the reliance on subsurface flow conditions is significantly reduced. Moreover, there is potential to offset the initial drilling cost by exploiting existing wells, such as abandoned oil and gas wells or failed geothermal exploration wells (Watson et al. 2020; Brown et al. 2024). As a trade-off to the minimised technical risks, heat transfer between the closed-loop system and the reservoir is restricted to conduction. A resulting far smaller volume of subsurface rock contributes to heat transfer. The reduced heat transfer potential limits the opportunities for electricity generation (Kolo et al. 2023) due to exergy losses and low conversion efficiencies (e.g. Alimonti et al. (2018, 2019); Renaud et al. (2019); Kolo et al. (2023); Chen et al. (2022); Alimonti et al. (2021)). Nonetheless closed-loop systems are well-placed to reduce greenhouse gas emissions in direct or heat pump-mediated heating applications (Ball 2021).

Closed-loop systems are not restricted to heat extraction applications. Shallow borehole heat exchangers (BHE) have also been widely demonstrated to provide effective heat storage services. Given the transient nature of heating and cooling demand profiles, with seasonal and climatic dependency, thermal energy storage systems, such as borehole thermal energy storage (BTES), have been shown to reduce energy production demands by time-shifting sources of heat and coolth. By storing heat in, and subsequently extracting heat from the ground by closed-loop fluid circulation, the subsurface acts as a thermal battery. The mode of operation holds true for cold storage.

Closed-loop BHEs come in various configurations of either a U-tube or coaxial tube. Most shallow BHE systems (< 300 m) use single or double-U tubes but triple-U tubes are also available (Zarrella et al. 2013). Although U-tube configurations are reliable, cheap and easy to install, coaxial pipes are frequently chosen due to their low thermal resistance, despite their installation difficulty and susceptibility to leakage (Gehlin 2016). The selection of coaxial BHEs is more common in deeper borehole designs (see Fig. 1), as described later, in part due to the lower thermal resistance and pressure losses of this configuration over U-tube designs (Brown et al. 2024).

The outer BHE pipe is commonly held in place, and thermally-connected to the surrounding rock matrix, via a grout medium. However, Scandinavian countries, characterised by hard crystalline rocks and high levels of groundwater (Skarphagen et al. 2019), typically leave BHEs ungrouted, thereby submerging the pipe(s) up to groundwater level. Through natural convection (i.e. an active groundwater flow in these semi-open BHE systems), heat transfer between BHE pipe and surrounding media can be enhanced (Gustafsson 2008).

In Deep BHE systems (DBHE)—classified herein as deeper than 500 m, as per the pre-existing UK Renewable Heat Incentive (Watson et al. 2020) and thus inclusive of the 'middle-deep' range considered in other works (Breede et al. 2015; Brown et al. 2024)—coaxial (concentric) pipes are mainly used due to issues related to strength and high hydraulic resistance (and thus unacceptably high parasitic pumping power) characteristic of narrow U tubes at high depths (Pan et al. 2019). Heat extraction via coaxial DBHEs operates by injecting a cold heat transfer fluid into the annulus or outer pipe (the CXA mode of operation), whilst gaining heat through conduction from the surrounding formation (Fig. 1). The heated fluid is extracted from the central or inner pipe and directed to the end-user (e.g. for space heating or greenhouse applications). The flow direction can be reversed when intending to inject heat into the surrounding subsurface media using the coaxial DBHE central pipe as the fluid inlet (the CXC mode of operation). Seasonally reversible combination of CXA and CXC is thus recommended for heat storage cycles comprising heat extraction and injection, as discussed further in "Thermal Energy Storage" section. Some practitioners have found, however, that practical considerations are far more important than the small marginal gains from reversing flow polarity in BTES systems (Heat pumps 2021; Brown et al. 2023). Further practical considerations

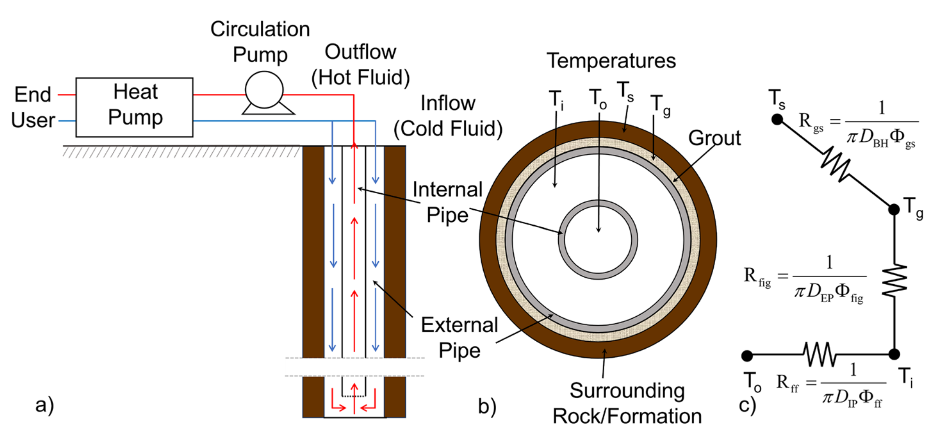

Fig. 1 Schematic diagram showing a complete coaxial DBHE system (adapted from Kong et al. (2017)): **a** whole system; **b** coaxial tube; **c** thermal resistances ($R_\bullet$) for coaxial configuration used to describe the heat transfer coefficients ($\Phi_\bullet$) in the governing equations. It is noted that ($R_\bullet$) is a function of the heat transfer coefficient ($\Phi_\bullet$) expressed as a function of the borehole diameter (D_{BH}), external pipe (inner) diameter (D_{EP}) or internal pipe (inner) diameter (D_{IP})

include the requirement to increase flow rates as the depth of the BHE increases. This is necessary in order to maintain effective heat transfer and minimise thermal "short-circuiting" between inflow and outflow fluid streams. The BHE pipe cross-sectional area must increase respectively to avoid large pressure drops (Holmberg et al. 2016) and drilling costs are likely to increase as a result.

Given the range of space heating applications, DBHE systems have received significant interest in recent times as demonstrated by other published reviews on DBHE technology. For example, Sapinska-Sliwa et al. (2016) presented a conceptual review of installed DBHE systems around the world without comprehensively addressing numerical modelling studies. Alimonti et al. (2018) reviewed modelling of DBHE systems with a focus on their design and performance for heat and/or electricity generation. Advanced Geothermal System (AGS) technologies, to which DBHEs belong, have been reviewed by Budiono et al. (2022), but their work does not include deep BTES. This work therefore aims to provide a comprehensive review on numerical and analytical modelling of closed-loop conventional (vertical) DBHEs and their various applications in heating, cooling and storage, including those not captured by Sapinska-Sliwa et al. (2016). The review extends to describe a range of existing and planned projects. By comprehensively reviewing the applied and theoretical work in this research field, the work herein intends to elucidate remaining gaps and directions for future DBHE research.

Modelling approach

Experimental or pilot studies on DBHE systems are limited and research has tended to focus on analytical or numerical modelling studies, due to cost and time constraints (Jahangir et al. 2018; Bu et al. 2019). Analytical models work with simple geometries and use the Cartesian and cylindrical coordinate system of DBHE systems; however, insights from the full dimension can become important under complicated geological conditions (Skarphagen et al. 2019). For example, many quasi-three-dimensional analytical models assume a constant borehole temperature for the boreholes, but the effect of the geothermal gradient is an important consideration in deep boreholes (Pan et al. 2019). Analytical models struggle with combining geothermal gradient and heterogeneity in the subsurface formations. Also, it is difficult to get realistic values of borehole thermal resistance, because in DBHEs, thermal short-circuiting becomes more important (and flow rate dependent) and there may also be complex radial geometry to the borehole construction (several strings of casing and grout). It is worth noting that analytical models are more efficient in dealing with long year-on-year simulations, with complex (but annually repeating) heating loads. Numerical models are required to cope with the complexity ignored by analytical attempts, which can lead to long run-times. Different discretisation schemes have been used for subsurface numerical modelling of DBHE systems including finite element method (FEM)(e.g. Diersch (2013); Chen et al. (2019)), finite-difference method (FDM) (e.g. Brown et al. (2021)) and finite volume method (FVM) (e.g. Renaud et al. (2019)).

Governing equations

To model DBHE systems, two processes have to be described: heat and mass transport in (i) the surrounding subsurface and (ii) the DBHE pipes. It is important to quantify the heat flux exchange between the surrounding subsurface and DBHE pipes. Therefore, three sets of governing equations have to be included—(a) mass and energy conservation in the surrounding subsurface; (b) mass and energy conservation in the DBHE pipes; (c) heat flux coupling between DBHE pipes and surrounding subsurface.

Mass and energy conservation equations in surrounding subsurface

Considering the surrounding subsurface as a porous medium, the mass conservation equation can be written as

$$S\frac{\partial p}{\partial t} + \nabla \cdot \mathbf{v}_{\mathrm{w}} = 0 \tag{1}$$

where S is the constrained specific storage (1/Pa) and $\mathbf{v}_{\mathrm{w}}$ is the Darcy's velocity (m/s) that is given by

$$\mathbf{v}_{\mathrm{w}} = -\frac{\mathbf{k}}{\mu}\left(\nabla p + \rho_{\mathrm{w}}\mathbf{g}\right) \tag{2}$$

where $\mathbf{k}$ is the permeability (tensor) of the porous medium (m^2), μ is the dynamic viscosity (Pa s), ρ_{w} is the water density ($\mathrm{kg/m}^3$) and $\mathbf{g}$ is the gravitational acceleration vector.

If there are fractures in the surrounding subsurface, the mass conservation equation should include the fracture effect (Deng et al. 2023). The fracture flow can be described in general as

$$bS_{\mathrm{frac}}\frac{\partial p}{\partial t} + \nabla \cdot (b\mathbf{v}_{\mathrm{frac}}) = 0 \tag{3}$$

where b is the fracture aperture (m), S_{frac} is the specific storage of fracture (1/Pa) and $\mathbf{v}_{\mathrm{frac}}$ is the Darcy velocity in the fracture (m/s) that can be calculated according to the cubic law (He et al. 2021),

$$\mathbf{v}_{\mathrm{frac}} = -\frac{b^2}{12\mu}\left(\nabla p + \rho_{\mathrm{w}}\mathbf{g}\right) \tag{4}$$

The surrounding subsurface temperature T_{s} is determined by the following energy conservation equation considering both heat convection and conduction in porous media,

$$[\epsilon\rho_{\mathrm{w}}c_{\mathrm{w}} + (1-\epsilon)\rho_{\mathrm{s}}c_{\mathrm{s}}]\frac{\partial T_{\mathrm{s}}}{\partial t} + \rho_{\mathrm{w}}c_{\mathrm{w}}\mathbf{v}_{\mathrm{w}} \cdot \nabla T_{\mathrm{s}} - \nabla \cdot (\Lambda_{\mathrm{s}} \cdot \nabla T_{\mathrm{s}}) = H_{\mathrm{s}}, \tag{5}$$

where c_{s} is the solid mineral phase specific heat capacity, ρ_{s} is the solid mineral phase density and ϵ is the rock porosity. c_{w}, ρ_{w}, and $\mathbf{v}_{\mathrm{w}}$ refer to the specific heat capacity, density, and velocity of groundwater, respectively. Λ_{s} denotes the tensor of thermal dispersion and H_{s} represents the heat source or sink terms.

In analogy to the hydraulic mass balance equation in fractures, the heat transport equation also needs to be multiplied by the fracture aperture b accordingly when there is fractured media in the surrounding subsurface. The velocity in the fractures is calculated according to the cubic law and the Darcy law as shown in Eq. (4). When considering the various thermal properties in the subsurface groundwater, such as density, viscosity, thermal conductivity, and specific heat capacity, the water equation of state based on the International Association for the Properties of Water and Steam (IAPWS-IF97) (Wagner and Kretzschmar 2007) can be further applied in the models.

Mass and energy conservation equations in DBHE pipes

When analysing mass conservation in DBHE pipes, most studies assumed that the total flow rate of the circulation fluid is constant. Therefore, no additional mass conservation equation needs to be considered. In this case, the thermosiphon effect caused by variable-density process in DBHE pipes cannot be simulated. When the DBHE systems are very deep or of high temperatures with significant variable thermal properties, Computational Fluid Dynamics (CFD) techniques and models have to be applied in the DBHE coaxial pipes, e.g. Renaud et al. (2019); Doran et al. (2021); Hu et al. (2021); Alimonti et al. (2021). In this method, the fluid flow in the DBHE pipes is governed by general equations of mass and momentum continuity:

$$\frac{\partial A\rho_{\mathrm{f}}}{\partial t} + \nabla \cdot (A\rho_{\mathrm{f}}\mathbf{v}_{\mathrm{f}}) = 0 \tag{6}$$

$$\rho_{\mathrm{f}}\frac{\partial \mathbf{v}_{\mathrm{f}}}{\partial t} + \rho_{\mathrm{f}}\mathbf{v}_{\mathrm{f}} \cdot \nabla \mathbf{v}_{\mathrm{f}} = -\nabla p + \nabla \cdot \tau + \mathbf{F} \tag{7}$$

where A is the cross-sectional area of the pipe (m^2), and $\mathbf{v}_{\mathrm{f}}$ refers to the cross-section averaged velocity vector in the DBHE pipes. τ (Pa) is the viscous stress tensor and $\mathbf{F}$ ($\mathrm{N/m}^3$) is the volume force (i.e. gravity force).

From the energy conservation principle, the governing equation of the circulation fluid inside the inner and outer pipes can be written as

$$\rho_{\mathrm{f}}c_{\mathrm{f}}A_k\frac{\partial T_k}{\partial t} + \rho_{\mathrm{f}}c_{\mathrm{f}}A_k\mathbf{v}_k \cdot \nabla T_k - \nabla \cdot (A_k\Lambda_{\mathrm{f}} \cdot \nabla T_k) = H_k,\ (k = \mathrm{i}, \mathrm{o}) \tag{8}$$

where ρ_{f}, c_{f} refer to the density and specific heat capacity of the circulation fluid. The symbols $\mathbf{v}_k$ $(k = i, o)$ denotes the flow velocity of inner (i) and outer (o) pipes of the DBHE. The symbol H is the heat sink/source term. The thermal dispersion tensor Λ_{f} is defined as

$$\Lambda_{\mathrm{f}} = (\lambda_{\mathrm{f}} + \rho_{\mathrm{f}}c_{\mathrm{f}}\beta_{\mathrm{L}}\|\mathbf{v}_{\mathrm{f}}\|)\mathbf{I} \tag{9}$$

where β_{L} denotes the longitudinal heat dispersivity and $\mathbf{I}$ refers to the identity matrix. $\mathbf{v}_{\mathrm{f}}$ is the circulation fluid velocity, λ_{f} is the thermal conductivity of the circulation fluid.

Generally, the coaxial pipe is embedded and fixed inside the borehole by a grout material to enhance the thermal exchange area and efficiency as shown in Fig. 1. Assuming that heat convection within the grout is negligible, the grout temperature (T_{g}) is governed by the heat conduction equation:

$$\rho_{\mathrm{g}}c_{\mathrm{g}}A_g\frac{\partial T_{\mathrm{g}}}{\partial t} - \nabla \cdot \left(A_g\lambda_{\mathrm{g}} \cdot \nabla T_{\mathrm{g}}\right) = H_{\mathrm{g}} \tag{10}$$

where the subscript g represents the grout component inside the borehole.

