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Putting the Potential of Deep Borehole Heat Exchangers into Perspective: a Gas Well Repurposing Case Study, Onshore in the UK

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ABSTRACT

Unlike open-loop geothermal systems, closed-loop types require no direct hydraulic interactions with a reservoir. Deep Borehole Heat Exchangers (DBHEs) consist of a single closed well configuration, with conductive heat transfer taking place between a circulating fluid and the surrounding geological formations through the borehole walls. There is potential to offset drilling costs of DBHEs by repurposing abandoned or suspended oil and gas wells or unsuccessful geothermal exploration wells. However, due to the much smaller volume of subsurface rock that can contribute to heat transfer, in addition to exergy losses and low conversion efficiencies, DBHEs have limited potential for electricity generation. Nevertheless, they can contribute to the decarbonization of heating and cooling as proven by the number of DBHE projects already implemented in China. This paper is based on a demonstration project, located in northern England, which aims to assess the feasibility of repurposing a deep, tight gas appraisal well as a DBHE. The results of independent modeling work are presented which extend the wellbore performance to include connectivity to different surface uses of thermal energy. The findings highlight that different modi operandi of a given DBHE correspond to different levels of success, and expectations need to be commensurate to the intended end-use.

1. INTRODUCTION

The UK government needs to use all the sustainable resources at its disposal in order to decarbonize heat production and take a major step in meeting the country's net-zero energy goals. Although wind and solar power are being harnessed aggressively in the UK, geothermal energy is underutilized and overlooked. To rectify this "poor relation" status, it has been suggested that a win-win situation might be possible via repurposing abandoned onshore hydrocarbon wells by installing deep borehole heat exchangers (DBHEs) in them. In this way, not only can oil and gas infrastructure be reused and its significant decommissioning expenditure delayed, but also geothermal heat could be 'mined' whilst lowering commercial risks by avoiding drilling costs. OpenGeoSys (OGS) was used to model the DBHE, incorporating site-specific data from a suspended gas well in northern England, allowing the geothermal potential from installing a DBHE to be evaluated.

1.1 Background to the case study well

The case study well, KM8, is sited in the agricultural countryside of North Yorkshire, England, located in the "Vale of Pickering" gas fields, which include Malton, Pickering, Marishes, and Kirby Misperton. The fields were developed over a 20-year period, primarily to supply the nearby Knapton power station. The hydrocarbon production licence areas, the fields, and the location of KM8 are shown in **Figure 1**.

With regards to the regional geology, the primary target reservoir is the Permian Kirkham Abbey Formation (KAF), a conventional dolomitised and naturally fractured limestone. These tight carbonate reservoirs of the Zechstein Group are surprinted by a high permeability fracture system, are subject to aquifer encroachment and experience early water breakthrough. The secondary reservoir targets are the deeper, less permeable sandstones of the Carboniferous Formation, which also hosts the Bowland Shale unconventional gas play.

At the cessation of production in November 2019, the then operator, Third Energy, allowed the licences to lapse, but retained ownership, rights and obligations of the "infrastructure portfolio" of 12 gas wells, located at 8 well sites, which are connected to 22 km of gas gathering pipelines (Hayhurst, 2024). Regarding the status of the well stock, two of the wells were never perforated, whilst the remainder have two mechanical plugs installed and are classed as being "temporarily suspended". As no operator in the UK has ever reused a gas well as a geothermal well, they remain categorized as gas wells by the regulator, the North Sea Transition Authority (NSTA). If the operator fails to prove that the wells can be effectively repurposed for geothermal operations, they will simply come under existing NSTA abandonment rules for oil and gas wells (CeraPhi, 2024).

Studies were carried out to assess the potential geothermal of the "infrastructure portfolio", and in February 2024, the assets (and their abandonment liabilities) were acquired by CeraPhi Energy, a UK-based geothermal development company. One well in particular stood out from the portfolio as a potential candidate for potential heat extraction using a DBHE, this was Kirby Misperton well KM8. Its completion is shown schematically in **Figure 2**.

