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Repurposing Onshore Wells for Geothermal Use in the United Kingdom: Application as Deep Borehole Heat Exchangers

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ABSTRACT

Repurposing onshore hydrocarbon wells for thermal energy extraction presents an opportunity for low-cost progress on decarbonising the heat supply of the United Kingdom (UK), with capital expenditure being minimised by saving on drilling costs. This study builds on previous work into the suitability of abandoned oil and gas wells for geothermal exploitation. Herein, previous work is expanded to encompass well repurposing for closed-loop co-axial deep borehole heat exchanger (DBHE) systems.

Through the application of GIS mapping and a multi-criteria screening survey, 62 onshore hydrocarbon wells in the UK are identified as having potential repurposing suitability to be reconfigured as DBHEs. Of these, 25 wells are currently operational and a further 15 are approaching cessation of production. Higher heat loads are achievable in wells that are either located in areas of increased geothermal gradient or that have been drilled to greater depths, thus high bottom-hole temperatures remain the focus for repurposing. High-ranking candidate wells are identified in several fields located in England.

Using these candidate wells as case studies, preliminary numerical modelling in MATLAB is used to estimate the potential of DBHEs as a means for repurposing hydrocarbon wells, while providing a feasible alternative heat source to natural gas. A dual-continuum numerical model with finite-difference solver is used to simulate heat flow within the DBHE, incorporating the borehole dimensions and site-specific geological formations. For example, initial modelling of KM8 (an abandoned gas well located in the Kirby Misperton gas field of the Cleveland Basin in north-east England) suggests that a DBHE at the site may have the capacity to provide heating to a commercial-scale glasshouse for low-carbon horticulture. The thermal power and performance of this well, and others, are subsequently assessed over a typical heating season of six-months in constant operation. Modelling suggests that thermal power in the order of hundreds of kilowatts can be expected from each well, with KM8 offering the greatest potential, yet outlet temperatures are too low for building heating applications without the addition of heat pumps.

1. INTRODUCTION

Heat consumption in the UK accounts for 47% (0.73 PWh) of the nation's total energy consumption (1.56 PWh), yet, as of 2021, renewable sources contributed just 7.3% (0.05 PWh) in meeting this heating demand. While this represents a 4.4% increase in absolute renewable heat production from 2020 to 2021, the increased capacity did not keep pace with the increase in total heat consumption, representing a decline in the overall share of renewable sources in heat generation. Currently, this renewable heat supply is derived mainly from solid biomass (64%), while heat pumps and deep geothermal contribute 27% and 0.02%, respectively (UK Government, 2022). Significant efforts are needed to meet the ambitious net-zero climate goals set out by UK Government and devolved executives (UK Government, 2019; Scottish Government, 2019), triggering a clear demand for deployable low-carbon heating solutions (Abesser and Walker, 2022).

The repurposing of hydrocarbon wells to become geothermal systems presents a range of upcycling benefits such as postponed decommissioning costs and low-carbon energy extraction, yet it remains unexploited for heat production in the UK. By capitalising on existing infrastructure, the cost of drilling deep geothermal wells (with measured depths greater than 500 m) can be bypassed, reducing capital expenditure for thermal energy extraction by over 40% in the low-enthalpy basins across the UK (Kurnia *et al.*, 2021). Despite numerous analyses into repurposed-well feasibility (Alimonti *et al*., 2014; Falcone *et al.*, 2018; Liu *et al.,* 2018), such systems have historically lacked commercial backing due to low exergy outputs, high risk-to-reward ratios, and less attractive revenue streams than power generation. However, a growing realisation of the need to decarbonise heating applications may motivate government financial support mechanisms and/or incentivise acceptance of lower rates of returns – particularly as repurposed legacy assets may provide oil and gas companies with the opportunity to move the dial on Environmental, Social and Governance (ESG) initiatives. There are indications that preliminary steps are being made in this direction (Hayhurst, 2020).

The numerous technologies available when exploiting pre-drilled boreholes are commonly defined with reference to a bifurcated classification: open- and closed-loop systems. Whilst the technologies of each branch offer benefits, deep closed-loop geothermal single well technologies – such as co-axial deep borehole heat exchanger (DBHE) systems (Figure 1) – offer the potential for 'off the shelf' deployment and so support the acceleration of low-enthalpy geothermal energy extraction. Simultaneously, many of the inherent operational risks associated with open-loop geothermal systems are bypassed, such as exploration failure and induced seismicity (Collins and Law, 2016; Falcone *et al*., 2018). Additionally, closed-loop single-well systems can prevent the migration of harmful dissolved gases to surface, addressing the documented issue of methane leakage and fugitive emissions from abandoned hydrocarbon wells (Townsend-Small *et al.*, 2016). When considering using either of the two most common single-well technologies as prospective repurposing tools, namely U-tubes or co-axial DBHEs, one would favour the latter system: the co-axial design has greater heat transfer areas (a critical design criterion when relying solely on thermal conduction for heat extraction) and lower pumping power requirements arising from pressure losses (Kurnia *et al.*, 2021). Furthermore, when considering the installation of co-axial DBHEs in low-temperature sedimentary basins, Gascuel *et al.* (2022) conclude that repurposing oil and gas wells offers the most cost-efficient method, outperforming vacuum-insulated tubing designs of new geothermal systems for the same location. The work herein aims to assess whether targeted deployment of the co-axial DBHE technology in abandoned hydrocarbon wells could catalyse geothermal use in an array of heating applications across the UK.