Heat flux coupling between DBHE pipes and surrounding subsurface

In closed-loop DBHE systems, it is assumed that no mass of circulation fluid inside the DBHE pipes will be in contact with the surrounding subsurface; there is only conductive heat exchange. Thus, the first important coupling term is the heat flux exchange between the grout material (if existent) and the surrounding subsurface. The dynamic coupling heat flux ($q_{nT_{gs}}$) can be quantified by the following equation (using Cauchy-type boundary condition):

$$q_{nT_s} = -\Phi_{gs}\left(T_g - T_s\right) \text{ at } \Gamma_s, \tag{11}$$

where Γ_s and Φ_{gs} are the boundary and the heat transfer coefficient between the borehole grout and surrounding subsurface, respectively, see Fig. 1.

The heat flux exchange for the component of the grout (q_{nT_g}) includes two parts: one is the exchange with surrounding formation, and the other is the exchange with the inflow fluid in the annulus pipe in the CXA configuration. The total heat flux can be then expressed as

$$q_{nT_g} = -\Phi_{gs}\left(T_s - T_g\right) - \Phi_{fig}\left(T_i - T_g\right) \text{ at } \Gamma_g \tag{12}$$

where, Φ_{fig} denotes the heat transfer coefficient between the outer pipe and grout (Fig. 1).

For the coaxial pipes in the DBHE system, the heat flux (q_{nT_i}) between the grout material and the circulation fluid in the outer pipe, and the heat flux (q_{nT_o}) between the circulation fluid in the outer and inner pipes can be expressed as

$$q_{nT_i} = -\,\Phi_{fig}\left(T_g - T_i\right) - \Phi_{ff}(T_i - T_o) \text{ at } \Gamma_i \tag{13}$$

$$q_{nT_o} = -\,\Phi_{ff}(T_o - T_i) \text{ at } \Gamma_o \tag{14}$$

where Φ_{ff} refers to the heat transfer coefficient between the circulation fluid in inner and outer pipes, and Γ is the heat transfer boundary, subscripts i and o denote the inflow fluid in the annulus pipe and outflow fluid in the inner pipe, respectively.

There are multiple expressions for the heat transfer coefficient Φ_{gs}, Φ_{fig}, and Φ_{ff}; the widely used method is so-called thermal resistance and capacity model (TRCM) introduced by Bauer et al. (2011) and further implemented in numerical models by Diersch et al. (2011) and Chen et al. (2019). These heat transfer coefficients are strongly dependent on the pipe geometry, thermal properties of the circulation fluid and the flow state, leading to local non-equilibrium and global non-linear problems and thus posing challenges for the transient simulation. For example, as shown in Fig. 1, the heat transfer coefficients (Φ) are a function of thermal resistances (R), see Diersch et al. (2011) for the detailed computation of thermal resistance. In addition, for the thermal properties of the circulation fluid in the closed loop, the open source package CoolProp can be used to calculate pure and pseudo-pure fluid equations of state and transport properties for 122 components (Bell et al. 2014). It is noted that single-phase liquid flow has been assumed for the circulating water as this is phase at the temperatures and pressures encountered for DBHEs. Moreover, according to Chen et al. (2019), the variation in thermo-physical properties of water along the depth of a 2.6 km DBHE resulted in negligible effects making it reasonable to consider constant thermo-physical properties for the circulating water.

Analytical

The most widely used analytical tools for analysing heat transfer in DBHEs are Kelvin's theory of heat sources and the Laplace transform method (Jaeger and Carslaw 1959). It is difficult to obtain analytical solutions directly to the governing equations presented earlier for general cases. Therefore, some assumptions and simplification must be made to avoid complex derivations and calculations when developing a mathematical model of the DBHE to be solved analytically. These assumptions and simplification can be mainly summarised as three points:

1. **Infinite or semi-infinite surrounding subsurface**. In this case, the far-field temperature is the same as the initial temperature and fixed as the boundary condition for analytical solutions.
2. **Homogeneous groundwater flow**. When the effect of groundwater is considered in the multi-layer subsurface with some or all of the layers having groundwater movement, the flow is generally assumed to be homogeneous and parallel to the ground surface.
3. **Constant and uniform thermal properties**. The thermal properties of all materials remain constant within the investigated temperature range. Only heat transport equations are solved analytically, mass conservation equation inside the coaxial pipe is not taken into account.

The first assumption is the basis for all the analytical solutions and is widely used from infinite line-source (Ingersoll 1950), infinite cylindrical source (Kavanaugh 1985) and finite line source (Eskilson 1987), to more advanced analytical solutions with various heat flux segment (Luo et al. 2019) and including geothermal gradient effect (Beier 2020). The second assumption is commonly applied in shallow BHE systems rather than DBHEs. For example, Diao et al. (2004) extended the infinite line source solution under homogeneous groundwater convection over the whole shallow BHE domain. In cases where the BHE penetrates the entire depth of the 3D porous medium, the analytical solution proposed by Molina-Giraldo et al. (2011) was applied to solve the spatio-temporal distribution of the induced ground temperature change. Hu (2017) also improved the infinite line source solution to investigate the effect of groundwater flow in multiple-layer geologies in a shallow BHE system. However, when the DBHE system is surrounded by fractured media or very heterogeneous porous media of inclined aquifers, this assumption limits the analytical modelling of single DBHE and multiple DBHE array. For example, although Luo et al. (2022) applied stratified-seepage-segmented finite line source method to semi-analytically model the DBHE system with multiple groundwater layers, the model could not simultaneously couple the effects of geothermal gradient, subsurface stratification and groundwater flow. In more recent analytical solutions, another strategy is adopted where the unit-step temperature response of the surrounding subsurface (i.e. G-function) is calculated together with the coaxial pipe inside the DBHE to have the temperature values inside the coaxial pipe. However, the usage of superposition principle restricts the analytical solution to linear physics (Li and Lai 2015). As for the third assumption, it will become unreasonable when the coaxial DBHE system goes deeper with larger pressure and temperature variation in the operation because of the heterogeneous heat transfer coefficients between pipes.

In some advanced analytical solutions, Beier (2020) improved upon the analytical solution presented in Beier et al. (2014) to include the influence of the geothermal gradient under variable heat extraction rates. The improved solution relied on the Stehfest (Stehfest 1970) algorithm to numerically perform an inverse Laplace transform and calculate temperatures in the time domain. Later, Beier et al. (2022) extended the analytical solution to a more advanced semi-analytical solution to include multiple ground layers and the geothermal gradient. Other examples of analytical solutions used to investigate heat extraction performance and analyse the influence of different parameters are those presented by Pan et al. (2019) and Pan et al. (2020). Additionally, some commercially-available software packages rely on analytical solutions to achieve fast computations and efficiency when designing ground loop heat exchangers. For example, Earth Energy Designer (EED 2021) and Ground Loop Heat Exchanger Design Software (GLHEPRO) (Cullin et al. 2015; Ground Loop 2023), specifically suited for designing shallow BHEs, account for the geothermal gradient by effectively setting the initial rock temperature as equal to the average temperature over the borehole depth (Eskilson 1987). However, key limitations to the analytical approach persist in its incapability to simulate i) complex boundary conditions and geological settings, ii) the impact of heterogeneous groundwater flow, and iii) non-constant thermal properties, especially for DBHE systems.

Numerical

Different numerical discretisation methods have been successfully adopted to model the heat transport process in coaxial DBHEs and their surrounding formation, including the FDM, FVM and FEM. Since the depth of a DBHE system can reach several thousand metres, cm-scale components inside the borehole will significantly increase the number of elements in the numerical model. Therefore, different numerical strategies have been devised (see Table 1) that can generally be divided into three main types:

1. **Dual-continuum methods:** A 1D discretisation for the DBHE is combined with a 3D discretisation for the surrounding formation. The approach was originally proposed by Al-Khoury et al. (2010) and extended in FEFLOW software by Diersch et al. (2011a), Diersch (2013), and Diersch et al. (2011b). Thereafter, Chen (2022) developed and presented two deep closed-loop borehole heat exchanger models implemented in the OpenGeoSys (OGS) software using the dual-continuum FEM method. Kong et al. (2017), Chen et al. (2019), Cai et al. (2022), and Kolo et al. (2023) compared the numerical results simulated by this implementation with Beier's analytical solution (Beier 2020), showing a very close match with temperature differences below 1 K. A difference of 0.57 K was recorded for extraction after one heating season (120 days) corresponding to a 2.2 % difference (Cai et al. 2022). Similarly, a 0.37 K temperature difference was recorded after 25 years of extraction (Kolo et al. 2023). The 2014 version of Beier's model Beier et al. (2014) which was generally intended for shallow BHEs also showed good comparison of $\Delta T < 0.7K$ with a DBHE model

Table 1 Features of typical single coaxial DBHE numerical models, discretisation method and corresponding software

Discretisation	Software	Depth (m)	Features	References
FVM	Inhouse MATLAB code	2500	2D model including fluid momentum balance equation, variable thermal properties, using water and CO_2 as circulation fluid	Bai et al. (2022)
FDM	Inhouse MATLAB code	2800	Nodal domain, 1D DBHE embedded in 3D subsurface	Brown et al. (2021)
FVM	Inhouse MATLAB code	4000 and 2600	Cylindrical axisymmetric domain, includes pressure loss in pipes, single DBHE	Bu et al. (2012, 2019)
FEM	OpenGeoSys	2000	3D subsurface element domain with 1D DBHE, multiple homogeneous DBHEs	Cai et al. (2021)
FVM	Inhouse MATLAB code	2000	2D model, single homogeneous DBHE	Liu et al. (2019), Cai et al. (2019)
FEM	COMSOL	1000-5000	2D model including Navier-Stokes for fluid flow, incompressible circulation fluid	Caulk and Tomac (2017)
FEM	OpenGeoSys	2600	3D subsurface element domain with 1D DBHE, locally thermal non-equilibrium	Chen et al. (2019)
FVM	Inhouse code	1000-3000	Cylindrical axisymmetric domain	Deng et al. (2020)
FDM	TOUGH2	2866	2D model including fluid mass and momentum balance equation, variable thermal properties, single heterogeneous DBHE	Doran et al. (2021)
FDM	Inhouse code	2600	2D model, single homogeneous DBHE	Fang et al. (2018), Zhang et al. (2021)
FDM	Inhouse MATLAB code	300-1000	Cylindrical axisymmetric domain, heat extraction and injection	Holmberg et al. (2016)
FDM	Inhouse Fortran90 code	500-800	Cylindrical axisymmetric domain, variable ground properties	Morchio and Fossa (2019)
FDM	SHEMAT	100-3600	Cylindrical axisymmetric domain, multiple heterogeneous DBHEs, heat extraction and injection	Mottaghy and Dijkshoorn (2012)
FVM	ANSYS Fluent	2070	2D CFD model, single heterogeneous DBHE	Renaud et al. (2019)
FDM	Inhouse code	5000	2D model, single heterogeneous DBHE	Song et al. (2018)
FEM	FEFLOW	400-1000	3D subsurface element domain with 1D DBHE, multiple homogeneous DBHEs, heat extraction and injection	Welsch et al. (2015)

Note that homogeneous DBHE implies a uniform geometry and thermo-physical properties across the whole DBHE depth. Heterogeneous DBHE implies non-uniform geometry and thermo-physical properties across the DBHE depth implemented in OGS (Chen et al. 2019) under matching assumptions. Cai et al. (2022), Wang et al. (2022), and Cai et al. (2022) used an OGS model to further investigate the long-term performance and sustainability of the BHE array system.

2. **Cylindrical axisymmetric methods:** Since the coaxial DBHE system can be simplified as an axisymmetric problem, many researchers adopted a cylindrical axisymmetric domain to simulate it as listed in Table 1. In order to take into account the effect of groundwater flow, Mottaghy and Dijkshoorn (2012) coupled the finite-difference formulation of cylindrical axisymmetric DBHE to heat and flow transport code SHEMAT. To describe the pipe flow in coaxial DBHE, Bu et al. (2012) included a simple pressure loss equation and quantified the flow resistance of the circulation fluid along the pipes.
3. **Full component-discretisation methods:** A full 2D or 3D discretisation for the DBHE as well as the surrounding formation is adopted, for example, in Boockmeyer and Bauer (2014) and Doran et al. (2021). Besides, Cai et al. (2019) and Renaud et al. (2019) used fully discretised FVM models in 2D to simulate a DBHE system as listed in Table 1. Fully discretised models have also been used to generate simplified representations of complex heat exchanger configurations with thermally equivalent behaviour in thermal energy storage applications in order to simplify meshing as well as lower the computational cost (Nordbeck et al. 2020).

The first method is particularly attractive due to its computational efficiency compared to fully discretised 3D models but requires special element formulations. When simulating systems from single DBHE to arrays, computational cost of fully discretised models becomes prohibitive. Thus, the trend towards large arrays brings with it a need for special element formulations / dual continuum approaches for the internal heat transfer processes and the coupling to the rock mass. The second method uses cylindrical coordinate system to describe and simulate the DBHE system; every component inside the DBHE borehole can be fully discretised. However, the limitation is that the groundwater effect and DBHE arrays cannot be easily simulated as indicated by Mottaghy and Dijkshoorn (2012). The third method is computationally very expensive for 3D simulations but requires no special implementation and can therefore be set up in any general-purpose code like ANSYS/Fluent (Li et al. 2020), TOUGH2 (Doran et al. 2021) and COMSOL (Hu et al. 2020; Janiszewski et al. 2018; Villa 2020). Besides the DBHE model implemented using the dual-continuum method in OGS (Shao et al. 2016; Hein et al. 2016; Chen et al. 2019, 2021), a fully discretised FEM model developed using OGS was also used by Boockmeyer and Bauer (2014) which allows a direct comparison between both approaches. Other specialised software packages such as FEFLOW (Diersch 2013; Le Lous et al. 2015; Rapantova et al. 2016) also have capabilities for both approaches.

In addition to the single DBHE system, deep arrays have also been studied recently by many researchers (e.g. Welsch et al. (2015); Cai et al. (2021)). Table 1 lists some of the modelling studies in the literature showing different discretisation techniques. Most studies only consider a subsurface model focussing on the heat transfer interaction between the DBHE and the surrounding medium, with occasional consideration given to the effects of groundwater flow. In extended models, the surface (building) component of a Heating, Ventilation and Air-Conditioning (HVAC) unit (e.g. heat pump) can be coupled to the subsurface process models thereby investigating the complete loop of space heating/cooling. An example is the DBHE array coupled with a heat pump model in the study of Cai et al. (2021).

All these studies have mainly relied on a single modelling technique (FEM, FDM, or FVM) to discretise the spatial domain. There are few studies comparing different numerical techniques. For example, Ozudogru et al. (2015) compared FDM and FEM for modelling a shallow U-tube BHE. They indicated that the FDM model has a higher computational efficiency. They also highlighted that whilst FEM can model a heat exchanger with multiple circulation tubes, the FDM model can only work with a single loop. It is to be noted that they used a two-dimensional FDM model comparing it to a three-dimensional FEM model. Moreover, computational time is not listed in many studies, which is an important consideration when evaluating software suitability.