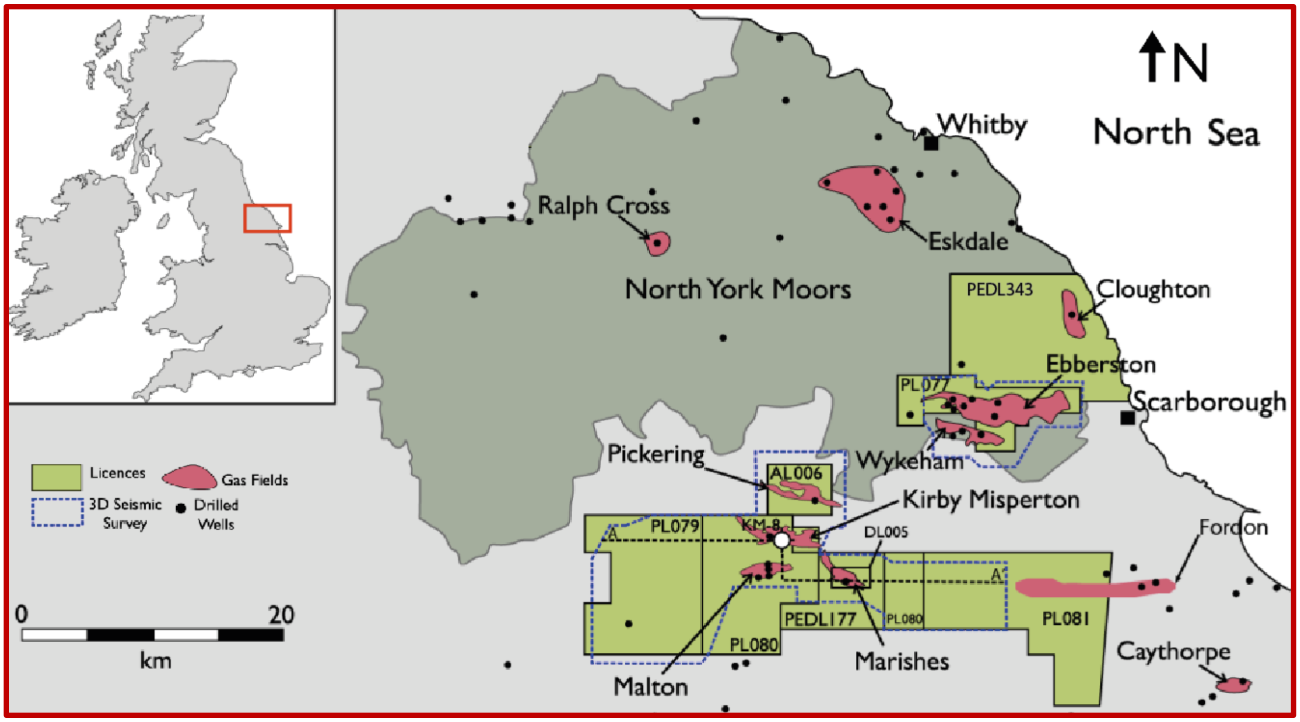

Figure 1: Area of Interest map (outlined in red) with UK onshore licences for petroleum exploration & development (PEDL), appraisal (AL), and production (PL). The North York Moors, shaded in dark green, is a national park, where energy operations are tightly controlled and restricted. The map, from circa 2020, depicts licences operated by Third Energy, along with gas fields and seismic and well coverage. The case study well, KM8, is denoted by the white dot. (Adapted from Extractive Industries, 2023).

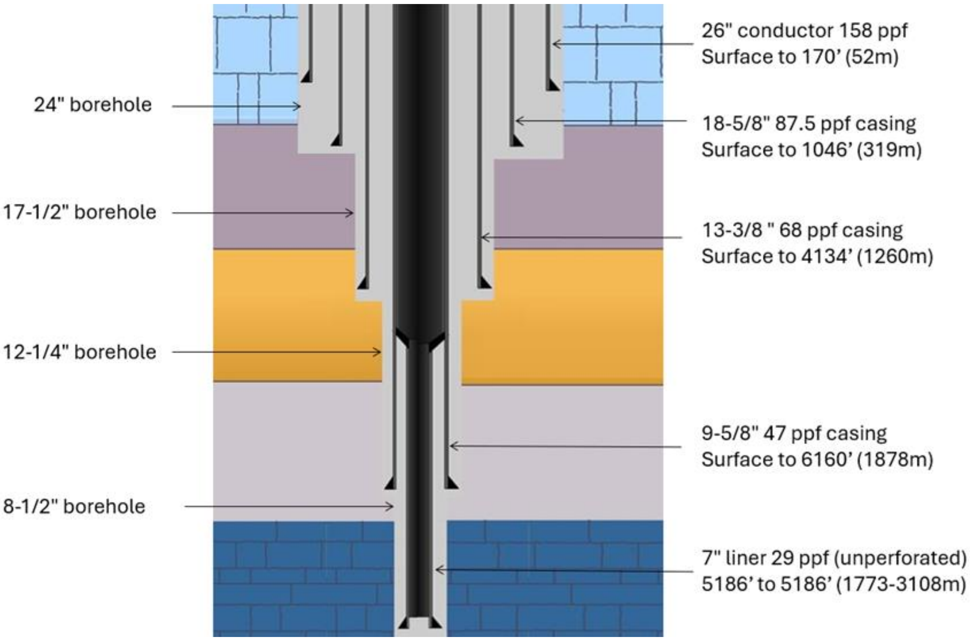

Figure 2: Well completion schematic of case study well, Kirby Misperton KM8. The colors are merely to reflect the fact casing shoes are set in different formations. Depths are measured depth. Data taken from the KM8 well composite log from the UK Onshore Geophysical Library (UKOGL, 2025).

In 2013, KM8, a vertical exploration well, reached 3,099m (10,167ft) true vertical depth (TVD). It failed to penetrate the deeper reservoir target of the Carboniferous Namurian sandstone due to borehole stability (Hughes *et al*., 2018). The operator, Third Energy, did obtain hydraulic fracturing permission for shale gas extraction from shallower intervals of the Namurian Bowland Shale formation. The approval to frack gave rise to daily anti-fracking protests during the autumn of 2017 and, in 2019, the UK government's volte-face saw the banning of onshore fracturing operations. This meant that KM8 had a 3 km deep borehole with cemented casing and liner to its total depth (TD), but it was never perforated and has lain dormant in a suspended state ever since. The new operator, CeraPhi, was awarded a grant to carry out a closed loop demonstration project in KM8 during several weeks of September and October 2023. At the time of writing this paper, the data from the 2023 pilot has yet to be put in the public domain. This paper uses an OGS DBHE model to predict what heat flux the well may be capable of delivering.

1.2 Modeling DBHE Performance

DBHEs have been thoroughly investigated, highlighting their strong potential to provide heat; however, they provide far lower thermal yields than open-loop geothermal systems. DBHEs operate by circulating fluid within a closed system, typically coaxial as it limits parasitic losses in the circulation pump, whilst maximizing the thermal yield (Brown *et al*., 2024a). In heat extraction mode, cold fluid is circulated down the annulus, warming with depth before being pumped to the surface through the central pipe (**Figure 3**). Recent reviews by Alimonti *et al*. (2018), Chen and Tomac (2023) and Kolo *et al*. (2024) encompass the progress in the field to date, highlighting: i) new approaches in numerical and analytical modeling, ii) engineering and geological parameters influence on performance, and iii) new case study developments. Many have focused on the potential to repurpose existing hydrocarbon wells (e.g., Nibbs *et al*., 2023), shale gas wells (e.g., Westaway, 2016) and ex-geothermal exploration wells (e.g., Kolo *et al*., 2023a) for both heat extraction (e.g., Huang *et al*., 2022) and thermal energy storage (e.g., Brown *et al*., 2023a; Brown *et al*., 2024b).