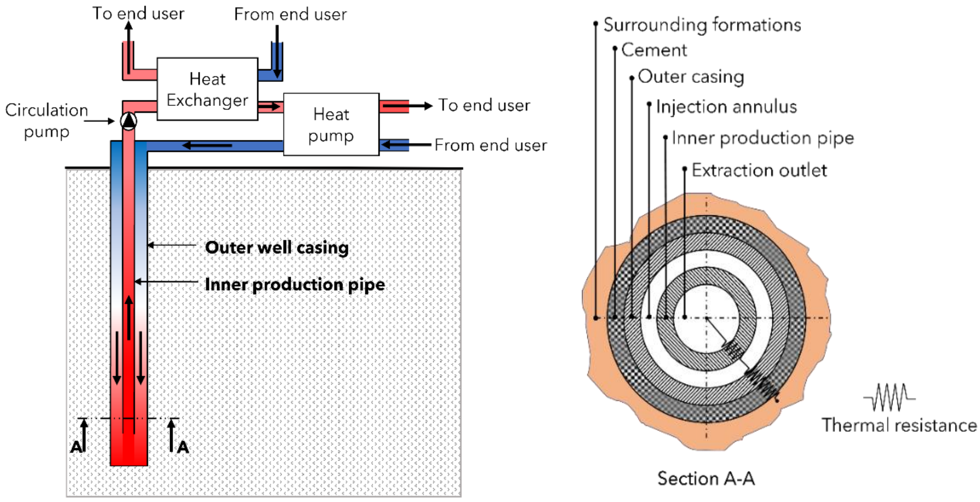

Figure 1: Schematic of closed-loop co-axial deep borehole heat exchanger system (left) and cross-section (right).

2. SCREENING OVERVIEW

Following the approach of Watson *et al*. (2020), the Onshore Well Database produced by the North Sea Transition Authority (NSTA) – formerly the Oil and Gas Authority (OGA) – was interrogated to determine candidate onshore wells in the UK suitable for repurposing as DBHEs. The present study applies additional screening criteria on operational status, well depth and deviation.

Operational status is a critical factor in assessing hydrocarbon well accessibility. The NSTA's Well Operations Notification System (WONS) reports the operational status of hydrocarbon wells in the UK. Wells are thus classified as: drilling, completed (operating), completed (shut in), plugged, or in abandonment phase 1, phase 2, or phase 3 (OGA, 2018). Wells with greatest relevance to the present study are those currently in operation – identified as potential future repurposing candidates – or approaching cessation of hydrocarbon production (*i.e*., shut-in or plugged), for which repurposing would delay the onset of decommissioning operations and prolong the life of the well. As reported in Watson *et al.* (2020), of the 2242 existing onshore hydrocarbon wells in the UK, 333 wells are currently operational, 98 wells are 'shut-in' and 27 wells are classified as 'plugged', presenting a total of 458 candidate sites.

To provide targeted deployment of co-axial DBHEs, further screening criteria are placed on well depth and deviation: wells must extend to depths beyond 500 m measured depth (MD) with minimal deviation from vertical. Of the 458 candidate wells screened, 62 are classified as vertical (five of which had insufficient publicly-available data for further screening) – in total 48 vertical wells have been drilled with MD greater than 500 m (Figure 2). These wells are classed as candidates for repurposing as DBHEs.

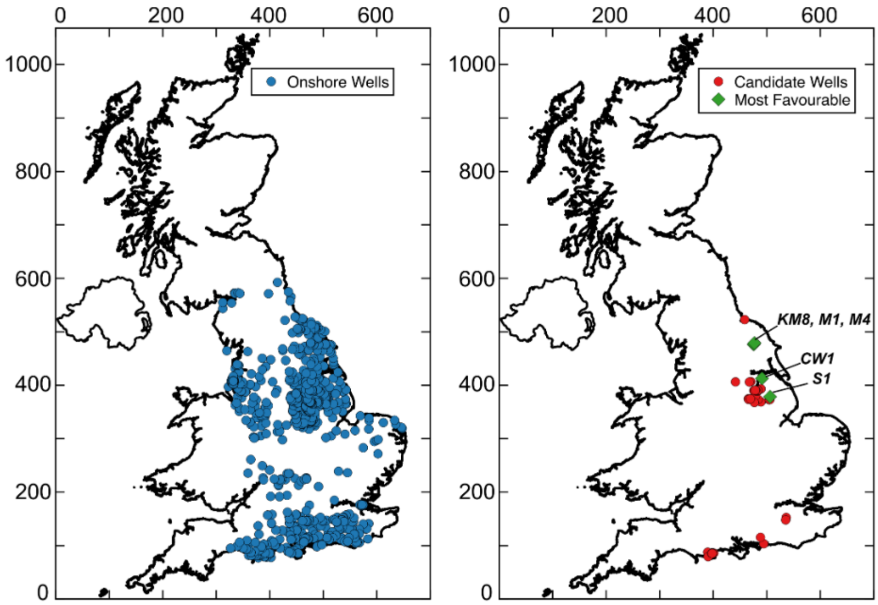

Figure 2: Onshore hydrocarbon wells in the UK (left). Candidate and most favourable hydrocarbon wells for repurposing as DBHEs (right), using bottom-hole temperature for an initial metric of favourability. British National Grid coordinates (north and east) are in 100 km intervals. © Crown copyright and database rights 2022 Ordnance Survey (100025252).

Bottom-hole temperature (BHT) was selected as the final criterion of a well's capacity for repurposing as a DBHE. For each of the 48 favourable candidates identified in the screening analysis, BHT estimates were derived from historical borehole heat flow measurements, many of which have been corrected via the Horner Correction (Burley, 1984; Rollin, 1987) (Figure 3). Using the coordinates for each of the measurement boreholes, inverse-distance weighting was applied to heat-flow measurements within a defined radius from the candidate well, thus enabling a thermal gradient estimate at the candidate location. Knowledge of the depth and thermal gradient of each well allowed the BHT metric to be applied, highlighting the five most favourable sites for DBHE installation in the UK (Figure 2). These were identified as Kirby Misperton 8 (KM8), Malton 1 (M1), Malton 4 (M4), Crosby Warren 1 (CW1) and Stainton A1 (S1).