In summary, numerical models are very flexible in simulating a diverse range of operational modes for DBHE systems, including both variable extraction and injection scenarios generating non-trivial temperature distributions or depending on surface installations. Importantly, the assumptions in analytical solutions can be discarded in numerical models. This provides a physically richer simulation, more closely resembling reality. Other features reserved largely for numerical methods include complex property distributions/heterogeneity in the subsurface, settings without any symmetry, state-dependent properties (e.g. equations of state of water), complex flow fields and partial saturation effects. Nevertheless, in order to flexibly simulate full-scale DBHE systems, the computational time of detailed numerical modelling is significantly and unavoidably higher than analytical solutions. One solution to the current trade-off is parallel computation, which is becoming increasingly available.

Semi-analytical

Considering the fast calculation speed of analytical solutions and the flexibility of numerical methods, some researchers have combined analytical solutions with numerical methods to obtain a semi-analytical solution of DBHE systems. For example, Wang et al. (2021) proposed a semi-analytical solution to simulate the DBHE system taking into account the geothermal gradient and validated the solution against OGS numerical simulation results. Previously, Ramey (1962) proposed a semi-analytical solution to quantify the temperature change in wellbores. Zhang et al. (2011) combined the semi-analytical solution of heat flux exchange between wellbores and surrounding formations with the numerical model of the heat transport in formations to improve the simulation efficiency.

Generally, in semi-analytical solutions, because the heat transfer inside and outside the DBHE belong to different domains, their temperature field solution is solved separately. The overall simulation of DBHE can then be performed efficiently by linking water and soil heat transfer through the borehole wall via boundary coupling, which needs to be updated in each time step by the soil heat transfer model. For the heat transfer in the surrounding formation, the heat flux going through the borehole wall can be regarded as the heat source. Thus, within a time step, the borehole wall temperature can be updated, which represents the thermal boundary condition for heat transport in surrounding formations. The iteration between the compartments will continue until reaching the convergence criteria. Based on such methods, Luo et al. (2020) used a semi-analytical solution to evaluate the performance of a DBHE coupled ground source heat pump with non-uniform internal insulation. Gordon et al. (2018) made simplifications of the DBHE, and developed a 1D radial composite cylindrical-source model to calculate the inlet and outlet fluid temperatures. In their model, the vertical fluid temperature distribution is not analysed, and the heat flow from each pipe is assumed to be proportional to the total heat flow and the fluid volume ratio. Whilst semi-analytical solutions combine the advantages of analytical solutions and the flexibility of numerical methods, some assumptions from the analytical solution cannot be avoided, e.g. heat transfer inside the borehole usually adopts steady-state equations for each time step, and the borehole is considered as a cylindrical heat source with finite depth.

Numerical modelling studies

In this section, numerical modelling of closed-loop DBHE systems is discussed for—(i) heat extraction which involves using DBHEs to extract heat from the ground to be used for space heating or other applications (e.g. horticulture); (ii) BTES, in which, through DBHEs, surplus heat is deliberately stored in the subsurface to be re-extracted in periods of high demand (Banks 2012), and (iii) cooling applications, where, the same BTES system used to store heat, is also used for space cooling with particular reference to rejection of heat from the building to the subsurface.

Heat extraction

Modelling has largely been undertaken with the purpose of investigating DBHE heat extraction capacity. The developed models have been used to understand (i) the influence of different engineering and geological parameters (Dijkshoorn et al. 2013; Liu et al. 2019; Renaud et al. 2020; Brown et al. 2021; Brown and Howell 2023; Kolo et al. 2023, 2023); (ii) the varying modes of operation, i.e. constant base load versus intermittent (Cai et al. 2019; Luo et al. 2022; Jiao et al. 2021; Huang et al. 2022; Brown et al. 2023; Perser and Frigaard 2022); (iii) system optimisation (Pan et al. 2020; Gascuel et al. 2022), and (iv) the potential to scale the technology using arrays (Cai et al. 2021, 2022; Zhang et al. 2022a, 2022b). Many studies have arrived at similar conclusions regarding the sensitivity of DBHE performance to these parameters, as described in the following sections.

Impact of geological parameters

Parametric uncertainty has been investigated to understand the implications of geological conditions including rock thermal conductivity, volumetric heat capacity, geothermal gradient, groundwater flow, heterogeneity (i.e. lithological layering) and natural advection in the subsurface.

Generally, an increase in **rock thermal conductivity** improves the performance of the DBHE by allowing faster thermal recovery of heat in proximity to the borehole (Banks 2012; Brown et al. 2021). Chen et al. (2019) show that for a 2.6 km long DBHE with a mass flow rate of $0.00833 \mathrm{kg\,s^{-1}}$, the outflow temperature can increase by 9.45 K at the end of a 4-month extraction period as thermal conductivity of the surrounding rock is varied from 2 to $3 \mathrm{W\,m^{-1}\,K^{-1}}$ (Fig. 2). Similar findings have been made by Nalla et al. (2005), Le Lous et al. (2015), Song et al. (2018), and Nian et al. (2019), amongst others,

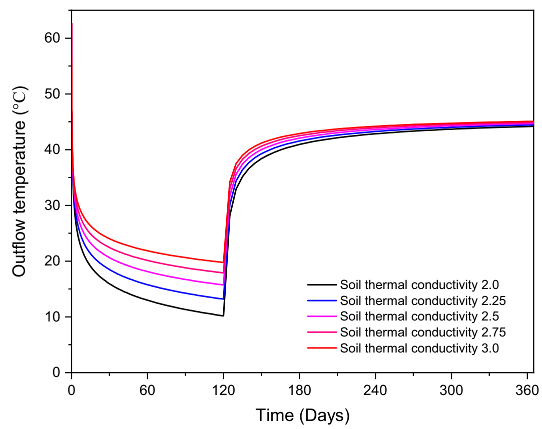

Fig. 2 Example outflow temperature versus time for a range of thermal conductivities of the subsurface rock (from Chen et al. (2019)). Note that the operation conditions were heat extraction to day 120 (recovery thereafter) with a flow rate of 0.00833 m^3/s and heat load of 390 kW

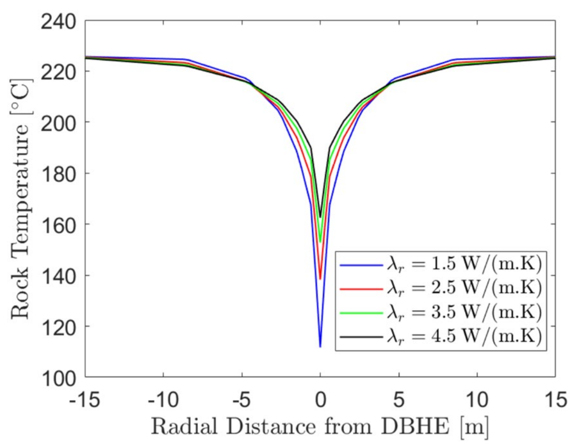

Fig. 3 Example temperature propagation around a DBHE for a range of thermal conductivities of the subsurface rock (adapted from Kolo et al. (2023)). Note that the DBHE was being operated for 6 months at a depth of 6 km, flow rate of 0.00833 m^3/s and thermal power of 800 kW

which collectively find a near-linear to logarithmic proportionality between increasing thermal conductivity and increasing DBHE thermal power outputs (at constant mass flow rates) (Brown et al. 2021). Greater rock thermal conductivity also leads to an extended radius of thermal influence around the DBHE (e.g. Kolo et al. (2023); Fig. 3).

When considering the thermal properties of geological media, the thermal diffusivity (rate of heat transfer) is defined by the ratio of thermal conductivity and **volumetric heat capacity** (the ability of the material to store heat (Banks 2012)). Whilst the thermal conductivity has been well documented in DBHEs, the attention given to the volumetric heat capacity has been less pronounced. The reason for this is likely due to the fact that when operating at a constant base load or inlet temperature, the influence on production temperature is somewhat limited; however, it can impact the thermal recovery of a system which uses intermittent modes of operation (Le Lous et al. 2015). Therefore, in long-term near steady-state operation, the impact of volumetric heat capacity is minor, but when there is cyclic or transient operation, it could be more important as it limits the thermal recovery of the system. This is because the volumetric heat capacity controls the storage of heat or coolth with increased or decreased temperature. It has been shown to be particularly important in thermal energy storage systems (Gehlin 2016).

Geothermal gradient, or **bottom-hole temperature**, is directly proportional to the maximum thermal power output (Fang et al. 2018; Brown et al. 2021; Niu et al. 2023). Increased geothermal gradients lead to an increase in available thermal energy, and achievable heat load (Holmberg et al. 2016) and it strongly influences the profitability of any system (Xiao et al. 2023). This is due to there being more available heat in the subsurface which can be mined.

Groundwater flow and natural convection in the porous subsurface media surrounding DBHEs can strongly influence the system; however, the conditions required to impact thermal efficiency are seldom established in reality. Chen et al. (2019) highlighted that groundwater flow from relatively thin aquifers has an extremely minor impact on production of heat from DBHEs. Similar findings were also produced by Le Lous et al. (2015). Others have suggested that Darcy velocities greater than $1 \times 10^{-7}\,\mathrm{m\,s^{-1}}$ can strongly impact the system (Jiao et al. 2022; Brown et al. 2023). The latter study highlighted that at the end of a heating season of 6 months, a Darcy flow velocity of $1 \times 10^{-6}\,\mathrm{m\,s^{-1}}$ in comparison to a conduction only scenario could increase outlet temperature from 7.84°C to 9.04°C (Fig. 4). This would correspond to an increase in thermal power of 25.2 kW or specific heat extraction rate of about $27\,\mathrm{W\,m^{-1}}$. Similarly, by modelling natural (free) convection in an aquifer, and the associated variations in groundwater density, Bidarmaghz and Narsilio (2022) report that thermal efficiency (i.e. increase

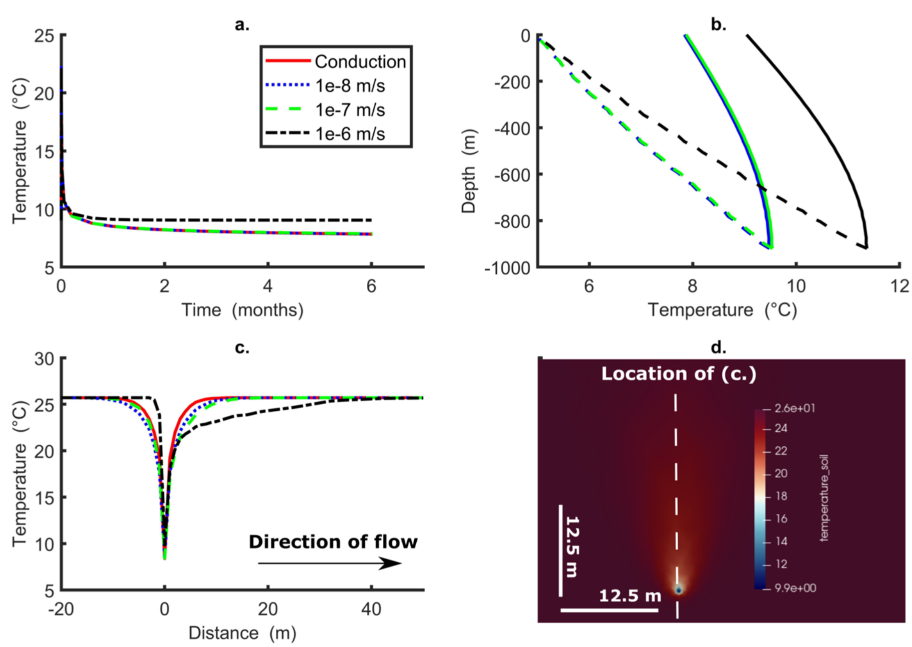

Fig. 4 Example of impact of groundwater flow around a DBHE: **a** outlet temperature vs time (constant inlet temperature of 5 °C, flow rate of 0.005 $\mathrm{m^3/s}$, rock thermal conductivity of 2.55 W/(mK)); **b** inlet (dashed lines) and outlet (solid lines) temperatures against depth; **c** thermal propagation around the DBHE, and **d** cross-slice through thermal plume at 500 m depth (from Brown et al. (2023))

in thermal power output) improved by up to 63 %. The modelled environment simulated Darcy velocities of up to $8.9 \times 10^{-5}\,\mathrm{m\,s^{-1}}$ (Fig. 5). The consensus of modelling results suggest that DBHE thermal performance improves in scenarios of increased groundwater flow and natural convection. The likelihood of encountering such high permeabilities and high Darcy velocities as those reported in Bidarmaghz and Narsilio (2022) and Brown et al. (2023) at depth are unlikely. A Darcy velocity of $1 \times 10^{-7}\,\mathrm{m\,s^{-1}}$ would be encountered where hydraulic conductivities are $1 \times 10^{-5}\,\mathrm{m\,s^{-1}}$ with a hydraulic gradient of 0.01 (1 %) (e.g. Nguyen et al. (2017)). This is unlikely to occur at depth, particularly over large portions of the DBHE, and it is reasonable to conclude that in most systems, groundwater flows will inflict a minor impact on heat extraction. Although in some rare scenarios, such as the Mesozoic Basins across the UK, sandstone thicknesses can reach 2 km and it is possible groundwater could impact DBHE performance under these conditions (Brown 2023).

Another important aspect of the subsurface geology is the method of modelling the rock itself (i.e. homogeneous or heterogeneous strata). Many studies consider a homogeneous geology with constant thermal and hydraulic properties (e.g. Liu et al. (2019); Brown et al. (2021); Piipponen et al. (2022)). Others model depth-dependent thermal properties (e.g. Hu et al. (2020, 2021)), whilst some consider lithological layering (e.g. Liu et al. (2020); Doran et al. (2021); Gascuel et al. (2022); Kolo et al. (2022, 2023)).

Despite improving the geological representation of the model, the addition of **lithological layering** only produced a minor difference in outlet temperature of $< 1°\mathrm{C}$ in comparison to the homogeneous model equivalent for a variety of depths (Kolo et al. 2023). The discrepancy was found to increase with depth due to the additional vertical lithological variations. It is also worth noting that whilst many have investigated lithological layering, few, if any, have considered realistic geological features or facies modelling which are typically incorporated into reservoir modelling in conventional geothermal

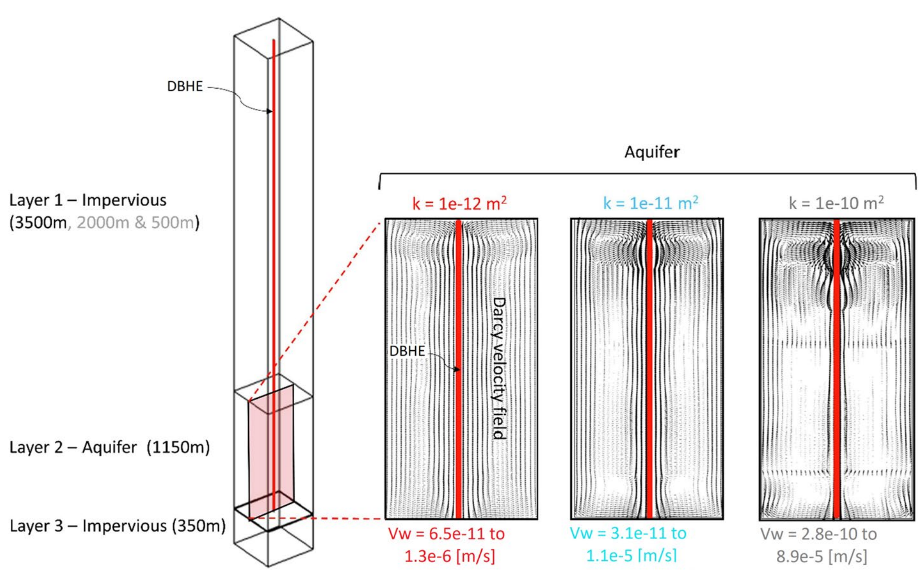

Fig. 5 Darcy velocity through a 5 km deep model with varying aquifer properties highlighting free convection (adapted from Bidarmaghz and Narsilio (2022)). Note: DBHE is the coaxial borehole heat exchanger, Vw is Darcy velocity and k is permeability

systems (e.g. Crooijmans et al. (2016); Wang et al. (2021); Major et al. (2023)) or petroleum applications (e.g. Abdelmaksoud et al. (2019); Mitten et al. (2020)) and impact the hydraulic/thermal subsurface characteristics. It is difficult to quantify the impact such systems could have on the performance of a DBHE; however, it is likely in highly heterogeneous systems which could correspond to variable thermal properties, degree of fluid saturation or groundwater flow would be most influential on results.