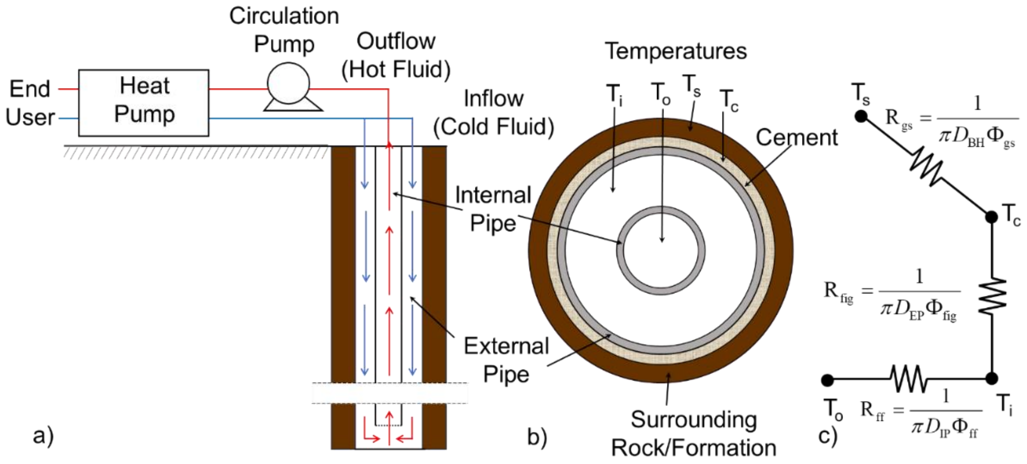

Figure 3. Schematic diagram showing a complete coaxial DBHE system, modified from Kolo *et al.* (2024): a) whole system; b) coaxial tube cross section; c) thermal resistance network. *T* indicates temperature, *R* is thermal resistance, and *Φ* is heat transfer coefficient. D_{BH}, D_{EP} and D_{IP} represent the diameters of the borehole, external pipe and internal pipe, respectively.

In this work, numerical modeling was undertaken using OGS to test the potential of an existing hydrocarbon well to be repurposed as a DBHE for geothermal exploitation. OGS is an open-access, flexible, finite-element solver, capable of modeling DBHEs with high degree of accuracy (e.g., see Kolditz *et al*., 2012; Shao *et al*., 2016; Chen *et al*., 2019). Models developed on OGS for KM8 can help with: i) quantifying how much heat could be gained through repurposing, ii) investigating modes of operation, and iii) evaluating parametric uncertainty.

2. METHODS

This study focuses on the numerical modelling of DBHEs using OGS (e.g., Kolditz *et al*., 2012; Shao *et al*., 2016). OGS models DBHEs using the dual continuum method which treats the DBHE as 1D line elements and the surrounding rock as 3D prism elements (see **Figure 3**) (e.g., Chen *et al*., 2019). This approach allows the rock, completions cement, inlet and outlet fluid within the borehole to be modeled. In this study, the DBHE uses a centred coaxial configuration, with fluid circulated down the annular space. This approach has been widely used with models validated and verified against other numerical software, real data and analytical solutions (e.g., Shao *et al*., 2016; Cai *et al*., 2022; Brown *et al*., 2023a, 2023c, 2024b; Ma *et al*., 2024).

2.1 Governing Equations for the Subsurface Geothermal Modeling

The rock is assumed to be governed by conductive heat transfer only. Past studies have highlighted that groundwater flow will have a minor impact if occurring in thin aquifers (Chen *et al*., 2019), or at Darcy velocities less than 1e^{-6} m/s (Brown *et al*., 2023b). The energy balance can thus be described as:

$$\frac{\partial}{\partial t}[\phi\rho_w c_w + (1-\phi)\rho_r c_r]T_r - \nabla\cdot(\Lambda_r\cdot\nabla T_r) = H_r \quad (1)$$

where ϕ is the porosity of the surrounding rock, ρ_r and ρ_w are the density of the surrounding rock and pore-water, respectively. The specific heat capacity of the rock and pore-water are represented by c_r and c_w, respectively. T_r, H_r and Λ_r denote the temperature of the rock, the source term, and the thermal hydrodynamic dispersion tensor, respectively.

The heat flux between the DBHE and the surrounding rock formation, q_{nT_r}, is given by (Chen, 2022):

$$q_{nT_r} = -\Phi_{cr}(T_c - T_r) \quad (2)$$

which is imposed at the boundary between the rock and the borehole, where Φ_{cr} is the heat transfer coefficient between the cement and surrounding rock and T_c is the temperature of the cement.

2.2 Governing Equations for Deep Borehole Heat Exchangers

The DBHE was modelled as a coaxial system, where a concentric central pipe is located within the borehole and fluid circulated down the annular space, warming with depth via conduction through the borehole wall before being pumped to the surface via the inner tubing. To model the processes within the fluid, cement and surrounding borehole walls, three governing equations are utilised (**Equations 3, 5, and 7**) (e.g., Diersch *et al.*, 2011, Hein *et al*., 2016; Chen *et al*., 2019; Kolo *et al*., 2023b). The respective boundary conditions are described in **Equations 4, 6, and 8.**

The inlet pipe is governed by the equation:

$$\rho_f c_f\frac{\partial T_i}{\partial t} + \rho_f c_f\boldsymbol{v}\cdot\nabla T_i - \nabla\cdot(\Lambda_f\cdot T_i) = H_i \quad (3)$$

and the boundary condition by:

$$q_{nT_i} = -\Phi_{fig}(T_r - T_i) - \Phi_{ff}(T_o - T_i) \quad (4)$$

while the outlet pipe is defined by:

$$\rho_f c_f\frac{\partial T_o}{\partial t} + \rho_f c_f\boldsymbol{v}\cdot\nabla T_o - \nabla\cdot(\Lambda_f\cdot T_o) = H_o \quad (5)$$

the boundary condition by:

$$q_{nT_o} = -\Phi_{ff}(T_i - T_o) \quad (6)$$

the cement by:

$$(1-\phi_c)\rho_c c_c\frac{\partial T_c}{\partial t} - \nabla\cdot[(1-\phi_c)\lambda_c\cdot\nabla T_c] = H_c \quad (7)$$

and the boundary condition by:

$$q_{nT_c} = -\Phi_{cr}(T_r - T_c) - \Phi_{fic}(T_i - T_c) \quad (8)$$

T is temperature, $\boldsymbol{v}$ is the fluid velocity vector, Φ is the heat transfer coefficient, λ_c is the thermal conductivity of the cement, and ϕ_c is the cement porosity. The heat transfer coefficient depends on the thermal resistance; Φ_{fic} is between the inlet pipe and cement, Φ_{ff} is between the inlet pipe and outlet pipe and Φ_{cr} is between the cement and surrounding rock. Heat transfer coefficients can be found in detail in Diersch *et al.* (2011).