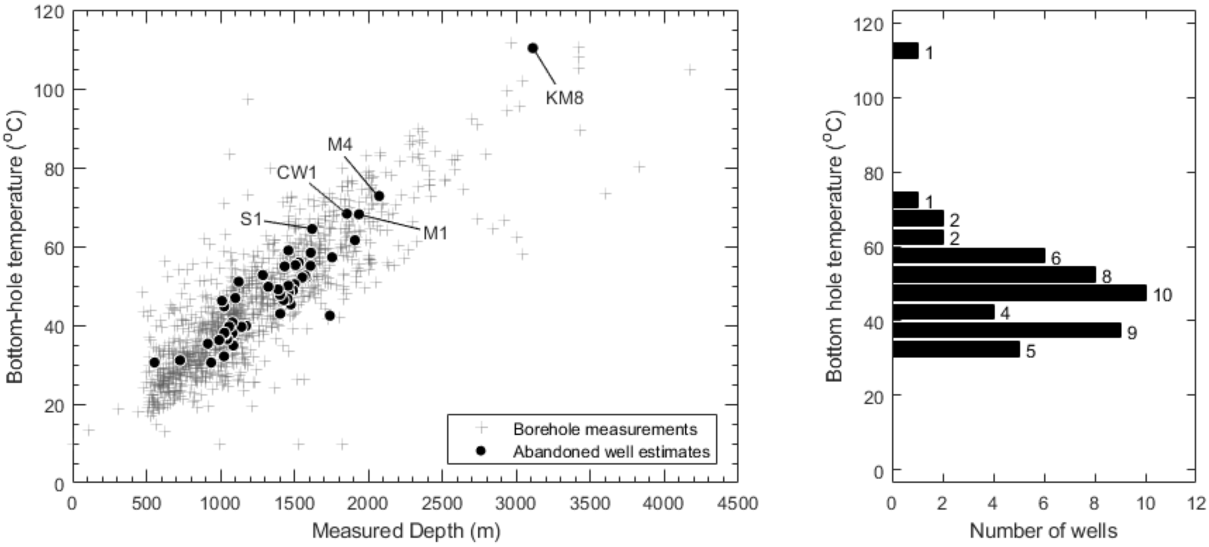

Figure 3: Borehole measurement data from Burley (1984) and Rollins (1987) used to estimate bottom-hole temperatures of abandoned vertical hydrocarbon wells in the UK. KM8 = Kirby Misperton 8, M1 = Malton 1, M4 = Malton 4, CW1 = Crosby Warren 1 and S1 = Stainton A1.

3. METHODS

Modelling was undertaken with MATLAB software using a finite-difference method. The model was designed by Brown *et al.* (2021), simulating the wellbore as a 1D line source coupled to a 3D medium of the subsurface. This design saves computational time and has been applied to a variety of problems from open-loop systems to 'Eavor-style' closed-loop U-tubes (Brown *et al*., 2020; Doran *et al*., 2022). The model has been validated, or benchmarked, against analytical solutions and open-source simulators, such as OpenGeoSys software (see Brown *et al*. 2021; Brown *et al*., 2022; Doran *et al*., 2022; Kolo *et al*., 2022).

3.1 Governing Equations

3.1.1 Heat Flux in the Rock

Heat transfer within the subsurface is assumed to be fully conductive around the DBHE, thus ignoring the impact of groundwater flow on such systems (Chen *et al*., 2019). Conductive heat flux is modelled using Fourier's law:

$$\frac{\partial T}{\partial t} = \alpha \nabla^2 \mathrm{T} \tag{1}$$

where T is the temperature, t is time and α is the thermal diffusivity of the rock.

3.1.2 Heat Flux in the Wellbore

Heat transfer within the borehole is modelled as a 1D series of nodes which simulates the fluid, pipes, cement and surrounding rock. Heat flux is modelled vertically against the cross-sectional area and horizontally using thermal resistance, analogous to electrical resistances (Figure 4). Heat flux between the central co-axial pipe, annulus and cement can be calculated as (summarized after Brown *et al*., 2021):

$$\rho_f C_f \frac{\partial T_{po}}{\partial t} A_{po} - \lambda_f \frac{\partial^2 T_{po}}{\partial z^2} A_{po} - \rho_f C_f v_{po} \frac{\partial T_{po}}{\partial z} A_{po} = b_{poi}(T_{pi} - T_{po}) 2\pi r_{po} \tag{2}$$

$$\rho_f C_f \frac{\partial T_{pi}}{\partial t} A_{pi} - \lambda_f \frac{\partial^2 T_{pi}}{\partial z^2} A_{pi} + \rho_f C_f v_{pi} \frac{\partial T_{pi}}{\partial z} A_{pi} = b_{poi}(T_{po} - T_{pi}) 2\pi r_{po} + b_{pig}(T_g - T_{pi}) 2\pi r_{pi} \tag{3}$$

$$\rho_g C_g \frac{\partial T_g}{\partial t} A_g - \lambda_g \frac{\partial^2 T_g}{\partial z^2} A_g = b_{pig}(T_{pi} - T_g) 2\pi r_{pi} + b_{gs}(T_s - T_g) 2\pi r_g \tag{4}$$

$$\rho_s C_s \frac{\partial T_s}{\partial t} A_s - \lambda_s \frac{\partial^2 T_s}{\partial z^2} A_s = b_{gs}(T_g - T_s) 2\pi r_g \quad (5)$$

where subscripts are defined as: f refers to the fluid of the central pipe or annulus, po the central outlet pipe, pi the annular injection space, g the cement and s the solid rock formations surrounding the borehole. The variables are defined as: ρ the density; C the specific heat capacity; A the area; r the radii; λ the thermal conductivity; v the fluid flow velocity; T the temperature of the relevant material and b the reciprocal of thermal resistance, R (*i.e.*, conductance) – *e.g.*, b_{pig} represents the heat transfer coefficient between the pipe and cement, or inversely R_{pig} defines the thermal resistance. The value for the reciprocal of thermal resistance of a casing layer is calculated as a constant value from the fluid flow, material conductivity and thickness. Further information on model design is available in Brown *et al*. (2021). The respective parameters, symbols and units can also be found in Table 1 and Figure 4.