Constant thermal properties (rather than those varying with temperature and time) appear to produce reasonable estimates to real data obtained from sites (Cai et al. 2019, 2021). Yet, it has been suggested that temperature-dependent properties can in some cases increase the outlet temperature by 1°C or c. 11 % relative deviation for a DBHE of 3500 m depth (Hu et al. 2020). When comparing models which include constant properties against those using temperature-dependent properties, such as OGS (homogeneous) against T2Well-EOS1/TOUGH2, the discrepancy for a 922 m well was < 0.6°C (Brown et al. 2023). Comparing this result to the findings of Hu et al. (2020) could imply that depth amplifies any influence of temperature-dependent properties. Similarly, higher temperature systems also exhibit naturally greater influence of temperature-dependent properties (Doran et al. 2021). Therefore systems that encounter a wider range of temperatures may require temperature-dependent modelling of properties.

Impact of engineering parameters

Parametric studies have been conducted to investigate the variations in engineering conditions, including: (i) operational mass flow rates; (ii) borehole and pipe structural design; and (iii) material thermal conductivity and insulation. These characteristics will impact both thermal (e.g. Abdelhafiz et al. (2023)) and hydraulic performance (e.g. Morchio and Fossa (2019)).

One of the most important parameters for determining the thermal drawdown in a DBHE, the outlet temperature and thermal power, is the **mass flow rate** within the system. This is not primarily because high flow rates lead to greater heat production from the formation, but because they minimise the contact time between upward and downward flow streams and thus minimise internal thermal “short-circuiting” in the borehole. Assuming an insulated central pipe, lower flow rates result in higher outlet temperatures, but correspond to lower thermal powers (Toth et al. 2018; Doran et al. 2021; Guo et al. 2023). When considering the thermal power, performance of the system and net energy, all of these parameters will have optimal values dependent on the flow rate. Kolo et al. (2023) highlighted that increasing flow rates leads to an increase in thermal power extraction, but also an increase in pressure drop. Increased energy expenditure in the circulation pump results in lower net energy production and lower coefficients of performance (Brown et al. 2021; Gascuel et al. 2022; Kolo et al. 2023). A trade-off exists for mass flow rate between pressure drop and maximum thermal power output. This was highlighted by Brown et al. (2024), who highlighted that optimal conditions could be achieved to minimise the parasitic losses whilst maximising the thermal output as a function of engineering parameters.

In combination with the operational flow rate of the DBHE, the **geometrical design** of the borehole and coaxial pipe design will have important consequences for system pressure drop and heat transfer. Larger borehole radii allow a greater thermal performance by generating slower downward velocities in the annular space, larger contact area around the DBHE and greater heat extraction from the formation (Li et al. 2021; Wang et al. 2022). Similarly, a narrower central pipe leads to higher production temperatures and thermal powers, as the heat transfer area between central pipe and annulus is reduced (Brown 2020). Whilst larger boreholes are preferable, drilling costs may increase as a result. Additionally, many studies have focussed on repurposing oil and gas wells (e.g. Sapinska-Sliwa et al. (2016); Westaway (2016); Hu et al. (2020); Gascuel et al. (2022); Gizzi et al. (2021); Brown and Howell (2023); Santos et al. (2022); Guo et al. (2023)) or geothermal exploration wells (e.g. Renaud et al. (2019); Kolo et al. (2022, 2023); Brown et al. (2023, 2023, 2023); Noorollahi et al. (2016)) and are constrained to a pre-existing narrow diameter borehole. Depth also influences thermal performance as it leads to higher outlet temperatures, thermal power and specific heat extraction rate (e.g.Piipponen et al. (2022); Deng et al. (2020)). Whilst it is useful to increase the depth, it will also result in greater pressure losses and hence a decline in system efficiency (Brown et al. 2021).

Closed-loop geothermal systems have lower extraction rates than open-loop systems due to low heat transfer rates between the subsurface and the limited surface/contact area (Beckers et al. 2022). In addition to targeting high-temperature resources, the slow heat transfer rates can be addressed by (i) increasing the DBHE contact area with the rock and (ii) increasing turbulence in the DBHE flow, although this can lead to increased parasitic losses (Brown et al. 2024). To achieve the former, coaxial DBHEs can be augmented with a long horizontal section (Guo et al. 2023) (see Fig. 6). Wang et al. (2021) conclude that a 2000 m horizontal section increases the outlet temperature by a margin of around 20 K (0.96 MW thermal power). Introducing lateral sections will inevitably also come with drilling complexities and cost (Beckers et al. 2022). The second method to enhance heat transfer, by increasing internal DBHE turbulence, has been explored through the modelling of vortex generators (Sun et al. 2022) (Fig. 7). The addition to pipe design was found to successfully increase overall heat output but simultaneously increased the pressure drop within the DBHE, thereby increasing parasitic losses from the circulation pump. Whilst the

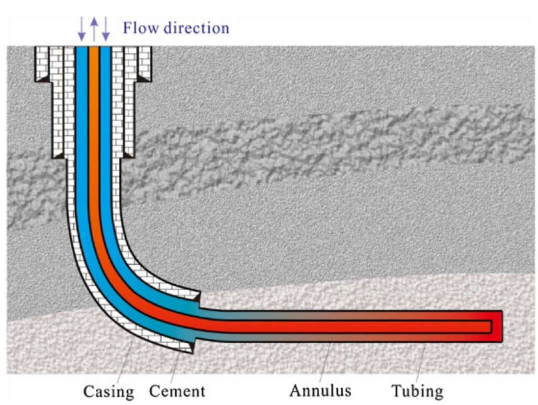

Fig. 6 Schematic diagram of a DBHE with horizontal extension. Tubing indicates the central outlet pipe. (from Sun et al. (2019))

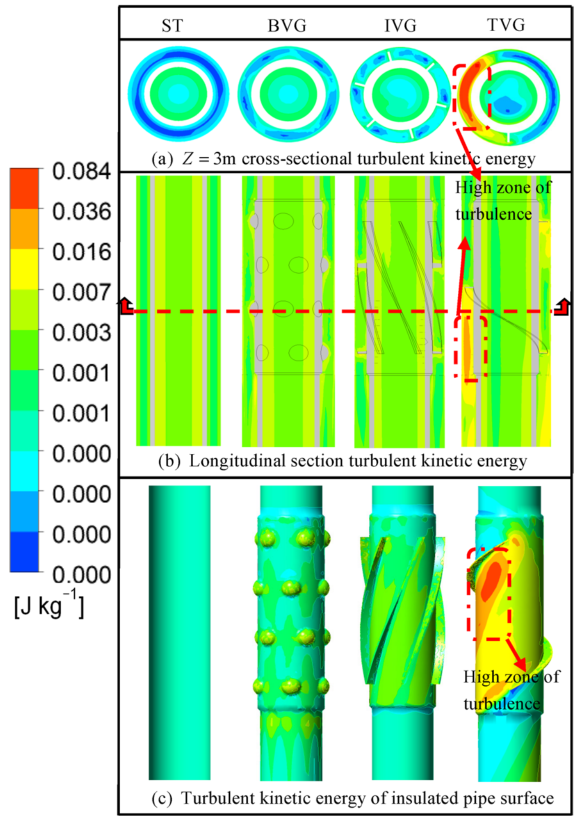

Fig. 7 Distributions of turbulent kinetic energy (from Sun et al. (2022)). Note that ST is smooth tube, BVG is a bump vortex generator, IVG is an impeller vortex generator and TVG is a thread vortex generator

discretisation method in the study was not stated, future modelling of DBHEs with vortex generators can vary in modelling approach. They can apply either full computational fluid dynamics models to more accurately represent key processes, or alternatively, the thermal resistance of the casing string could be modified to represent the increased turbulence.

The influence of **grout or cement properties** is generally regarded as minimal to moderate impact for lower temperature systems (e.g. Le Lous et al. (2015); Brown et al. (2023)), with an increase in thermal conductivity resulting in an increase in thermal power. A continuous increase of the grout thermal conductivity does not continuously improve the production fluid temperature, but can enhance the transmission of heat; however, this impact does appear to decline with operational time (Huang et al. 2020). In higher temperature systems, it would appear that variations in thermal conductivity of the grout can impact results more strongly (e.g. Doran et al. (2021)). Some researchers have also gone further to investigate enhanced thermal conductivity zones using a soilcrete zone created through jet grouting, enhancing the thermal power by 1.27 times in contrast to normal grout (Yu et al. 2021). However, Yu et al. (2021) conclude that the length/radius of the zone are more important than its thermal conductivity considering typical ranges. Some studies have considered insulation of the DBHE casing and inner pipe. The insulation of casing at the top of the borehole typically has a minor or negative impact on the thermal performance (Hu et al. 2020; Fang et al. 2018), but insulation of the central pipe improves performance (Hu et al. 2020) as it mitigates thermal short-circuiting. Lower thermal conductivity materials of the central pipe such as high-density polyethylene or vacuum insulating tubing have the potential to significantly improve performance, but can require higher investments and installation costs (Śliwa et al. 2017, 2018). Thermal performance also increases as the thickness of the insulation layer increases (Guo et al. 2023).

Optimisation of the aforementioned engineering parameters can help improve performance, particularly when focusing on varied flow rates to meet variable heating load demands throughout the heating season. Wang et al. (2022) used a mathematical optimisation procedure that utilised a convex function and interior-point method to find the minimum total power consumption; this allowed overall energy savings. Further optimisation studies have been performed by Pan et al. (2020) on both engineering and geological parameters using a method based on the lowest Average Energy Cost index which allows a reduction of up to 22.1 % in power consumption. Similarly, optimal parametric studies can also help to identify key parameters that influence thermal and hydraulic performance (e.g. Brown et al. (2021); Gascuel et al. (2022); Jia et al. (2022)).

Impact of deep borehole heat exchanger arrays

Scalability at a single site can be achieved by increasing the number of DBHEs to establish a greater thermal power output (i.e. Fig. 8). In designing such a system, the lateral spacing of DBHEs and shape of the array must be considered to minimise negative thermal interference (Cai et al. 2022). Optimal inter-borehole spacing is likely to vary depending on the local geology and method of operation, although modelling has demonstrated that line arrays may have better performance than square arrays for heat extraction due to reduced thermal interference (Brown et al. 2023). Larger spacing for arrays results in reduced thermal interference and thus, higher outlet temperatures (Fig. 9). DBHE arrays are impacted by similar parameters as are single DBHEs

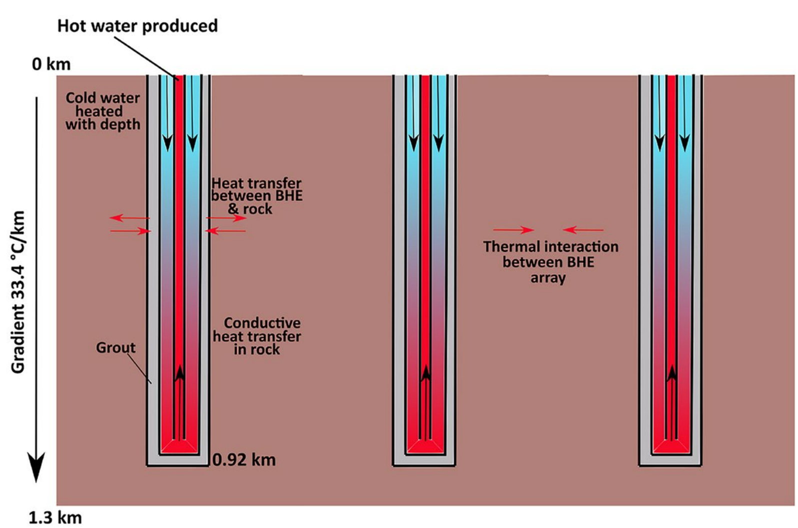

Fig. 8 Schematic of a DBHE array (from Brown et al. (2023))

(Zhang et al. 2022b). Unlike single DBHEs, arrays can operate in parallel by incorporating a merger and splitter to apply a heat load across the array, rather than individually to each DBHE (e.g. Cai et al. (2021)).

Impact of boundary conditions

Finally, the influence of boundary conditions has been evaluated for heat extraction performance, e.g. Ma et al. (2023) and Jiashu et al. (2022). Jiashu et al. (2022) performed a comparative study of (i) constant inlet water temperature; (ii) constant fixed power boundary condition, and (iii) constant wellbore temperature. They concluded that the constant temperature boundary conditions and constant wellbore temperature provide similar results. They also suggest that the constant heat output, or power boundary condition are less likely to be implemented in practice. This seems unusual considering that many shallow closed-loop systems operate using a power boundary condition since they are coupled to a heat pump and building load. Further research is required to explore this uncertainty. By considering Neumann no flow and Dirichlet constant temperature boundary conditions, Kolo et al. (2022) found that the choice of boundary conditions at the upper surface of the model domain has minimal impact on fluid inlet and outlet temperatures. This is plausible considering that surface temperature fluctuations typically only affect depths shallower than 10 m (e.g. Al-Khoury et al. (2010)), thus significantly small compared to the DBHE length.

Thermal energy storage

By exploiting sources from curtailed wind power (Brown et al. 2023) to rooftop solar thermal (Sibbitt et al. 2007, 2012; Kolo et al. 2023) to waste heat (Mahon et al. 2022; Guo and Yang 2021), seasonal thermal energy storage (STES) supports the security of supply in multi-vector low-carbon heating and cooling solutions in strongly seasonal climates (BEIS 2016; Gluyas et al. 2020; Kallesøe et al. 2020; Xu et al. 2014; Lyden et al. 2022).