2.3 Parameterisation, Initial and Boundary Conditions

A simplified version of the well schematic in **Figure 2** has been adopted in this study which incorporates one equivalent borehole diameter, one equivalent casing size, and one central pipe diameter. The borehole diameter was calculated as a length-weighted average over the relevant borehole depth. The casing size was also calculated as a length-weighted average of the 9-5/8" casing and the 7" liner. The simplified schematic of the simulated borehole, casing and central pipe is given in **Figure 4** for the different scenarios considered.

In OGS, the DBHE was set up in a fixed domain of 500 m by 500 m by 2400 m (x, y ,z) for the 2 km DBHE base case, with the geothermal gradient of the ground set to increase linearly with depth at a rate of 30 °C/km, with a surface temperature set as a fixed Dirichlet boundary of 10 °C. For the 3 km case, a domain of 500 m by 500 m by 3600 m (x,y,z) was used. The finite element mesh for the base case is presented in **Figure 5**. The basal boundary was set as a fixed heat flux, calculated as a function of thermal conductivity and geothermal gradient, whilst the surrounding lateral boundaries were set with Neumann no-flow conditions. These lateral boundaries were extended to be 250 m away from the DBHE to ensure no thermal interaction impacted results. The parameters were defined to represent the KM8 borehole and are highlighted in **Table 1**.

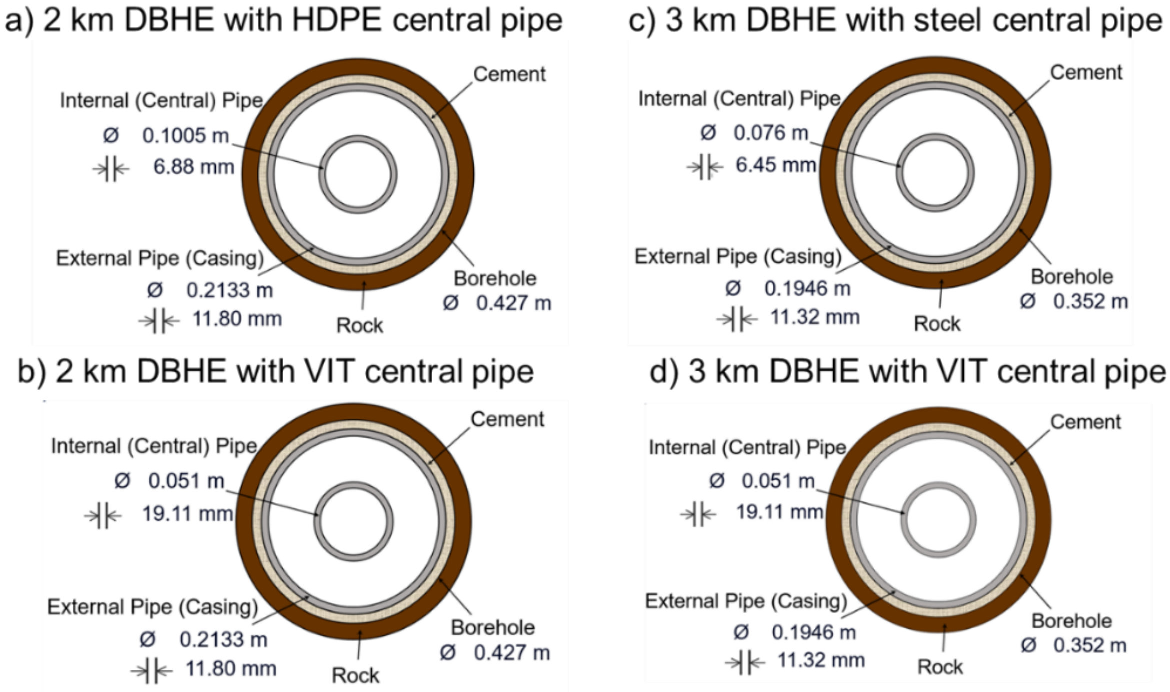

Figure 4: Cross-section showing dimensions of the simplified well completion diagrams considered: (a) 2 km deep DBHE with HDPE central pipe; (b) 2 km deep DBHE with vacuum insulated tubing (VIT) as the central pipe; (3) 3 km deep DBHE with steel central pipe; (d) 3 km deep DBHE with VIT central pipe.

Figure 5 and **Table 1** represent the base case scenario where the DBHE is 2 km deep with a central pipe made of high-density polyethylene (HDPE). Brine with a salinity of 120,000 ppm was adopted as the heat transfer fluid, to reflect the fluid being used for the demonstration project (CeraPhi, 2024); relevant properties were obtained based on the work of Sharqawy *et al.* (2010) and Nayar *et al.* (2016). An inlet temperature of 5 °C has been used since it is not too low as to approach the freezing point of water. Moreover, going below this temperature might require active cooling.

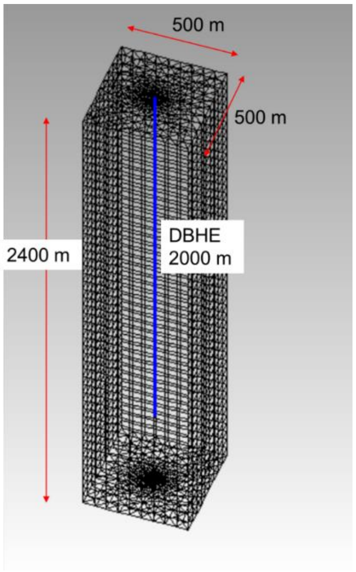

Figure 5. Finite element mesh showing the dimensions of the DBHE and surrounding rock domain.