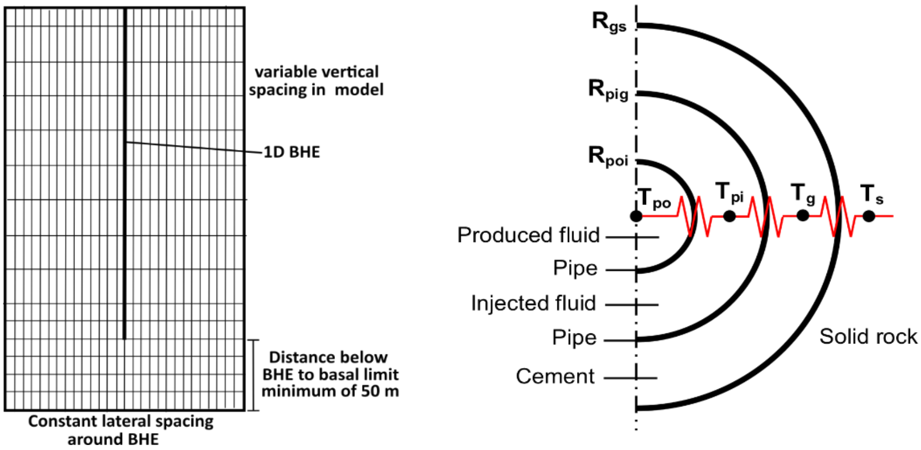

Figure 4: Mesh discretization (left) and thermal resistances of casing materials, analogous to electrical resistances (right).

3.2 Incorporating a Heat Pump

A heat pump is used at DBHE outlet to increase fluid extraction temperatures before reaching the end-user. The heat supplied to the end-user therefore varies from the heat extracted from the DBHE, with the difference representing the work done by the heat pump:

$$\dot{Q}_{DBHE} = \dot{Q}_{user} - W_{hp} \quad (6)$$

in which $\dot{Q}_{DBHE}$ is the heat extracted from the DBHE, $\dot{Q}_{user}$ is the heat reaching the end-user and W_{hp} is the work done by the heat pump. The latter depends on the performance or efficiency of the heat pump, which is estimated using the coefficient of performance (COP). The COP can be computed as a linear function of the outlet temperature from the DBHE. For a heat pump that has a floor heating temperature of 35°C, the COP is given by (Chen *et al*., 2019):

$$COP = \frac{\dot{Q}_{user}}{W_{hp}} = aT_{out} + b \quad (7)$$

where a = 0.083 and b = 3.925 are constants and T_{out} the DBHE outlet temperature. In addition, a circulation pump is used to circulate the heat transfer fluid as the thermosiphon effect is assumed to be negligible at the expected fluid temperatures (Chen *et al*., 2019). Since the COP only accounts for the work done by the heat pump, a different metric can be used to analyse the overall system efficiency – the coefficient of system performance (CSP), computed as:

$$CSP = \frac{\dot{Q}_{user}}{W_{hp} + W_{cp}} \quad (8)$$

with W_{cp} representing the work done by the circulation pump; a function of the volumetric flow rate ($\dot{V}$) and the pump head (ΔP) for both inflow and outflow:

$$W_{cp} = \frac{\dot{V} \cdot \Delta P}{\eta} \quad (9)$$

where η is the pump efficiency taken here to be 70%. The pressure drop for inflow and outflow is calculated using (Chen *et al*., 2019):

$$\Delta P = \left[\frac{L\rho_f v_{pi}^2}{2D_h[0.79\ln(Re_{in}) - 1.64]^2}\right]_{inlet} + \left[\frac{L\rho_f v_{po}^2}{2D_h[0.79\ln(Re_{out}) - 1.64]^2}\right]_{outlet} \quad (10)$$

where L is the DBHE depth, v the flow velocity, D_h the hydraulic pipe diameter and Re the turbulent flow Reynolds number.

3.3 Initial and Boundary Conditions

The model was discretised in Cartesian co-ordinates with the lateral domain extended to a minimum of 30 m radial distance from the centre of the borehole to minimize boundary influences. Similarly, the base of the model was set to a minimum of 50 m from the bottom of the DBHE. The surface boundary condition was set fixed at 10 °C, which is a typical average ground temperature for the UK, whilst lateral boundaries were set fixed to equal the geothermal gradient. The basal boundary was set to a constant heat flux, calculated using the corresponding geothermal gradient and thermal conductivity for each case study.

3.4 Benchmarking

The model was compared to the well-established OpenGeoSys (OGS) software (*e.g*., Chen *et al*., 2019; Kolo *et al*., 2022), which utilizes the similar dual-continuum method – modelling the wellbore in 1D and formation mesh in 3D – using finite-elements for spatial discretisation. The CW1 well was chosen as a test example. Over a heating season of six months, the outlet temperatures highlighted in Figure 5 are nearly identical. At the end of the simulation, the difference in outlet temperature is less than 0.1 °C – a difference in thermal power of less than 2 kW at the 4 l/s fluid flow rate (the fluid assumed here is pure water).