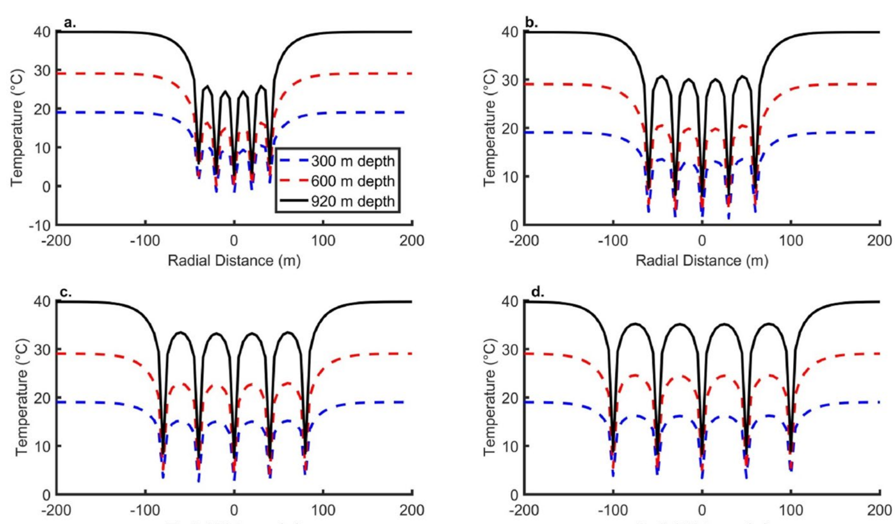

Fig. 9 Temperature profiles through the ground for different line arrays: **a** 20 m spacing; **b** 30 m spacing; **c** 40 m spacing; **d** 50 m spacing. Profiles taken directly through the line array (from Brown et al. (2023))

Underground thermal energy storage (UTES) is a subset of the wider branch of heat storage technologies (Nagel et al. 2016). Loosely segregated amongst pit, tank, mine, aquifer and borehole storage; offering an array of installed benefits and costs (BEIS 2016) but all assist in addressing the temporal mismatch in supply and demand of heating and cooling availability from low-carbon sources. The review herein is primarily concerned with the use of DBHEs in closed-loop deep BTES (DBTES; Fig. 10).

Much can be learnt from the experience with shallow BTES systems and applied to the deeper context. Reviews from Skarphagen et al. (2019) and Gao et al. (2015), for example, offer exemplary overviews of the key literature on shallow BTES. These reviews, amongst others, describe the fundamental operating and design considerations, many of which are applicable to both shallow and deep BTES contexts, with the notable exception that deeper systems favour a coaxial DBHE over the U-tube alternative (e.g. Brown et al. (2024)).

Both shallow and deep BTES operate with the same basic *charging* and *discharging* principles: by injecting warm fluid into a single BHE or BHE array, BTES systems transfer heat to the cooler insulating subsurface media (charging), and by subsequently reversing the flow direction and injecting cold fluid into the BHE(s), extract heat from the thermal plume proximal to the borehole residing from the prior charging phase(s) (discharging). If no prior charging is present, then the operation of mining the heat-in-place is termed

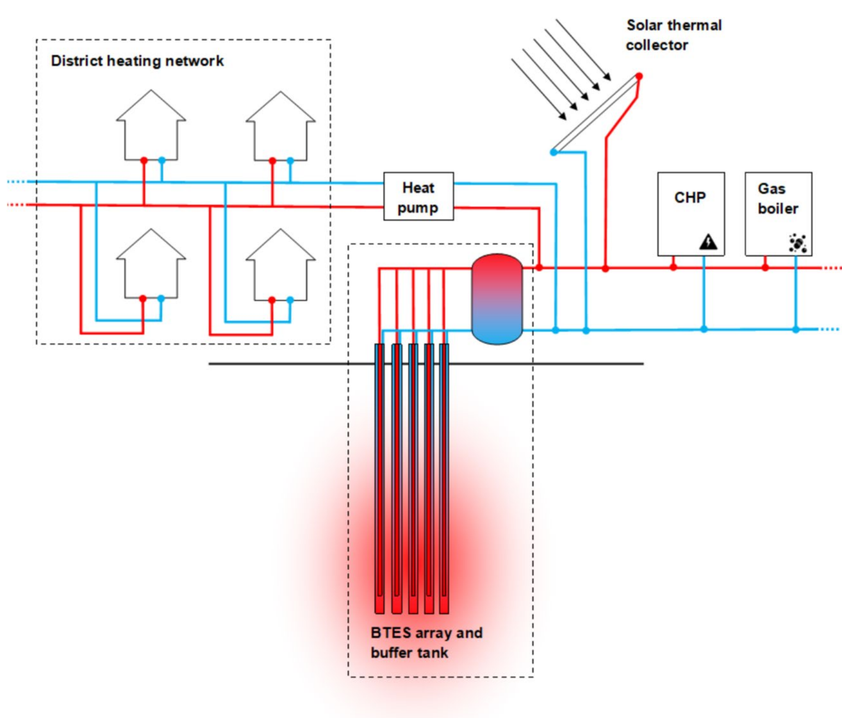

Fig. 10 Borehole thermal energy storage array with sources and end-users (adapted from Homuth et al. (2013) and Welsch et al. (2018)). Characterised by slow (seasonal) thermal responses, and hence suitable as STES systems, DBTES can be coupled with dynamic thermal energy storage (buffer tank) at the surface level to act as "thermal capacitors"—establishing a comprehensive thermal store used to meet both diurnal and seasonal fluctuations of demand

extraction. The choice of when to charge, discharge or extract is dependent on the application demand and the availability of alternative sources at each time step of the BTES control.

During charging, the thermal plume expands and the charging power (rate of heat transfer) typically reduces as the system approaches a steady-state equilibrium between the BHE and surroundings. Typically, in systems with large differences in fluid injection temperature and surrounding formations, an initial “start-up, or pre-charge” period is maintained, during which the majority of the annual operating cycle is spent charging the thermal store (Skarphagen et al. 2019). This initial start-up may take several annual cycles to bring the BHE into a pseudo-steady state with the surrounding media; however, once complete the start-up procedure assists in improving the system’s storage efficiency (Skarphagen et al. 2019). Cyclic charging and discharging operations should be initiated once the initial start-up period, if necessary, is complete.

The thermal losses are incurred during the annual cycling of charging and discharging from the BTES. These losses are a function of several design and operational parameters, including, but not limited to, inlet temperature of the working fluid; local geothermal gradient; DBHE geometrical design configuration; material properties of the DBHE and surrounding formation; borehole spacing in the array, and shape factor (surface area to volume ratio in an array) (Skarphagen et al. 2019) (Fig. 11). Thermal energy recovery can be maximised by tailoring these system parameters. For example, borehole arrays aim to minimise the shape factor of a BTES system—hexagonal or cylindrical arrays being favoured over a single row of BHEs or standalone BHE—thus reducing thermal losses to the surrounding formations and enabling constructive thermal interference between neighbouring BHEs (Skarphagen et al. 2019; Lanini et al. 2014). A preference for dense arrays in storage systems is in stark contrast to the extraction-only DBHE case which aims to avoid or minimise interactions across thermal drawdown effects. The optimal array configuration and DBHE design is distinctly use-case dependent. Despite the important role of shape factor in BTES

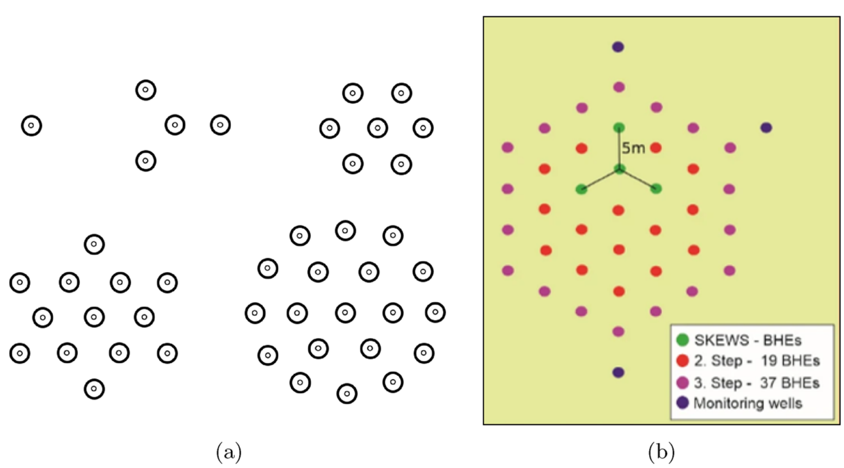

Fig. 11 **a** Borehole thermal energy storage array configurations with varying shape factors (adapted from Bär et al. (2015a, 2015b); Welsch et al. (2016); Skarphagen et al. (2019)) and **b** the planned and implemented BTES array configuration at the SKEWS site in Darmstadt, Germany (from Seib et al. (2022))

storage arrays, ongoing work has investigated the potential to reduce the number of boreholes in an array (increasing the ratio of surface area to volume ratio) in favour of borehole depth, resulting in single borehole or sparse arrays DBTES systems, e.g. Welsch et al. (2015, 2016); Schulte et al. (2016).

At the heart of the switch from shallow arrays to deep (typically more sparse) arrays is the stringency of regulatory bodies to minimise the environmental impact of heat storage, particularly high-temperature storage ($T > 35°C$), on shallow groundwater resources (e.g. Gao et al. (2015); Tsagarakis et al. (2020); Hähnlein et al. (2013)). Examples of the environmental impacts of heat storage in the shallow subsurface have been documented by Bonte et al. (2011) and Mielke et al. (2014), amongst others. To mitigate the risks posed to groundwater assigned for other purposes such as drinking water or irrigation, Homuth et al. (2013) propose the targeting of deeper geological formations whilst insulating the shallow section of the BHE. This minimises the interference of thermal plumes in the shallow subsurface. Although this switch to deeper sparse arrays has a detrimental effect on the surface area to volume ratio, advantages to DBTES adoption include: (i) reduced surface footprint requirements, potentially improving the feasibility of installing BTES systems in densely populated areas with existing infrastructure and (ii) higher temperature sources—such as Variable Renewable Energy (VRE) and Combined Heat and Power—can be integrated than is currently permissible in shallow BTES systems, thus improving heat pump COPs in the case of high demand-side temperatures (Homuth et al. 2013; Welsch et al. 2018; Gao et al. 2015; Malmberg 2017).

One must consider the metrics used when assessing DBTES performance and ensure consistency amongst metrics when drawing comparisons across systems. The issue of selecting performance metrics is particularly prominent in the DBTES literature, which suffers from ambiguity regarding the measurement of "storage efficiency." Although efficiency estimates are impacted by both operational and design parameters, the different choice of metrics makes comparison of published values challenging. For example, using different metrics, Welsch et al. (2016) and Brown et al. (2023) report thermal storage efficiency values of 83 % and 1 %, respectively, whilst other estimates lie within this range (e.g. Schulte et al. (2016) and Fu et al. (2023)). There is therefore a clear need to clarify the "efficiency" measure being reported. The following list (Eqs. 15–20) attempts to define common approaches to this performance metric and provides some suggested terminology needed to bring consistency to DBTES comparison. With the exception of the 'heat storage yield ratio', the metrics described below are typically expressed on a per-annum basis. The variables used in the storage efficiency metrics are shown in Fig. 12 and defined in Table 2.

1. *Thermal recovery factor (TRF)*: ratio of total heat extracted during discharging period to total heat injected into surrounding formations during charging period (Welsch et al. 2016; Hellstrom 1992; Seib et al. 2022; Bär et al. 2015b; Schulte et al. 2016):

$$\mathrm{TRF} = \frac{Q_{\mathrm{discharge}}}{Q_{\mathrm{S}}} \tag{15}$$

Table 2 Variables used in equations for storage efficiency

Symbol	Parameter
$Q_{discharge}$	Heat output during BTES discharge period (with prior storage).
$Q_{in,charge}$	Heat input at the wellhead during BTES charging period.
Q_S	Heat stored (transferred to subsurface) during the BTES charging period .
Q_{ex}	Heat output during BHE extraction period (without prior storage).
$Q_{out,charge}$	Heat content of return flow at the wellhead during BTES charging period.
Q_{gain}	Heat gained during the BTES discharging period as a result of storage.
W_P	Electrical power required by circulation pump for storage operations.

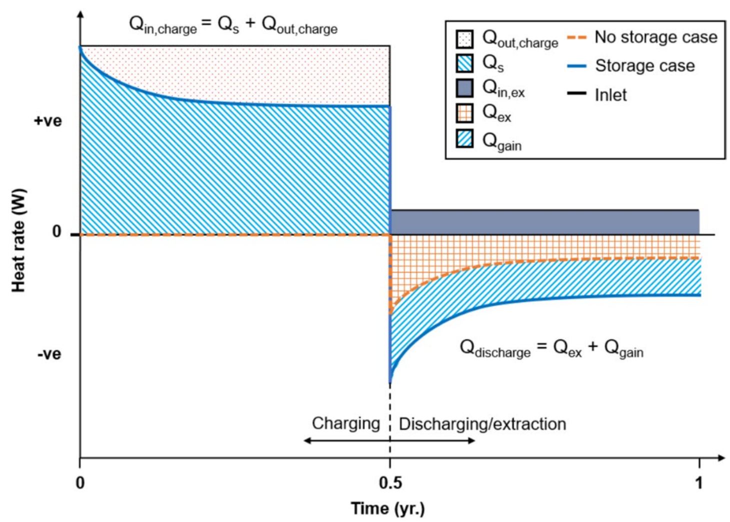

Fig. 12 Charging and discharging curves used in the proposed storage efficiency metrics for borehole thermal energy storage (adapted from Welsch et al. (2016) and Xie et al. (2018))

2. *Thermal storage efficiency (TSE)*: ratio of difference in total energy extracted with and without a storage charging period to total energy injected to surrounding formations during charging period (Brown et al. 2023, 2023):

$$\mathrm{TSE} = \frac{Q_{gain}}{Q_S} \tag{16}$$

3. *Thermal charging efficiency (TCE)*: ratio of total energy injected to surrounding formations during charging period to the total energy inputted at the wellhead during charging period (Xie et al. 2018):

$$\mathrm{TCE} = \frac{Q_S}{Q_{in,charge}} \tag{17}$$

4. *Thermal recovery advantage (TRA)*: ratio of difference in total annual energy extracted with and without charging to total energy extracted in the case without charging (Skarphagen et al. 2019; Fu et al. 2023). Also referred to as *heat extraction improvement rate (HEIR)* in Fu et al. (2023):

$$\mathrm{TRA} = \frac{Q_{\mathrm{gain}}}{Q_{\mathrm{ex}}} \tag{18}$$

5. *Thermal accumulation efficiency (TAE)*: the ratio of annual accumulation of heat stored in the BTES system to the amount of heat injected during the charging period (Skarphagen et al. 2019):

$$\mathrm{TAE} = \frac{Q_{\mathrm{S}} - Q_{\mathrm{discharge}}}{Q_{\mathrm{in,charge}}} \tag{19}$$

6. *Heat storage yield ratio (HSYR)*: ratio of the net energy gain in the entire service life to the electrical power consumed by the heat storage operations (Fu et al. 2023):

$$\mathrm{HSYR} = \frac{Q_{\mathrm{gain}} - W_{\mathrm{P}}}{W_{\mathrm{P}}} \tag{20}$$

Deep borehole thermal storage arrays

Modelling of DBTES arrays (Table 3) have been significantly informed by the ongoing work in Darmstadt, Germany and the resulting project "Seasonal Crystalline Medium Deep Borehole Thermal Energy Storage" (abbreviated to SKEWS; (Homuth et al. 2013; Bär et al. 2015a, b; Seib et al. 2022, 2022, 2024). Bär et al. (2015a) and Bär et al. (2015b) expand upon work by Homuth et al. (2013) using numerical modelling in FEFLOW to assess the initial capacity and sustainability of heat storage scenarios in the hydrogeological context of the Darmstadt site. Initial results showed that shallow BHE arrays (19 BHEs at 105 m) exhibited an annual TRF (Eq. 15) of approximately 10 % after year one of operation which tended to 25 % after 30 years due to annual thermal accumulation (Bär et al. 2015a). In contrast, DBHEs with similar total drilled lengths (4 BHEs at 500 m depth) settled at just *c.* 15 % at year 30 despite starting at a comparable TRF in year one (*c.* 10 %). This difference in TRF improvement over the BTES lifespan is likely a consequence of the change in shape factor, from dense to sparse arrays, and suggests,

Table 3 Some typical coaxial DBHE discretisation techniques as applied in software for deep borehole thermal energy storage

Discretisation	Software	Depth (m)	Array or Single Well	References
FEM	FEFLOW	750	Array	Seib et al. (2022)
FEM	FEFLOW	750	Array	Seib et al. (2022)
FEM	FEFLOW	750	Array	Seib et al. (2024)
FEM	FEFLOW	105-500	Array	Bär et al. (2015b)
FEM	FEFLOW	100-1000	Array	Welsch et al. (2016)
FEM	FEFLOW	0-1000	Array	Welsch et al. (2018)
FEM	MATLAB	100-500	Array	Schulte et al. (2016)
FDM	MATLAB code	920	Single	Brown et al. (2023)
FEM	OpenGeoSys	920	Single	Brown et al. (2023)
FDM	In-house code	2000	Single	Fu et al. (2023)
-	Semi-analytical	2000	Single	Xie et al. (2018)
-	Analytical	3000	Single	Westaway (2016)

assuming drilling costs increase exponentially with depth (Tester et al. 2005; Banks 2023), that shallower BTES arrays will yield a cheaper storage option per kWh. The tendency to form steady-state annual TRFs at year 30 arises from the movement towards thermal equilibrium between the circulating fluid and surrounding formations. This represents a steady decrease in thermal charging capacity and annual TAE (Equation (19)) over the BTES lifespan, as also reported in Skarphagen et al. (2019).