The simulations considered the influence of several key parameters, including (i) the choice of central pipe material of either HDPE or vacuum insulated tubing (VIT) for the 2 km case; (ii) the choice of central pipe material of either VIT or steel tubing for the 3 km case; (iii) reducing the circulating water density to 986 kg/m^3 by assuming fresh water; (iv) varying the circulating flow rate (2 L/s – 12 L/s); (v) varying the surface inlet temperature; and (vi) intermittent operating mode with an annual cycle of 6-month operation and 6-month rest, rather than continuous operation. A steel central pipe was used for the 3 km DBHE due to issues with the observed degradation of the mechanical strength of HDPE at increased downhole temperatures at depths over 2 km. For the 2 km DBHE, both HDPE central pipe and VIT central pipe were used. For the 3km DBHE, steel central pipe and VIT central pipe were used. These three different central pipe materials in four different configurations with their dimensions are detailed in **Figure 4**.

Table 1: Base case parameters.

Parameter	**Value**	**Units**
Saturated ground thermal conductivity	2.5	W/(m.K)
Saturated ground volumetric heat capacity	2.2962	MJ/(K m^3)
Water flow rate	5	L/s
Water density	1074	kg/m^3
Water salinity	120,000	ppm
Water volumetric heat capacity	3.919	MJ/(K m^3)
Water thermal conductivity	0.639	W/(m.K)
Dynamic water viscosity	0.000684	kg/(m s)
Basal heat flow	69.75	mW/m^2
Geothermal gradient	30	°C/km
Surface temperature	10	°C
Inlet temperature	5	°C
Cement thermal conductivity	1.05	W/(m.K)
Cement volumetric heat capacity	1.194	MJ/(K m^3)
Average borehole diameter	0.35	m
9-5/8” 47 lbs/ft casing inner diameter	0.2205	m
7” 29 lbs/ft liner inner diameter	0.1571	m
Casing (outer pipe) inner diameter	0.2133	m
Casing (outer pipe) thickness	0.0118	m
Casing thermal conductivity (steel)	52.7	W/(m.K)
Central pipe (DBHE) depth	2,000	m TVD
Central pipe (HDPE) inner diameter	0.1005	m
Central pipe thickness	0.00688	m
Central pipe thermal conductivity (HDPE)	0.45	W/(m.K)

3. RESULTS

3.1 Temporal Evolution of Base Case

Figure 6 shows the evolution of the outlet fluid temperature over 25 years. There is a sharp rise in the outlet fluid temperature to 26.5°C within the first 3 hours, after which the temperature drops significantly and progresses with a minimal decline rate. The sharp rise is because of the initial conditions which were set equal to the initial undisturbed geothermal gradient. Within the first 5 years, the temperature rapidly declines to 12.1 °C and thereafter drops gradually reaching 11.5 °C at 25 years. This outlet temperature corresponds to a thermal power of 127 kW at 25 years, as shown on the second y-axis of **Figure 6**. Hence, the DBHE can continuously provide a minimum of 127 kW for 25 years with an inlet temperature of 5 °C. The fluid inlet and outlet temperatures are plotted along with the initial geothermal gradient in **Figure 7**. At 42 minutes, the influence of the initial condition is still strong, making the temperature at depth approach the geothermal gradient. However, with time, this influence diminishes, and thermal drawdown causes the temperature of rock and fluid to stabilize. While the bottom hole temperature is 61 °C at 42 minutes, it drops to 20.1 °C after 25 years. There is also some amount of heat loss in the upward flow of the fluid to the outlet as only 11.5 °C is reached at the wellhead. This is due to the use of a HDPE central pipe.

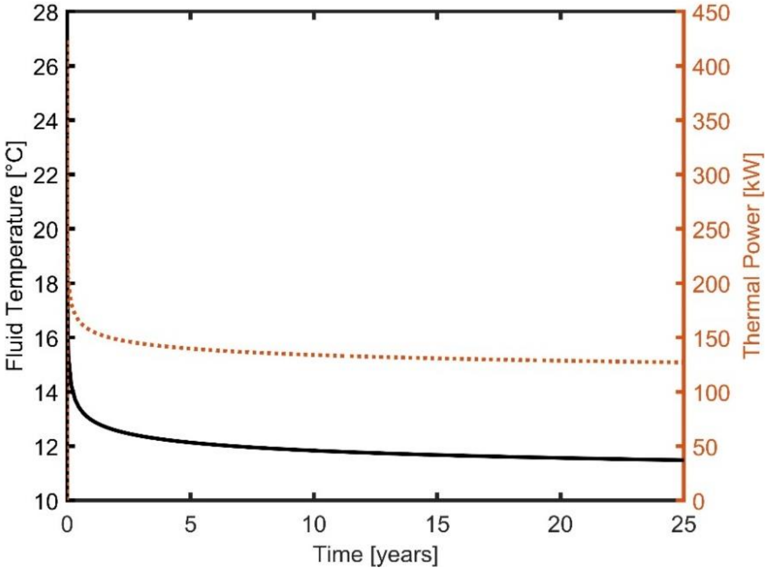

Figure 6: Fluid outlet temperature and thermal power for the base case with an inlet temperature of 5 °C and a flow rate of 5 L/s.

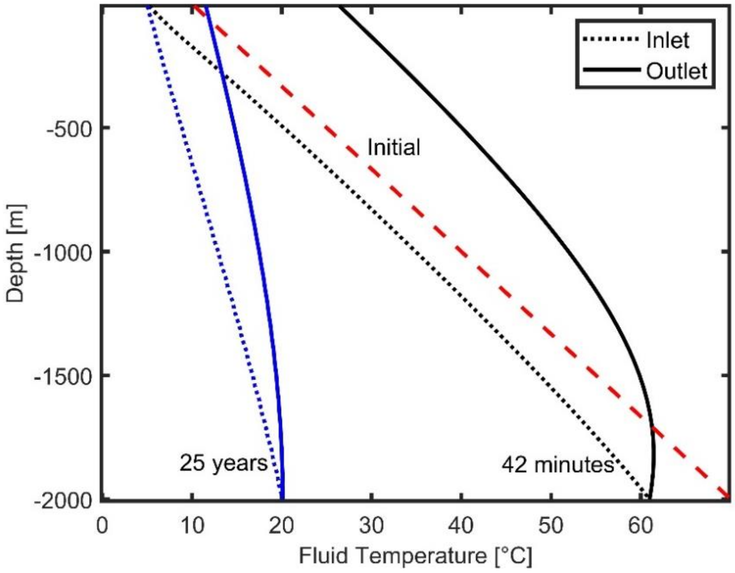

Figure 7: Distribution of temperature with depth for the base case at 42 minutes and 25 years. Dashed line shows initial conditions, coinciding with the geothermal gradient; dotted lines show inlet flow; and solid lines indicate outlet flow.