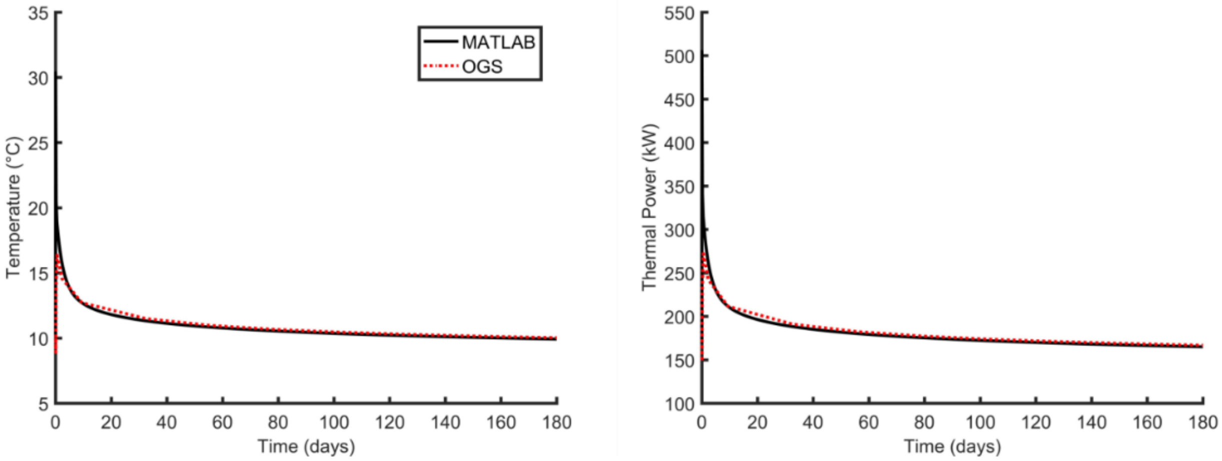

Figure 5: Software comparison for outlet temperatures (left) and thermal power (right) of Crosby Warren-1 well. A 0°C inlet temperature is set to define the maximum achievable thermal power. All other parameters are listed in Tables 1 and 2.

3.5 Parameterisation

In addition to reducing upfront drilling costs, retrofitting existing oil and gas infrastructure benefits from site-specific documentation into the near-field downhole formations. The thermal properties of formations surrounding a DBHE have been analytically and numerically shown to impact the thermal power output and lifetime from the repurposed well and are thus critically important (Sui *et al.*, 2019). The formation tops data were collected from the UK Onshore Geophysical Library (UKOGL, 2022) for each of the five highlighted candidate wells considered in this pre-feasibility modelling (KM8, M1, M4, CW1 and S1 wells). This reduces the extent of uncertainty with regards to the petrophysical and thermal properties, as well as thickness, of the formations encountered along the borehole. Knowledge of the present formations helped to form conceptual models using estimations of density and thermal properties (thermal conductivity and specific heat capacity of unsaturated rock matrices). Subsequent weighted averages were taken to estimate bulk thermal diffusivity values needed to parameterise well models (Table 1). Furthermore, the design of the DBHE casing dimensions is limited to the depth and radii of the existing boreholes used in hydrocarbon extraction, as detailed in manual drilling logs for the wells considered. The defined features of subsurface stratification and existing borehole dimensions assist in parameterising the DBHE numerical model. The inlet temperature of the circulating water is set to 0°C in order to represent maximum thermal power extraction attainable in each system – in reality, this brings risks of freezing in the DBHE components and higher injection temperatures would be used, resulting in a lower thermal power extraction capacity (Brown *et al*., 2022).

Table 1: General parameters for site-specific geological and dimensioning properties of existing wells (Bullard and Niblet, 1951; Bloomer, 1981; Cermak and Rybach, 1982; Downing and Gray, 1986; Midttomme *et al.*, 1998; 1999; Scharli and Rybach, 2001; Waples and Waples, 2004; Banks *et al.*, 2013).

Parameter	KM8	M4	M1	CW1	S1	Units	Symbol
Bulk rock thermal conductivity	2.50	2.70	2.60	2.80	2.70	W/m.K	λ_s
Bulk rock specific heat capacity	890	920	930	920	920	J/kgK	$c_{p,s}$
Bulk rock density	2580	2600	2570	2640	2600	kg/m^3	ρ_s
Measured depth	3110	2073	1907	1817	1601	m	z_m
Geothermal gradient	32.2	30.3	30.0	31.4	33.6	°C/km	u
Bottom-hole temperature	110.1	72.8	67.2	67.1	63.8	°C	-
Borehole diameter	0.329	0.295	0.292	0.311	0.283	m	-
Production pipe diameter	0.178	0.178	0.178	0.178	0.140	m	-

Table 2: General parameters of DBHEs kept fixed during all simulations. Parameters of wellbore properties defined after Westaway (2020), Banks (2021) and Kolo *et al*. (2022). Temperature dependencies of materials were not included in the model.