It should be noted that the BTES arrays studied in these models are connected in parallel. The BHEs of the array can also be linked in a combination of serial and parallel connections, with heat extraction occurring in the outer BHEs first and moving progressively towards the centre during the discharging period; meanwhile, injection occurs in the central BHEs first (the core of the array) and works radially outward during charging (Skarphagen et al. 2019). The advantage gained from this additional operational control may be partially mitigated by the resulting increase in hydraulic head, particularly as BHE depth increases (Skarphagen et al. 2019). Nonetheless, configurations in the literature discussed herein modelled BHEs in parallel unless stated otherwise.

Given the significant role of drilling on DBTES installation costs (operational costs being relatively low in comparison), Schulte et al. (2016) attempt to minimise the total drilled borehole length of BHEs in DBTES arrays, subject to constraint on meeting the annual heat demand and maintaining BHE depths beyond 200 m as a fictitious legal requirement. To achieve this, a surrogate model was initially trained on numerical models in MATLAB using 63 different BTES arrays (benchmarked against FEFLOW simulations) to explore the search space of possible array configurations whilst avoiding the computational burden of full numerical models. The proxy model was applied in a genetic algorithm, to identify the global optimum of BHE length and array size. In agreement with the findings of Bär et al. (2015a), the authors observe that TRF favours a larger number of shallow BHEs over a sparse array of DBHEs for the same total drilled length and find an array of 7 BHEs at 220 m depth offered an optimal solution under the imposed constraints. This solution, generated by the surrogate model and validated with a pre-existing MATLAB numerical model, operated at a TRF of 41 %, and reinforces the notion that sparse DBTES arrays are susceptible to greater thermal losses. Schulte et al. (2016) highlight the increasing inaccuracy of the proxy model towards the edge of the multi-dimensional parameter space as the training data become more sparse, bringing potential implications for the outputs generated for deeper BHE models in the genetic algorithm.

In assessing the impact of BTES parameters on system performance, Welsch et al. (2016) used a One-at-a-Time or local sensitivity analysis to compare 250 storage models implemented in FEFLOW. Variable parameters included borehole array layout (number of BHEs, BHE depth—100 to 1000 m—and spacing), fluid inlet temperatures and host rock thermal and hydraulic properties. The analysis indicates that stored heat, extracted heat and annual TRF values all increase with BHE length and number of BHEs in the BTES array (agreeing with the findings of Schulte et al. (2016)). The important role of the array shape factor (surface area to volume ratio) is again demonstrated by the positive short-term impact (years 1–3) on TRF values observed for circular array configurations. At year 30 of the simplified operating scheme considered, annual TRF values were found to range from 32 % (7 BHEs at 100 m depth) to 83 % (37 BHEs at 1000 m depth), up from approximately 25 % and 45 % in year 1, respectively. These estimates demonstrated a significant increase from Bär et al. (2015a, 2015b), highlighting the improved TRF values that can be achieved by DBTES over shallow systems for high inlet temperatures (in this case 90°C). The TRF values were also found to increase as the ratio of charging to discharging inlet temperatures increased, whereas increases in rock thermal conductivity and groundwater flow velocity are found to negatively impact TRF values (e.g. a rock hydraulic conductivity increase from $1 \times 10^{-7}\mathrm{m\,s^{-1}}$ to $1 \times 10^{-5}\mathrm{m\,s^{-1}}$ constitutes a drop in TRF from c.67% to *c*.30 % due to advective losses from groundwater flow). The impact of rock volumetric heat capacity is reportedly negligible to weakly positive. Finally, whilst Welsch et al. (2016) used a local sensitivity analysis to reduce computational costs, the interdependency between the variables in the model must be acknowledged. Potential compounding or conflicting effects on storage efficiency, storage capacity and extraction capacity indicate the need for global sensitivity analyses or experimental design in future modelling of DBTES systems.

Using a synthetic district heating network case study, Welsch et al. (2018) carried out an environmental and economic life cycle assessment to identify Pareto optimal solutions to energy system design, using levelised cost of heat (LCOH) and global warming potential as performance metrics. The study found that incorporating DBTES into a hybrid combined heat and power-solar thermal collector gave the most efficient Pareto optimal design heating system (minimisation of financial and economic costs) across all those considered. This result was observed for the "business-as-usual " case (constant electricity grid carbon intensity) without subsidies as well as the "evolution" case (forecasts a reduction of electricity grid carbon intensity) both with and without subsidies. This optimisation arises from the system becoming self-sufficient in the supply of power from the combined heat and power to operate the DBTES circulation pump, heat pump, and solar thermal collector. Welsch et al. (2018) conclude that when compared against the business as usual and evolution cases, the hybrid combined heat and power-solar thermal collector system produces a reduction in global warming potential by 54 % and 29 %, respectively.

As part of project SKEWS, Seib et al. (2022) investigated the impact of fault zone hydraulic conductivity and thickness on storage performance. Using a FEFLOW model of the case study area, the authors report just a 2.1 % variation in TRF values for the final BTES system proposal (750 m deep in a 37-BHE hexagonal array, see Fig. 11(b)) across all hydraulic conductivity and fault zone thickness parameters tested: ranging from 69.6 % at a 4 m fault zone thickness with a hydraulic conductivity of $1 \times 10^{-3}\mathrm{m\,s^{-1}}$ to 71.7 % at 0.5 m, 1 m, 2 m fault zone thicknesses and hydraulic conductivity of $1 \times 10^{-5}\mathrm{m\,s^{-1}}$. Consequently, the storage capacity and TRF are found to decrease with transmissivity, as the rate of increase in heat injection capacity is less than the rate of decline in heat extraction capacity. Details of the SKEWS project are discussed further in "Example of deep BTES project – Darmstadt (SKEWS)" section.

Deep single-well borehole thermal energy storage

Several attempts have been made to move beyond conventional thinking on BTES system design as arrays (Lanini et al. 2014; Skarphagen et al. 2019) (Fig. 11), and have extended the field to consider the technical feasibility of single-well DBTES systems (Westaway 2016; Brown et al. 2023, 2023; Xie et al. 2018; Fu et al. 2023) (Table 3). This is typically seen as a means for repurposing abandoned onshore hydrocarbon wells or geothermal exploration boreholes. The cost of drilling—which has been shown to make DBTES expensive in comparison to shallow BTES arrays (Bär et al. 2015a; Schulte et al. 2016)—is mitigated in such scenarios and is claimed to justify the adverse effect to shape factor (surface-area to volume) experienced in repurposed single wells.

Westaway (2016), using an analytical BTES model, estimated that the 2 km lateral section of a single shale gas well (Fig. 13) has the potential to sustainably store 1.6 GWh_{th} at a peak specific energy storage rate of 300 $W\,m^{-1}$ (or 0.6 MW_{th}). These findings neglect heat transfer in the vertical length of the borehole, but nonetheless provide possible orders of magnitude in storage. Advanced economic evaluation is needed, including considerations of the increased difficulty of installing coaxial BHE components within a heavily deviated deep borehole (Sun et al. 2019; Wang et al. 2021).

Abandoned geothermal boreholes also offer the possibility for repurposing. For example, the Newcastle Science Central Deep Geothermal Borehole (NSCDGB) in north-east England—drilled originally as a conventional geothermal exploration well—encountered unexpectedly low permeability in the targeted Carboniferous Fell Sandstone formation at depths beyond 1400 m. This led to the abortion of a planned open-loop geothermal system in the area (Younger et al. 2016). The NSCDGB has subsequently been assessed for its DBHE heat extraction potential in Kolo et al. (2022, 2023) and recently these modelling efforts have been extended to explore the site's feasibility for a single-well DBTES system (Brown et al. 2023, 2023). A sensitivity

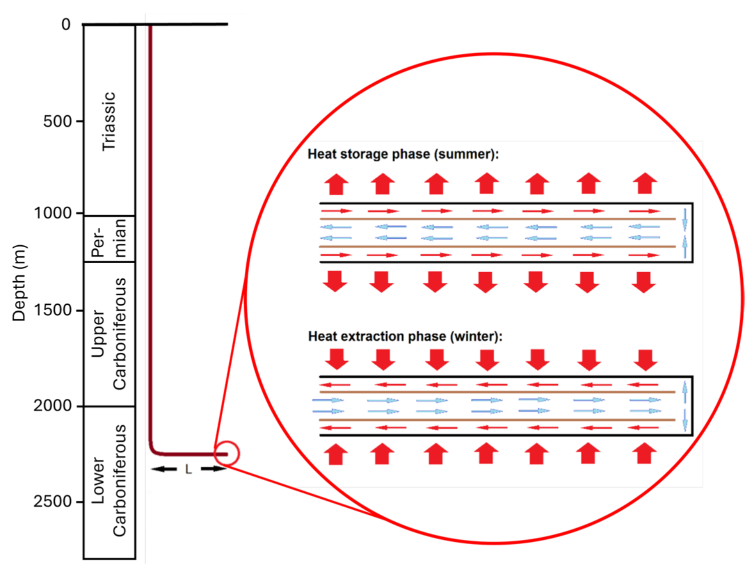

Fig. 13 Single-well DBTES design proposed by Westaway (2016) for heat storage in the lateral section of repurposed abandoned shale gas wells (figure adapted from Westaway (2016))

analysis of DBTES performance for the top 920 m of single-well design was carried out using an inhouse dual-continuum numerical model developed in MATLAB (benchmarked against OpenGeoSys) (Brown 2020; Brown et al. 2021). A 95°C constant inlet temperature (stored total of 1.23 GWh) resulted in a minimum increase of 15 kW in heat extraction from the DBTES, up 28% in comparison to the no-storage case by the end of a hypothetical 6-month charge–discharge cycle. Brown et al. (2023) used Spearman's and Pearson's correlation coefficients to assess the global sensitivity of stochastically-generated parameter values on thermal storage efficiency (TSE and TCE, Eqs. 16 and 17, respectively). It should be noted that these metrics would be difficult to apply in reality as they rely on comparing the energy extracted from the DBTES with and without the presence of a storage charging period. The low TSE and TCE values observed (< 20 %) for many of the parametric input spaces led the authors to conclude that single-well DBTES systems are unlikely to outperform shallow BTES arrays in most operating environments. The sensitivity analysis also found TRF to be most sensitive to changes in the undisturbed geothermal gradient, flow rate, and inlet fluid temperatures during charge and discharge phases. These findings are largely in agreement with those of Xie et al. (2018), who, using a semi-analytical model, likewise carried out sensitivity analysis of repurposed abandoned hydrocarbon wells and found inlet temperature to have the largest influence on TCE. Xie et al. (2018) subsequently presented an approach to optimise well depth for a given heat source temperature (BTES fluid injection temperature during charging) in order to maximise the TCE of the system (Eq. 17).

Considering again the NSCDGB case study, Brown et al. (2023) used OGS to investigate the influence of groundwater flow and charge–discharge cycle duration on a single-well DBTES system. An absolute reduction of up to 13 % in annual TSE was found for the extreme case of groundwater assumed to occur along the entire 920 m length of the DBHE (Darcy flow velocity of $1 \times 10^{-6} \mathrm{m\,s^{-1}}$) in comparison to the no-flow case. For alternating 6-month injection and extraction periods, Brown et al. (2023) reported annual TSE values as low as 1 %. These efficiencies could increase with time as reported in Welsch et al. (2016), however advective heat flow away from the DBHE is likely to significantly reduce the temporal improvement of annual TSE from thermal accumulation. Whilst TAE values may indeed increase in the high flow rate case, displacement of the thermal plume may inhibit discharge of the stored heat thus rendering the TAE misleading in high flow rate cases, particularly of single-well DBTES systems. Although the parameters used in Brown et al. (2023) represent a worst-case scenario, the impact of groundwater on storage efficiency indicates that single-well DBTES systems have limited applications in regions of thick formations with high hydraulic transmissivity and Darcy flow velocities. The findings also reinforce the prevailing evidence that shallower BTES arrays offer more efficient seasonal heat storage in comparison to single-well designs (Brown et al. 2023). Furthermore, the findings from both Brown et al. (2023) and Xie et al. (2018) highlight that only modest improvements can be made to efficiency by altering fluid inlet temperatures and instead repurposed hydrocarbon wells may look towards acting as a seed well about which deep arrays of DBHEs can be formed to improve the array shape factor. The drilling of the remaining wells in the array could also leverage the preexisting subsurface data.

Rather than specifically designing a DBTES system, Fu et al. (2023) investigated the injection of heat as a means to reduce thermal drawdown due to DBHE extraction, thus improving its technical sustainability. This was tested using an analytical model validated against short- and long-run empirical data from Li et al. (2020) and Song et al. (2021), respectively. For the case of a 2000 m deep DBHE, improvements in heat extraction capacity (quasi-steady-state heat extraction rate) of 12 kW and 29 kW were observed in year 1 and 30, respectively, in comparison to the base case without heat injection. This represents a 17% improvement. Extending the charging period and increasing the charging fluid flow rate and temperature also contributed to improved DBHE performance during heat demand phases. For an annual 6-month charge period in the DBHE, a total lifetime HSYR value (Eq. 20) of 47 is expected, suggesting a thermal power gain greater than the required increase in electrical power consumption. This ratio is found to decrease as the annual charging period increases as a result of declining heat storage capacity in the DBHE and increased pumping demands. Meanwhile the TRA, or HEIR, (Eq. 18) was found to increase from 6 % to 23 % as the annual charging period increased from 1 to 8 months, respectively.