3.2 Varying the Heat Transfer Fluid

The base case assumed a heat transfer fluid of brine with a salinity of 120,000 ppm. The effect of changing the heat transfer fluid was investigated by replacing brine with fresh water in the numerical models, assuming a density of 986 kg/m^3, specific heat capacity of 4,181 J/kg/K, thermal conductivity of 0.645 W/(m·K), and dynamic viscosity of 0.000684 kg/(m·s). Results showed only a slight reduction in performance, with a lower fluid outlet temperature of 11.3 °C and a corresponding lower thermal power of 122.9 kW.

3.3 Variation of Depth and Central Pipe Material

As seen in **Figure 7**, the bottom hole temperature increases linearly with the geothermal gradient. HDPE pipe would not be able to withstand the increased bottom hole temperature of a 3 km DBHE. An alternative pipe material would be required in case. The alternative pipe materials considered herein were steel and specialist VIT.

The former (steel) was chosen as 3 km of steel pipe tubing had been purchased by the operator some years earlier to evaluate the deliverability of the to-be hydraulically fractured Bowland Shale. This test did not go ahead as the UK government subsequently banned onshore fracking operations and the steel pipe was mothballed. In 2024, the Kirby Misperton operator saw an opportunity to request further funding to extend the KM8 geothermal pilot by running its steel tubing to a depth of 3 km in place of the HDPE pipe, but this application for extra funding was refused (CeraPhi, 2024).

The latter (VIT) was chosen to increase the amount of heat recovered from the central pipe because of a lower thermal conductivity (0.06 W/(m·K)). However, the improved performance comes at a significant hike in price and additional difficulties associated with VIT when installing in the well.

Figure 8 shows the results for a central pipe made of VIT for both 2 km and 3 km cases. When a VIT central pipe with dimensions shown in **Figure 4b** was used for the base case (2 km DBHE), the fluid outlet temperature after 25 years increased from 11.5 °C to 12.6 °C. The thermal power correspondingly increased to 149.3 kW, i.e. a 22.3 kW increase compared to the base case using a central pipe made of HDPE.

The deeper 3 km cases were run with all parameters remaining as per the base case, except for the borehole dimensions and the central pipe material, as per **Figures 4c** and **4d**. An outlet temperature of 17.6 °C was observed at 25 years, which corresponds to a thermal power of 245.8 kW, as shown in **Figure 8** (3 km Steel Central). Hence, a temperature increase of 6.1 °C or 118.8 kW results from the DBHE being set at a depth of 3 km. The 3 km VIT central pipe case gives an outlet temperature of 21.8 °C (328.1 kW). As expected, the use of VIT would improve thermal performance.

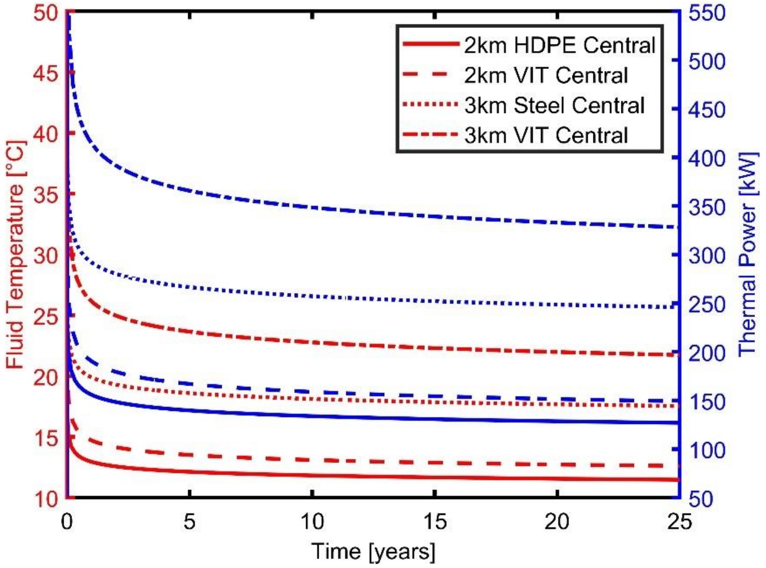

Figure 8. Fluid outlet temperature (red curves) and thermal power (blue curves) for DBHE depths of 2 km and 3 km using different central pipe materials.

3.4 Variation of Flow Rate

Figure 9 shows the outlet temperatures for different flow rates, from 2 L/s to 12 L/s, for the base case scenario of 2 km DBHE with HDPE central pipe. When flow rate increases from 2 L/s to 12 L/s, the fluid outlet temperature drops by 59%, from 13.9 °C to 8.2 °C. This is because of the reduced fluid residence time at a lower flow rate. The thermal power takes both flow rate and temperature rise into account and is presented in **Figure 10**. For the same change in flow rate, the thermal power more than doubles, from 69.6 kW to 152.3 kW.