Parameter	Value	Units	Symbol
Outer diameter of inner pipe	0.1005	m	-
Thickness of inner pipe	0.0069	m	-
Thickness of outer pipe	0.0081	m	-
Thermal conductivity of polyethylene inner pipe	0.45	W/(m.K)	-
Thermal conductivity of steel outer pipe	52.7	W/(m.K)	-
Density of casing cement	995	kg/m^3	ρ_g
Thermal conductivity of casing cement	1.05	W/(m.K)	λ_g
Specific heat capacity of casing cement	1200	J/kgK	C_g
Density of fluid	995	kg/m^3	ρ_f
Thermal conductivity of fluid	0.59	W/(m.K)	λ_f
Specific heat capacity of fluid	4180	J/kgK	C_f
Inlet temperature	0	°C	T_{in}
Surface temperature	10	°C	-
Volumetric flow rate	0.004	m^3/s	Q
Circulation pump efficiency	70	%	η

4. RESULTS

The aim of this study is to quantify the thermal power extraction potential from the UK onshore hydrocarbon wells with the highest BHT, and thus the greatest potential as DBHEs. Using the numerical model described in section 3, preliminary thermal power output performance for the deep vertical abandoned wells was simulated for an entire heating season, assumed to be 180 days (or approximately six months) at constant circulation flow rate.

4.1 Thermal Analysis

The modelling performed in MATLAB confirmed that higher BHTs correlate with higher predicted DBHE outlet temperatures but highlighted severe thermal losses in the single-well configuration (Figure 6). Due to the choice of materials for the injection annulus casing and production pipes, it is shown that heat extraction efficiency remains low. As heat extraction occurs through conduction only and exploits small diameter boreholes with associated small heat exchange surfaces, the choice of material in the annulus casing and cement type is critical. Furthermore, the insulation medium selected for the production pipe (*i.e.*, the interface between the warm production and cooler injection flows) resulted in significant heat losses to the surroundings during transit to surface. Regarding the heat gained by the DBHE at bottom-hole depth, energy losses on return to surface ranged from 52% in S1 to 67% in KM8. As transit duration increases with DBHE depth, the effect was more pronounced in the KM8 well case. The decision to design and install a production tubing with improved insulation properties must be evaluated via a cost-benefit analysis (CBA) to compare the expenditure of deployment with the increased revenue from improved thermal power extraction. Such a CBA was not carried out as part of this study.

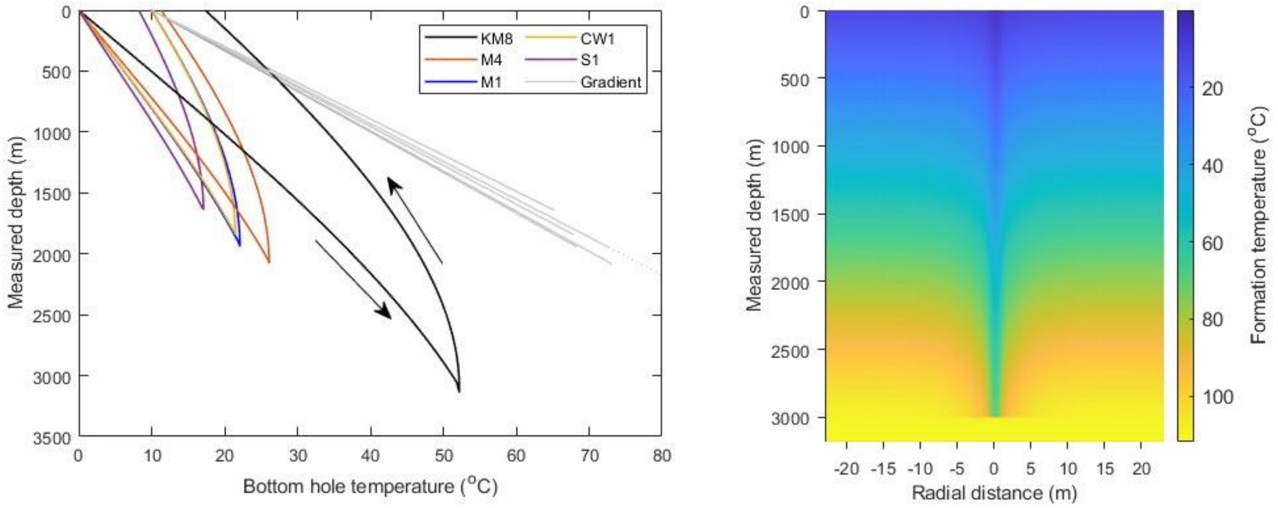

Figure 6: Preliminary spatial temperature variations in DBHEs for the inlet annulus and outlet pipe along borehole depths (left) and the six-month radial thermal drawdown effect in the modelled KM-8 surrounding formations (right).

The cold injection fluid will exert a radial thermal influence on the surrounding formation, with the radius of cooling expected to propagate proportionally at $2\sqrt{\alpha t}$, where α is the thermal diffusivity of the surrounding formations and t the duration of production in seconds (Westaway, 2018). This characteristic effect was observed in the numerical model; results suggests that after six-months of continuous operation, cold-front propagation effects at radial distances greater than 15m from the borehole are negligible, showing a less than 0.1°C drop in formation temperature compared with surrounding ambient conditions (Figure 6).

The results of the MATLAB dual-continuum model at constant flow rate display thermal drawdowns in output temperature and thermal power tending towards steady-state conditions (Figure 7), which is typical of results from existing analytical and numerical models of single well designs (*e.g.*, Westaway (2018) and Alimonti *et al.*, (2016)). This indicates that the expected temperature output is incompatible with direct heating in the absence of a heat pump at surface. In addition, despite the superior thermal power performance of the KM8 well, the power output per unit depth, or specific heat load, suggests that other wells are capable of comparable performance (Figure 7) by the end of the first six-month heating cycle. Thus, economic modelling is needed to assess the various payoffs (CBA) in repurposing deeper wells.