Cooling applications

The typical range of bottom-hole temperatures encountered in DBHE systems makes them inefficient sources of cooling. To address this inherent issue, Zhang et al. (2022) proposed a DBHE system for heating and cooling which uses the CXA configuration in the winter for heating and the CXC configuration in the summer for cooling (see Sect. "Introduction" for a discussion on CXA and CXC operation modes). A **check valve design**, embedded in the central pipe, allowed the cyclic flow regime to be achieved whilst ensuring that the CXC configuration only made use of the upper section of the

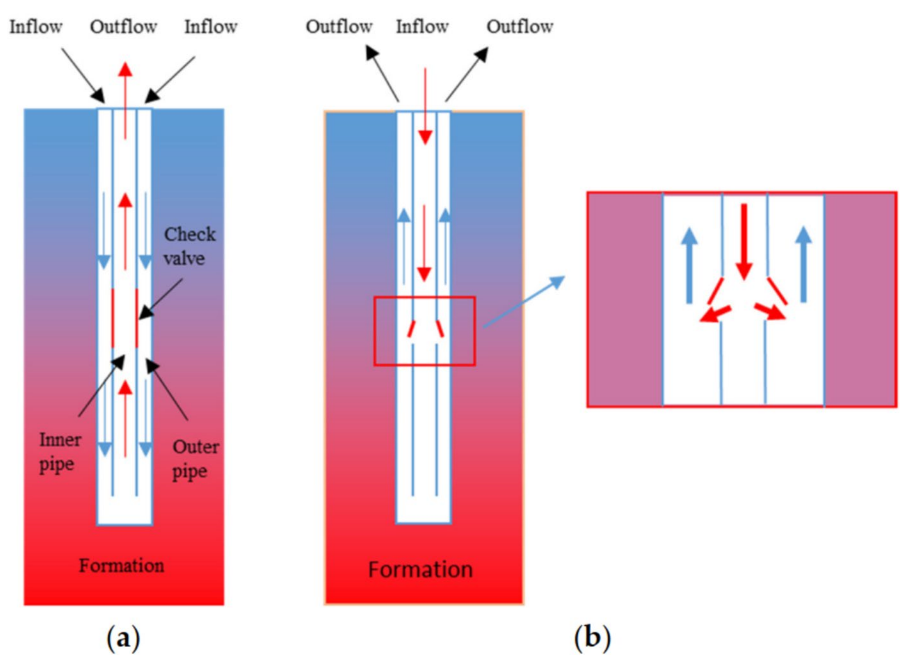

Fig. 14 Check valve DBHE from Zhang et al. (2022): **a** winter operation mode; **b** summer operation mode

DBHE (Fig. 14). By effectively creating a shallower DBHE, the system is expected to produce lower outlet temperatures suitable for cooling purposes. This design theory was modelled and tested in the numerical modelling software Fluent which found that heat injection rates increased with check valve depth whilst both heat injection and heat extraction rates increased with a higher formation thermal conductivity. Heat storage accrued in the lower DBHE section during the cooling seasons was also shown to improve heat extraction in subsequent heating seasons. Taking an example 2000 m DBHE, Zhang et al. (2022) found the optimum check valve operation condition to be at depth of 900 m with an inlet temperature of 50°C. Working temperatures of 40°C to 50°C are more attainable/practical for both cooling and heating compared to 85°C —90°C inlet temperatures used for other systems (Bär et al. 2015a; Schulte et al. 2016) (alternating between very high temperatures for cooling and very low temperatures for heating would be more challenging). Zhao et al. (2022) also proposed a system similar to the check valve DBHE of Zhang et al. (2022); by replacing the check valve with a **triple-layer DBHE** configuration (Fig. 15). For a 2000 m DBHE, the annular section was further partitioned into two using an 800 m pipe thereby adding an intermediate layer. During heating, the fluid inlet and outlet are through the outer annulus and central pipe, respectively. During cooling, the intermediate layer (inner annulus) serves as the inlet whilst the outer annulus is the outlet. The system performance is similar to that proposed by Zhang et al. (2022) with a maximum storage efficiency achieved was 9.4 % (the metric used was not stated).

Non-uniform insulation for the central pipe offers another potential DBHE design for supplying cooling loads (Luo et al. 2020). Based on analytical modelling carried out, full insulation of the central pipe was shown to exhibit better performance compared to upper half insulation (of the central pipe) case for heating whilst the inverse is true when attempting to use the DBHE for cooling purposes. Results showed that for a depth of 500 m, a central pipe with uniform insulation performed well in cooling whilst for a depth of 2000 m, a non-uniform insulation was required to restrict temperature rise in the deeper part of the DBHE and produce cooler outlet temperatures. Despite outperforming non-uniform insulation for heating, uniform insulation could not produce cooler water for inlet temperatures below 29°C and flow rates above 0.8 L s^{-1}. Luo et al.

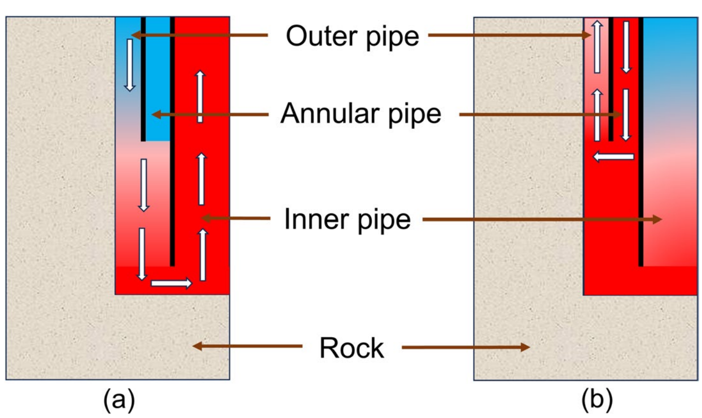

Fig. 15 Triple-layer DBHE concept reported by Zhao et al. (2022): **a** winter operation mode; **b** summer operation mode

(2020) identified the optimum DBHE operation range for insulation length to borehole depth ratio (k_L) and the ratio between the thermal resistance of the insulated section and non-insulated section (k_R) in both heating and cooling modes. Future work should look at using the optimum k_L and k_R ratios in both heating and cooling for the check valve DBHE and the triple-layer DBHE.

Rather than using the DBHE directly for cooling, the extracted heat can also be used to drive an **adsorption unit for adsorption cooling**. The case study by Dijkshoorn et al. (2013) had a climatic control adsorption unit which required a minimum of 55°C to operate in summer. Results showed that the DBHE could meet winter heating demand with temperatures between 25°C and 55°C and a maximum flow rate of $10\,\mathrm{m}^{-3}\,\mathrm{h}^{-1}$. However, the maximum outlet temperature reached in summer was around 51°C under cyclic operation and 49°C under continuous operation over 20 years. Hence, the DBHE could not maintain the required temperature to drive summer adsorption cooling in long-run scenarios even using the best available central insulation material. Adsorption cooling has seen limited practical applications in conjunction with DBHEs.

Deep borehole heat exchanger projects

In 1991, an abandoned 1962 m deep geothermal well was used to extract deep geothermal energy in Hawaii, thus representing the earliest prototype of the DBHE concept (Morita et al. 1992). Several DBHE projects were later implemented in Switzerland and Germany for exploring the feasibility of utilising deep geothermal energy through DBHE technology (Kohl et al. 2000, 2002; Sapinska-Sliwa et al. 2016). Starting in 2012, many DBHE projects have been implemented in China for building heating purposes (Wang et al. 2017; Cai et al. 2019). Due to the densely populated urban areas in northern China, DBHE projects are being explored from single DBHE to large DBHE arrays (Cai et al. 2021). Other recent developments include a coupled DBHE, with insulated central pipe, and adsorption unit for building cooling (Dijkshoorn et al. 2013) and initiatives for repurposing petroleum and geothermal wells (Brown et al. 2023). The reported data of existing operational DBHE projects, amongst others, are listed in Table 4. Several kinds of DBHE pilot projects are also introduced in detail in Table 5. For instance, the Eden Project is a UK-based project, which has also recently re-completed a deep geothermal well as a coaxial DBHE to ca. 4 km, delivering water at 85°C (Eden project 2023). Similarly, CeraPhi is currently retrofitting a well from the Kirby Misperton gas field (Gas Well Repurposing 2023), with an independent study suggesting that a thermal power of just under 300 kW over a typical UK heating season can be achieved (Nibbs et al. 2023). This section aims to provide an evaluation of new projects on deep borehole heat exchangers, with other papers reviewing established systems in detail (Falcone et al. 2018; Chen and Tomac 2023).

Example of large-scale DBHE array heating project—iHarbour

Located in the Xixian New Area in Shaanxi, China, iHarbour is the new campus of Xi'an Jiaotong University, capable of hosting more than 20,000 postgraduate students and tutors. The iHarbour consists of 52 buildings, including the research centre, student dormitory, and cafeteria, which contribute to a total heating area of 1.59 million m^2. To pursue low-carbon emissions on campus, DBHEs were selected as the main

Table 4 Operating DBHE heating projects reported in the literature

Number	Location	Year	Borehole depth (m)	Bottom temperature(°C)	Circulation temperatures(°C)	Flow rate (m^3/h)	Notes	References
1	Hawaii, USA	1991	1962	110	30/98 (in/out)	4.8	Abandoned geothermal well; inner dual-vacuum tube	Morita et al. (1992)
2	Weggis, Switzerland	1993 (drilled)[1]	2302	73	32/40 (in/out in 100 kW)/9/28 (in/out in 250 kW)	2.9-6.3	Insulated in 0-1780 m	Kohl et al. (2002), Sapinska-Sliwa et al. (2016)
3	Prenzlau, Germany	1996	2786	108	15 (in)	0.3-3.9	Double steel insulated pipe	Schneider et al. (1996)
4	Weissbad, Switzerland	1996	1213	45 (1200 m)	9-14 (10.6 in average)	10.8	Initially aimed to find an aquifer	Kohl et al. (2000)
5	Sucha Beskidzka, Poland	1997 (drilled)	4098.5	98 (4281 m)	16-18 in average	18	With an inner pipe of 2864.5 m; deviated borehole (2040 m)	Sliwa and Kotyza (2000)
6	Aachen, Germany	2004 (drilled)	2500	85	25-55 (outlet)	10 (max)	Both for heating and cooling (adsorption unit)	Dijkshoorn et al. (2013)
7	Xi'an, China	2012 (drilled)	1962	75.6	Over 25 (outlet)	28	Coupled with heat pump for 4-month building heating	Wang et al. (2017), Cai et al. (2019)
8	Qingdao, China	2016	2605	87.4	Lower than 20 with 5 inlet temperature	30	138-day experimental test with fixed inlet temperature	Bu et al. (2019)
9	Xi'an, China	2018	2100 (vertical) 205 (horizontal)	70.3	over 29.5(outlet) 19.5 (fixed inlet)	40.5	U-type DBHE 72 h experimental test	Li et al. (2018)
10	Songyuan, China	2020	2044	107.3	36.7/58.2 (1st day) 29.1/43.0 (60th day)	30	60-day experimental test with distributed optical fibre sensor	Huang et al. (2020)

Table 4 (continued)

Number	Location	Year	Borehole depth (m)	Bottom temperature(°C)	Circulation temperatures(°C)	Flow rate (m^3/h)	Notes	References
11	Xi'an, China	2021	2000	80.8	13.6/20.8 (average)	114.89 (total)	5-borehole DBHE array 106 days experimental test	Cai et al. (2021)
12	Jimo, China	2023	2600	83.2	14.5 (outlet)	30.5	Thermal attenuation was measured during 4-year operation	Zhang et al. (2023)

This indicates the year of drilling which does not necessarily coincide with the start of operation as a DBHE

method for space heating. The entire pilot project, completed in 2019 (and still in stable operation till date), consists of 91 2500 m deep DBHEs separated into 6 groups with an auxiliary natural gas boiler, producing a combined heating capacity of up to 75.69 MW (see Table 5). The building is cooled using independent water chiller units, which is the

Table 5 Pilot and planned DBHE heating projects worldwide

Number	Location	Planned construction year	Total heating capacity	Notes	References
1	Xi'an, China	2019	1590000 m^2 (75.69 MW) with 91 2500 m depth DBHEs	DBHE array heating project	/
2	Darmstadt, Germany	2023-ongoing	4 DBHEs (up to 37) at 750 m each	SKEWS BTES project	Landau et al. (2023), Bossennec et al. (2023), Seib et al. (2022), Bossennec et al. (2022)
3	Kiskunhalas, Hungary	2021	15000 m^2 greenhouse with 0.5 MW repurposed well	DBHE heating project	A (2021), WeHeat (2021)
4	California, United States	2019	1.2 MW net electric power was generated from a pilot repurposed well	DBHE project for electricity generation by GreenLoop closed-loop geothermal technology	Higgins et al. (2019), Amaya et al. (2020)
5	Yulin, China	2023	69.7 MW	Used for heating purposes in coal mine. Comprehensive multi-source energy system.	/
6	Newcastle, England	2023	50 kW	Pilot experimental borehole	Kolo et al. (2022, 2023), Brown et al. (2023)
7	Eden Project, UK	2023	Un-documented	85°C outlet temperature expected	Eden project (2023)
8	Kirby Misperton, UK	2023	300 kW	Note thermal power modelled independently	Gas Well Repurposing (2023), Nibbs et al. (2023)

conventional compressed cooling method. Therefore, the building's heating, cooling, and domestic water needs are all catered for, and the related types of equipment are integrated into 6 energy stations.

Because of the limited heat extraction capacity of a single DBHE, the use of DBHE array systems is gradually gaining popularity for building heating, especially in northern China. Pipe networks coupled with multiple DBHEs constitute such DBHE array systems, requiring a design approach taking into account influences by both the heat extraction process in the subsurface and the hydrothermal distribution in surface facilities (see Fig. 16).

To reduce long-distance transmission losses, the DBHEs are divided into 6 DBHE array groups, which are located in the distributed energy station on the iHarbour campus. The whole system has been operating for the last 3 years, with an average COP for each energy station of over 4.5, showing efficient energy extraction potential. The in-situ test indicates that the indoor temperature is maintained at over 20°C, and therefore meets the requirements for thermal comfort.

Example of deep BTES project—Darmstadt (SKEWS)

Supported by the Seasonal Crystalline Medium Deep Borehole Energy Storage System (SKEWS) research project, a pilot BTES system has been constructed at the Technical University of Darmstadt, Germany (Fig. 11(b)) (Landau et al. 2023; Bossennec et al.