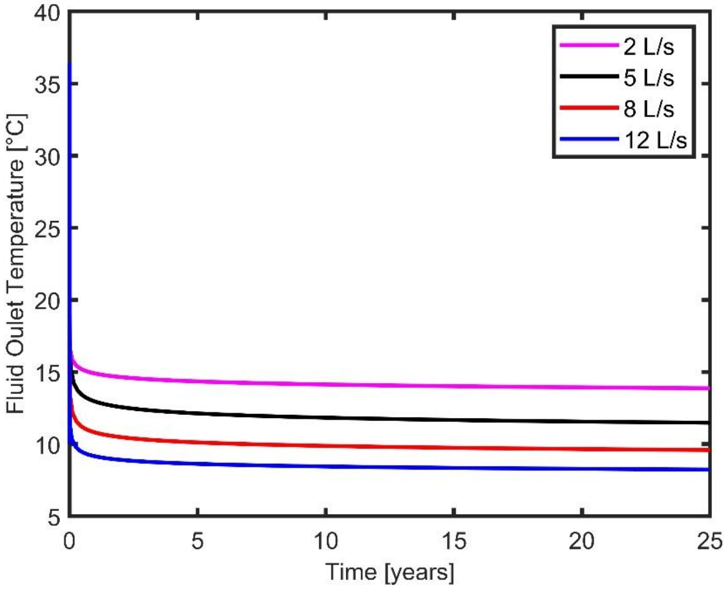

Figure 9. Evolution of fluid outlet temperature over a period of 25 years for different flow rates.

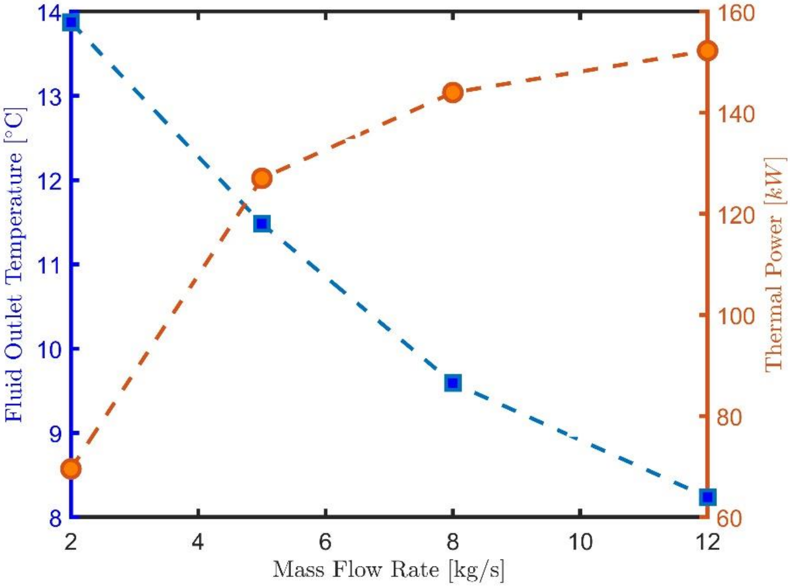

Figure 10. Fluid outlet temperature and thermal power for different flow rates at 25 years.

3.4 Variation of Inlet Temperature

Table 2 shows how the outlet temperature and thermal power vary at the end of the simulation for different values of inlet temperature taken between 5 °C and 30 °C. As seen earlier, a lower flow rate results in higher outlet fluid temperatures, but this does not necessarily imply higher thermal power. It was observed that the outlet temperatures and the temperature change between inlet and outlet temperature (*ΔT*) is higher for the lower flow rate of 2 L/s, but the thermal power is still higher for 5 L/s. As the inlet temperature increases, it approaches the ground temperature and therefore reduces the potential for more heat extraction as observed from a decrease in *ΔT*.

Table 2: Outlet temperatures and thermal power at 25 years for different inlet temperatures at flow rates of 2 L/s and 5 L/s. The temperature change between the inlet and outlet (ΔT) is indicated also.

Inlet temperature (°C)	2 L/s		5 L/s	
	Outlet temperature (°C)	Thermal power (kW) / ΔT(°C)	Outlet temperature (°C)	Thermal power (kW) / ΔT (°C)
5	13.9	69.5 / 8.9	11.5	127.0 / 6.5
12	18.9	54.2 / 6.9	17.2	101.5 / 5.8
22	26.1	32.2 / 4.1	25.3	65.3 / 3.3
30	31.9	14.7 / 1.9	31.8	36.1 / 1.8

3.5 Intermittent Operation

To simulate intermittent operation mode, corresponding to an annual cycle of 6-month operation and 6-month rest, rather than continuous operation, a flow rate control was used in the OGS model to turn the flow rate on when the DBHE is operational, and off during periods of rest, as shown in **Figure 11**.

The outlet temperature for the intermittent mode of operation is shown in **Figure 12** and compared with full-year, non-stop operation (base case). The temperature decline for the intermittent mode is slower as indicated by the blue dash-dotted trendline in **Figure 12**, indicated that the system could have longer sustainability under this mode of operation. After the last (25th) cycle, the outlet temperature for intermittent operation is 12.5 °C (146 kW thermal power) compared to 11.5 °C (127 kW thermal power) for continuous full-year operation. This indicates a slight increase in the seasonal thermal power compared to full-year operation of the DBHE, which is in line with past findings (Brown *et al*., 2023b).

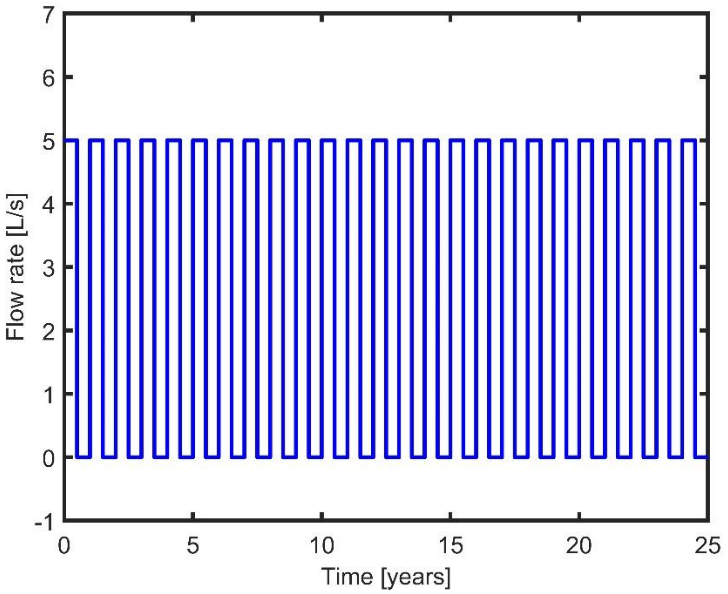

Figure 11. Flow rate curve for intermittent operation mode of the DBHE.