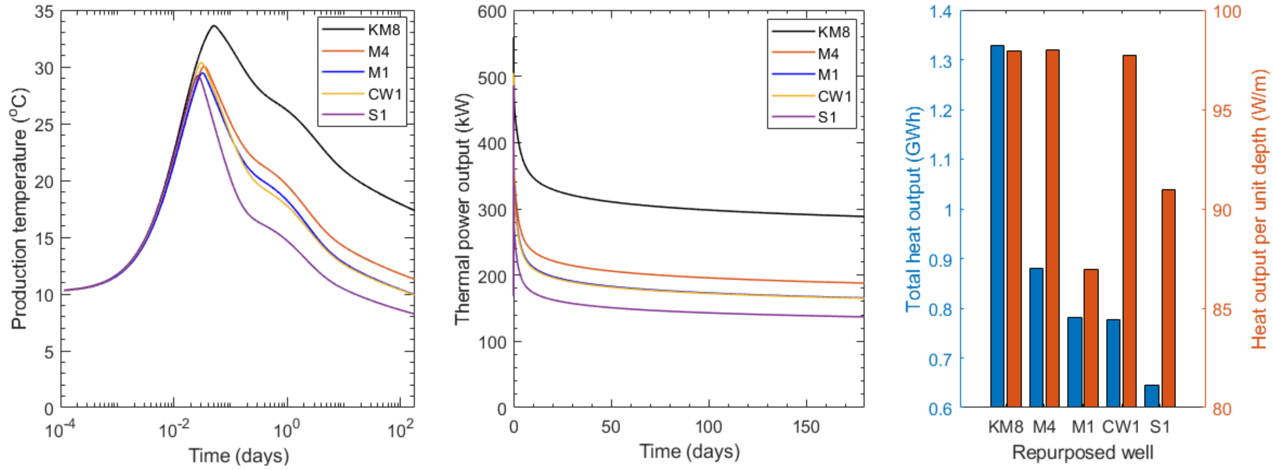

Figure 7: Temporal variations in deep borehole heat exchanger outputs over a six-month heating season for temperature (left) and thermal power (middle). Cumulative heat supplied per well and per unit depth for each repurposed well (right).

Figure 8 shows the COP for different wells after six months of operation. Gas well KM8, which has the highest production or outlet temperature, also has the highest COP of 5.4. The COP decreases with decreasing production temperature (*cf*. Equation 7). As shown in Figures 6 and 7, well S1 has the lowest production temperature and results in the lowest COP of 4.6. Figure 8 shows that the CSP also decreases with decreasing depth. Greater pressure losses would need to be overcome by the circulation pump for greater borehole depths, but the increase in thermal output dominates. Well KM8 has a pressure drop of 0.2 MPa, which reduces to 0.1 MPa for well CW1, and for well S1, despite being the shallowest well, the pressure drop is the highest at 1.2 MPa due to a reduced outer pipe diameter relative to the other wells.

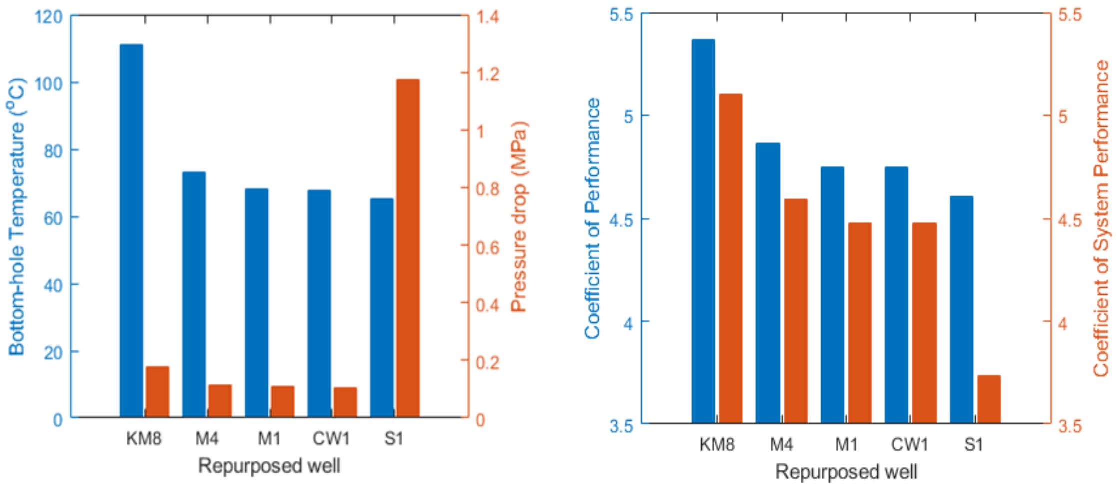

Figure 8: Initial bottom hole temperatures and pressure drop after six months for candidate wells (right). Coefficient of Performance (COP) and Coefficient of System Performance (CSP) after six months of operating repurposed wells (right).

4.2 Sustainable Thermal Power Lifetime

The expected well lifetimes were determined under assumed operating conditions of six-month heating cycles per year to assess the potential of the five candidate wells as potential geothermal energy sources worthy of investment for end-use applications. As derived in Westaway (2018), well lifetimes were calculated using:

$$t_L = \frac{\varepsilon r_g^2}{4\alpha} \exp\left(\frac{2\pi\lambda_r z_m^2 u}{\bar{Q}_{DBHE}}\right) \tag{11}$$

Where ε is the exponential of Euler's constant (*c.* 0.57722), r_g is the radius of the borehole, α is the bulk diffusivity of the surrounding aggregated formations and $\bar{Q}_{DBHE}$ the average power output of the well over its lifetime (taken here as the average annual thermal power extraction assuming a six-month heating season per year). The remaining variables are defined in Table 1.