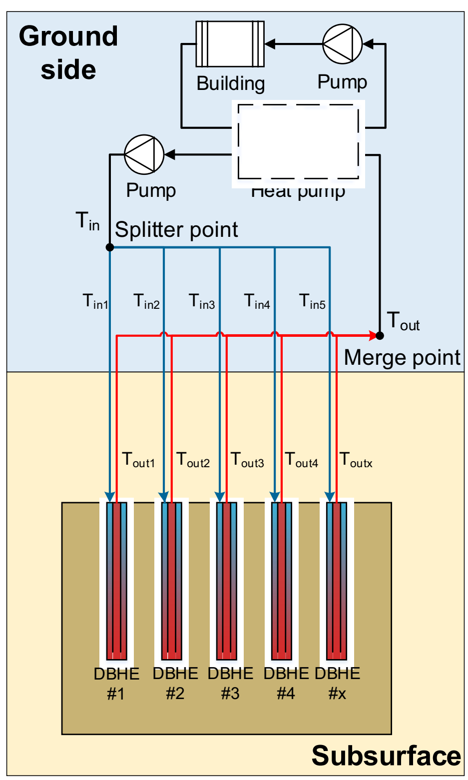

Fig. 16 Schematic diagram of the DBHE array heating system at iHarbour in Xi'an, China (from (Cai et al. 2021))

2023; Seib et al. 2022; Bossennec et al. 2022). The BTES system currently consists of four medium-deep borehole heat exchangers, which are located in the western area of the Lichtwiese campus. The first stage of the project plans to implement four boreholes, each with a depth of 750 m which will then be expanded to 19 DBHEs in stage 2 and 37 DBHEs in stage 3. The whole borehole array is expected to be arranged in a hexagonal shape, with 5 m borehole spacing (see Fig. 11(b)). Also, the DBHEs are of coaxial type to ensure reversibility of flow direction within boreholes during heat extraction and storage processes. Detailed geological and hydrogeological investigations have been executed for the project, which have improved parameter estimation when modelling the BTES system in FEFLOW to forecast the long-term performance (Seib et al. 2022). Comprehensive data collection and analysis, including electrical conductivity tomography, gravity measurements, and seismic profiles, are executed for this project (Seib et al. 2024). Moreover, considering the careful numerical pre-simulation for the borehole arrangement and several monitoring wells around the borehole array, insightful monitoring data are expected from future measurements and interpretive studies. It must be noted that the fault zone included in this study only crosses half of the BTES array and therefore more significant reductions in TRF are expected if a BTES array were to be located completely within a fault zone with high transmissivity.

Examples of planned projects

The DBHE technology deployment is currently experiencing rapid progress: single DBHE, DBHE arrays, and BTES systems are being constructed. In addition to the operating projects, there are several DBHEs planned for the near future for commercial or scientific purposes. This section outlines those in the public domain. Because of the uncertainty during the implementation of the projects, compared to the parameters of the built projects, the detailed information provided in this subsection may have slight deviations.

A DBHE heating project is planned to provide heating for mine buildings in the Xiaobaodang coal mine in Yulin, China. The construction of the system is scheduled to begin in the second half of 2023, with a planned total heating capacity of 69.7 MW. The Xiaobaodang heating system will combine the DBHE heating technology with solar thermal heating, mine water waste heat, and heat storage via electric boilers. The project will serve space heating, domestic water, and process heat demands within the whole coal mine park.

In the UK, there are several companies looking to develop abandoned (or depleted) oil and gas wells, whilst others are focussing on exploiting ex-geothermal wells targeting conventional resources. The NSCDGB was drilled in 2011–2014, targeting the Mississippian Fell Sandstone Formation; unfortunately, findings revealed poor hydraulic conductivity and flow rates ($< 0.1\,\mathrm{L\,s^{-1}}$) Younger et al. (2016). There are significant geothermal resources associated with the North Pennine Batholith and the underpinning high heat flows (Howell et al. 2021; Brown 2022). At present, plans are in place to develop the well as a DBHE as an alternative method of utilisation of legacy infrastructure. This will provide a pilot DBHE for thermal response testing and evaluation to contribute heat to either a heat network or directly to the adjacent Urban Sciences Building in Newcastle.

Recent numerical modelling has suggested that it could provide constant base load thermal power in excess of 50 kW (Kolo et al. 2022, 2023; Brown et al. 2023).

Conclusions and future outlook

Analytical and numerical modelling

Numerical modelling is necessary in some cases where analytical solutions are insufficient for detailed DBHE analysis, for example complicated boundary conditions and dynamic thermal plume simulation with the influences of groundwater flow and subsurface heterogeneity. It was frequently found that a 1D discretisation of the DBHE and 3D discretisation schemes (FEM, FDM, or FVM) for the surrounding formation—the so-called the dual-continuum approach—offers an efficient means for solving governing physical equations. This offers a practical alternative to the full model discretisation approach possible on general-purpose multi-physics CFD software or specialised subsurface software such as OGS and FEFLOW. Minimal difference are documented when comparing the dual-continuum approach in OGS (Chen et al. 2019; Cai et al. 2022) and analytical models (e.g. Beier's solution Beier (2020)—see Brown et al. (2023)), and bespoke models in MATLAB (Brown et al. 2023) against commercial codes such as T2Well (Brown et al. 2023). Co-simulation between subsurface and the surface energy systems can be achieved by coupling these DBHE numerical methods with energy system modelling software (Lyden et al. 2022; Witte and Tuschy 2020). Subsequent sensitivity analysis can investigate the impact of multiple operating modes on the DBHE long-term performance. Whilst most of the advanced modelling methods are capable of simulating all types of DBHE systems, uncertainty quantification remains a challenging area due to sparse datasets especially in the subsurface (Ahmed et al. 2023) and computation demand. This is highlighted by the relatively limited probabilistic analysis of DBHEs; however, some are beginning to conduct these analyses (Charlton and Rouainia 2024).

Thermal energy extraction applications

Despite the introduction of new DBHEs with improved heat extraction potential, the review of current pilot or planned projects revealed a market dominance of the conventional coaxial configuration due to the practicalities (and cost) of installation. Modelling studies on various DBHE applications have, in general, presented a poor outlook of DBHEs for power generation and large-scale direct heating systems. The reliance on conductive heat transfer through the borehole wall limits the expected thermal power extraction (kWs) to orders of magnitude less than open-loop geothermal system (MWs) (e.g. Brown et al. (2022a, 2022b); Saeid et al. (2015)). Although power generation is technically feasible using an Organic Rankine Cycle with isopentane or isobutane as a working fluid, it is unlikely to be economically attractive due to the low conversion efficiencies. Space heating via a heat pump is thus the most common DBHE application, due to rapid cooling of the subsurface and high thermal drawdown. They also perform best when producing constant base load energy due to inefficient capabilities to support high discharge rates (Ben et al. 2023). Initial drilling costs may be avoided with well repurposing (from failed geothermal exploration wells, or exhausted oil and gas wells) but a host of additional practical difficulties are introduced, including: water chemistry, residues of oil and gas (fugitive methane, explosion risk), insufficient diameter at base and in-hole obstructions (casing hangers, pumps, pipework, packers, etc.). Portland cement which is used in plugging low-temperature hydrocarbon reservoirs, might not withstand high temperatures when abandoned wells are repurposed for geothermal applications (Jello and Baser 2023). Extensive feasibility, operational, economic and environmental analyses are required on a per well basis to enable repurposing of hydrocarbon wells (Jello and Baser 2023).

The influence of several parameters on heat extraction has been studied. Increase in formation thermal conductivity, depth, geothermal gradient, and grout thermal conductivity results in an increase in the thermal power of DBHEs, for both single DBHEs and array systems. Whilst volumetric heat capacity has limited influence on thermal power, it is currently understood to influence the system's thermal recovery; this is yet to be fully explored. Groundwater flow positively influences heat extraction only when velocity exceeds $1 \times 10^{-7}\,\mathrm{m\,s^{-1}}$. However, such high-velocity values are not likely to be encountered at depth in the subsurface. Thermal interference in DBHE arrays has a negative impact on extraction-only systems and hence a line array performs better than a square array of DBHEs.

Whilst a wide range of investigations have been conducted in this field rich in publications, there still appear to be some areas which are not yet completely understood. Volumetric heat capacity can impact system recovery, which is particularly important when investigating operational conditions that are not limited to a constant base load (i.e. they require thermal recovery when production is paused). Heterogeneity of varying geological parameters has been limited to lithological layering with full-scale geological models of the subsurface neglected. Boundary conditions for the borehole are not always understood and many of the data necessary for model verification are absent. There are also limited applications of DBHE arrays and thus the operation, performance, hydraulics and system coupling (surface and subsurface) are under-explored.

Thermal energy storage applications

Investigations into thermal energy storage with DBHEs has been explored by several authors although most extensively in relation to the proposed Darmstadt storage system. Despite a number of available metrics for assessing storage efficiency, studies on DBTES arrays tend to report the TRF, which has been shown to increase with the increasing length and number of BHEs. Increased rock thermal conductivity and hydraulic conductivity on the other hand result in lower TRFs due to thermal losses. Such losses can be reduced by the productive thermal interaction between DBHEs during storage. Hence, TRF values for large arrays of shallow BHEs typically outperform sparse array of deep BHEs for the same total drilled length. However, DBTES projects are incentivised by their reduced surface footprint, use of high-temperature storage sources (especially when insulation is installed in the shallow section of the DBHE), and minimised dependency on geological formations and groundwater flow. Shallow arrays also display superior TCE and TSE values in comparison to single-well DBTES, again emphasising the importance of thermal interaction in storage arrays. The technical advantage of DBTES over shallow BTES therefore seems limited at present. Important insights will be gathered from the Darmstadt DBTES SKEWS project to judge the validity of this stance.

The storage metrics provided are an attempt to resolve the currently disjointed reporting on DBTES performance. When describing system storage efficiency, it is suggested that the most accurate metric should represent the impact of heat injection on the heat extraction potential of a DBHE or DBHE array. It is thus proposed that the efficiency metric for DBTES system modelling is the TSE metric (Equation (16)) used in Brown et al. (2023, 2023). Resorting to the commonly-used TRF may be most practical for realised DBTES systems, offering scope for model validation from empirical findings. The HSYR metric also provides a powerful means for assessing the potential impact of storage on DBHEs from a power balance perspective, leading more naturally to economic analyses of DBHEs as DBTES systems. Wider application of these metrics (HSYR and TRA/HEIR) would enable more detailed comparisons across the aforementioned studies. Fundamentally, when reporting and comparing on the storage efficiency, consistency and clarity are key for the system application all over the world.

Cooling applications

Cooling can be difficult with high bottom-hole temperatures since to ensure heat rejection, heat must be rejected at a temperature higher than the average formation temperature and heat pumps are not typically designed to operate at this temperature range. Some studies have explored concepts that enable the use of the same DBHE for heating and cooling by employing only the upper part of the DBHE during cooling. With a check valve or an additional intermediate layer, this is made possible. The check valve DBHE or the Triple-layer DBHE can be integrated with a non-uniform central pipe insulation to enable cooling in the summer and heating in the winter.

Future outlook

Conventional modelling studies have been deployed to provide fundamental insight into the design and operation of DBHEs for heat extraction and storage, however new techniques are necessary to move the field forward. An absence of fast and accurate evaluation tools continues to impact the integration of closed-loop geothermal systems into whole-system design and application modelling. In this direction, the development of data-driven surrogate models would offer significant improvements to integrate model run-times and may be viewed as an area of focus for future research. The use of statistical learning techniques should also be considered in future parametric modelling studies aimed at investigating the effect of volumetric heat capacity on system recovery when operating in variable load scenarios. Additionally, full-scale geological facies models remains relatively unexplored when assessing DBHE model sensitivity to heterogeneity (i.e. anisotropy). Field-scale optimisation of arrays with close inter-borehole spacing of DBHEs to minimise thermal drawdown and maximise system efficiency should also be considered. Some researchers have developed useful tools (such as BASIMO), but they neglect the influence of advection in the formations around the BHE (Schulte et al. 2016).

Another important direction for future research is the whole-system techno-economic evaluation. As summarised in this review, DBHEs are typically capital intensive with significant upfront costs associated with drilling or repurposing of boreholes. Comprehensive techno-economic models over the project lifespan are therefore vital for investor confidence in securing an adequate rate of return for the risk associated with the initial project funding. Whilst projects like the iHarbour DBHE heating project are producing heat efficiently, the DBHE project in Aachen was declared economically unfeasible in 2011 (Dijkshoorn et al. 2013) because of additional high cost required for insulating the inner pipe. It is thus very important for decision-makers to consider the trade-offs in techno-economic feasibility studies to ensure that available materials and costs are realistic before embarking on project implementation. A first step when evaluating and comparing the feasibility of integrated DBHE systems should be an insistence on consistency in the use of storage efficiency metrics.

Whilst the DBHE literature and market to date has been dominated by the coaxial single-well design, additional closed-loop technologies have been explored. As described, modelled modifications to the DBHE system with a check valve (Zhang et al. 2022) or a triple-layer design (Zhao et al. 2022), for example, have indicated the potential for combined heating and cooling applications when used in conjunction with non-uniform central pipe insulation. Horizontal extension to the original vertical DBHE have also shown to improve heat extraction (Wang et al. 2021). Further proof-of-concept pilot projects have been carried out for alternative single-well closed-loop geothermal designs which do not rely on a coaxial pipe configuration but instead use (multi-)lateral sections to enhance the heat transfer surface area between the DBHE and surrounding media (Fig. 17), thus improving thermal power outputs (Budiono et al. 2022). These so-called U-loop/U-type DBHEs are forming a growing closed-loop geothermal market. Pilot projects in Alberta, Canada (Eavor 2023) and Xi'an, China, (Li et al. 2018), including the Caotan heating project, have spurred interest in the technology leading to the development of the first commercial project in Geretsried, Germany (Longfield et al. 2022). Modelling has also been performed to help in understanding the design, operation and expected performance of these U-type systems (Sun et al. 2019; Mingzhi et al. 2021; Zhang et al. 2021; Fallah et al. 2021; Chen et al. 2021; Jiang et al. 2022; Doran et al. 2022; Kelly and McDermott 2022). For example, Malek et al. (2022) optimised the system mass flow rate for electric power generation and, for a given well depth, were able to estimate

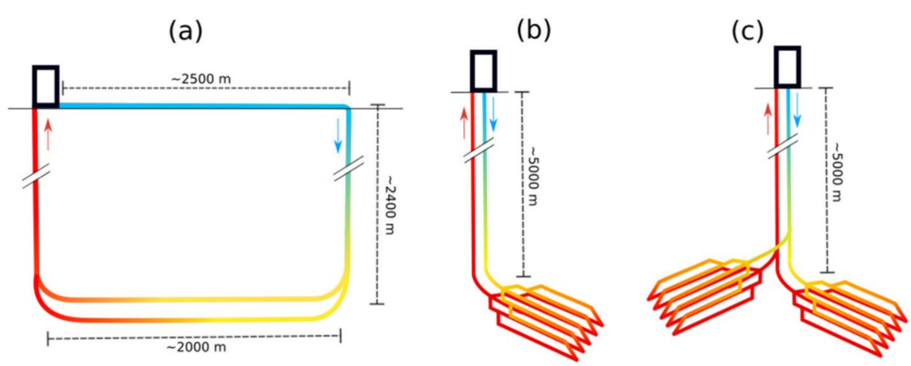

Fig. 17 Schematic diagram of proposed Eavor-Loop systems: **a** Eavor-Lite demonstration plant, **b** "James Joyce" design with adjacent vertical wells and folded lateral array and **c** Expanded "James Joyce" configuration with additional stacked lateral arrays (from Kelly and McDermott (2022))

an optimal lateral length and an optimal well diameter to minimise specific capital cost. Collectively, the aforementioned closed-loop variations form the Advanced Geothermal Systems (AGS) class of geothermal energy technologies. Continued detailed modelling and dedicated demonstrator projects will be required to demonstrate the ability of the evolving AGS designs to deliver commercially viable low-carbon heating across a range of future applications. Furthermore, significant advancements in drilling technologies, that have the potential to reduce drilling costs by over 50 %, are required to enable cost-competitive AGS implementations (Malek et al. 2022).

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

Declarations

Competing interests
The authors declare no conflict of interest.

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