Assuming material properties of the subsurface matrix and DBHE remain fixed and independent of temperature, the lifetime of the system decays exponentially with increased average thermal power extraction (Westaway, 2018) (Figure 9). The mode of operation (*i.e.,* the working fluid circulation flow rate) used in extracting geothermal energy must therefore be altered in order to extract the maximum potential heat while maintaining a hypothetical 25-year lifetime. Due to the relationship between extraction temperature and thermal power with flow rate (Alimonti *et al.*, 2016; Brown *et al.*, 2021), this optimal thermal power extraction may not be achievable, but it does highlight the potential underutilization of all repurposed wells at the assumed flow rate (4 l/s) (after Brown *et al.*, 2021), particularly for well KM8 (Figure 9).

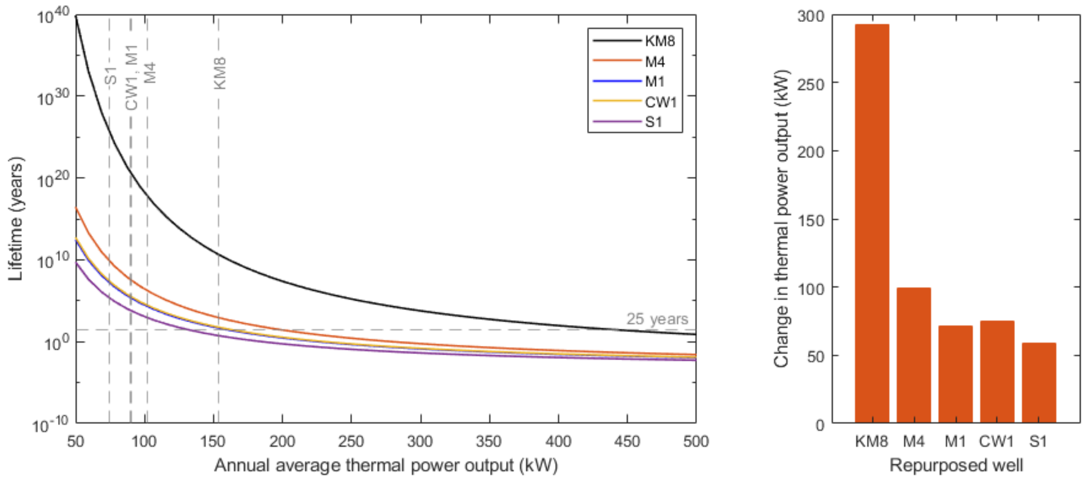

Figure 9: Exponential relationship between the lifetime of deep borehole heat exchanger and average thermal power output, after Westaway (2018) (left), and the change in thermal power extraction required to obtain the maximum heat potential while maintaining a 25-year lifetime (right).

5. CONCLUSIONS AND FUTURE WORK

This work aimed to identify abandoned onshore oil and gas wells within the UK with the greatest potential for repurposing as DBHEs. The wells identified are Kirby Misperton 8, Malton 1, Malton 4, Crosby Warren 1, and Stainton A1, which are all located in the north of England. Site-specific properties and borehole dimensions have been applied to a dual-continuum MATLAB model and run for a heating season of six months to produce preliminary results of expected thermal power and temperature outputs. With the assumptions used in the model, this work clearly highlighted KM8 as the hydrocarbon well with the greatest thermal power capacity (Figure 7) due to its associated high BHT and large borehole diameter. However, shallower wells such as M4 and CW1 showed similar performance per unit depth – both producing 98W/m – the same as KM8 (Figure 7). These shallower candidates may offer a preferred alternative as the greater depth and recorded borehole stability issues of KM8 may raise well integrity concerns (Hughes *et al.*, 2016).

The location and quasi-steady-state thermal power output of all five wells showed limited potential for integration as a heat source for direct or district heating, yet results indicate that they may present technical scope for thermal energy balancing of low-enthalpy processes (*e.g.,* greenhouses). The end-use case also dictates the mode of operation (*i.e.,* flow-rate controls) and impacts on the lifetime of the well (Figure 9). It is clear that, under the assumed modelled operation constraints, well KM8 has a significant safety margin on the 25-year critical lifetime, whereas other candidate wells do not offer the same buffer against thermal drawdown; some wells would have to curtail production in order to provide a safety margin on the minimum lifetime expected from a DBHE, which might further limit the "sustainable use" cases of the repurposed hydrocarbon wells.

The assumptions made in the modelling processes greatly simplify the complexities involved in repurposing deep hydrocarbon wells, leading to a deterministic approach in what is a highly uncertain geological context. While efforts have been made to ensure that all parameters lie within the bounds of reasonable estimates, the model is deterministic and neglects the probability distributions and heterogeneity of these parameters as well as temperature dependencies of well materials and formation properties, which have been shown to impact the thermal power outputs of DBHEs (Sui *et al.*, 2019). Further work may aim to produce surrogate models using experimental design and response surface methods (Quinao and Zarrouk, 2018) and so provide probabilistic capacity estimates for each candidate well. In addition, when estimating thermal gradients, kriging (or Gaussian process regression) offers an alternative to the inverse-distance weighted averaging used herein thereby accounting for weighting redundancies incurred due to geospatial data clustering of the borehole measurements.

Moving beyond isolated geothermal energy resource estimates, it is made clear in the United Nations Framework Classification for Resources (UNFC), as applied to Geothermal Resources, that estimates should be evaluated within the broader context of a Project, which would create a link between sources and the products delivered at a point of sale in an established market (Falcone *et al.*, 2016). Future work should therefore aim to evaluate the geothermal potential of the proposed hydrocarbon wells with reference to the detailed end-use dynamics, such as the preliminary assessment for greenhouse heating that was carried out for well KM8 (Nibbs *et al.*, 2022). Application of the UNFC to such case studies will allow subsequent comparison with other Projects with regards to environmental-socio-economic viability, project technical feasibility and the degree of confidence in the resource capacity estimates and Project sustainability.

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