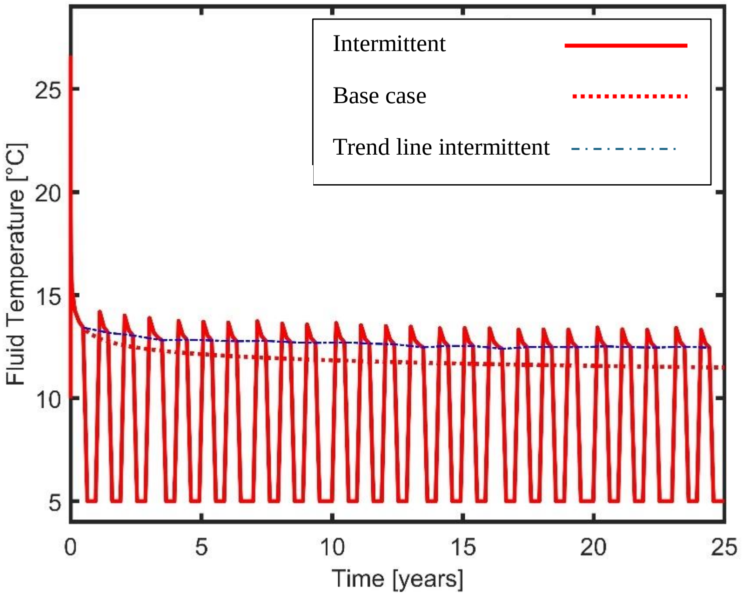

Figure 12. Fluid outlet temperature for intermittent operation mode compared to the base case. The trend of intermittent operation mode at the end of each 6-month operation period is shown.

4. CHALLENGES OF CONVERTING ABANDONED WELLS INTO CLOSED LOOP GEOTHERMAL SYSTEMS

Whilst this paper focusses ostensibly on modeling a DBHE, the specific practical challenges faced when repurposing oil and gas infrastructure must also be considered in the project feasibility assessment. From a technical perspective, the KM8 well was drilled for hydrocarbon production, not for geothermal heat extraction, so its configuration, diameter restrictions, and completion materials will inevitably be sub-optimal for use as a DBHE. The age of the well and its operating conditions throughout its lifespan will likely impact its ability to withstand new flow regimes and chemistries, in addition to corrosion and scaling resistance.

With respect to the commercial issues surrounding onshore well repurposing, there are the benefits of delayed abandonment expenditure (ABEX) and reduced (or eliminated) drilling expenditure. The estimated cost of decommissioning an onshore well in the UK is around $1.25 million (Star Energy, 2024), which suggests the ABEX for the Vale of Pickering “infrastructure portfolio” will be significant. As for drilling expenditure, which is usually the largest cost element of a deep geothermal project, having access to a drilled and completed borehole (such as KM8) can offer a significant saving. For example, Arup (2021) estimated that a geothermal well in the UK, drilled to a depth of 1 km, could cost up to $2.25 million, which, after adjustment for inflation, equates to approximately $3 million today.

While these savings potentially free up operator cash flows to allow investment in other projects, it is likely that most of the candidate wells for repurposing will require remediation before they are fit for geothermal operations. These workovers could include cutting and recovering tubing, cementing perforations, and setting abandonment plugs. Third Energy (2023) studied the possibility of repurposing two wells from its depleted Pickering gas field to supply heat to a community swimming pool in the nearby town. They estimated that remedial work on wells would cost $0.8 million with a further outlay of around $2 million for additional site preparation, DBHE configuration, surface pumping equipment and 2 km of heat connection piping for a low temperature system. Even though recent UK consumer gas prices are at historical highs, the study concluded that the project would be sub-commercial without financial support from the UK government.

A major constraint to repurposing any oil or gas well for geothermal operations is its location with respect to the heat demand. In the case of KM8, its rural location means that its potential customers are most likely to be the local villages and farms. Whilst there is demand for heat, the number of users will be small.

On a positive note, the local communities that were vehemently opposed to fracking operations in the Vale of Pickering gas fields back in 2017, are today thoroughly supportive of the repurposing the old wells in the area for geothermal heat extraction using closed-loop technology.

5. DISCUSSION AND CONCLUSIONS

Based on a demonstration project in northern England, this paper investigates the feasibility of repurposing a deep, tight gas appraisal well to become a DBHE. This independent modelling of the KM8 demonstration project predicts a maximum pseudo-steady outlet temperature of 21.8 °C with a corresponding thermal power output of 328.1 kW for the deepest (3 km) scenario, for an inlet temperature of 5 °C, a circulation rate of 5 L/s, a VIT central pipe, and assuming continuous mode of operation. The VIT option improves DBHE performance, but comes at a price. Overall DBHE performance is lower for the other modeled scenarios.

All the predicted output temperatures are insufficient to generate electricity, even if considering micro-scale organic Rankine cycle (ORC) technology.

With respect to thermal energy uses, as previously discussed by Nibbs *et al.* (2022), DBHE output temperatures and flow rates must be managed to produce value to an end user, of which there are theoretically many (Lindal, 1973). However, the area surrounding KM8 is sparsely populated and consists largely of agricultural land. The area could be suitable for food production in commercial-scale greenhouses that are geothermally heated, if the DBHE was combined with a heat exchanger and heat pump at the surface, but according to economic assessments by Nibbs *et al.* (2022), the KM8 DBHE appears only marginally commercial in the absence of a Renewable Heat Incentive (RHI)-style subsidy.

There is a slight increase in the thermal power output with an intermittent (6-monthly) mode of operation compared to full-year continuous operation of the DBHE**.** For the base case scenario at 2 km of depth, the predicted outlet temperature for intermittent operation is 12.5 °C with a corresponding thermal power output of 146 kW. For a hypothetical domestic space heating application (noting, however, that there currently are no homes in the vicinity of the well site), one can take the UK average energy use per unit floor area (kWh/m^2) per annum (OVO, 2024), the average floor area of dwellings in Yorkshire (Ministry of Housing, Communities & Local Government, 2020) and assume the UK's recommended average of 8 hours of heating per day, for a 6-month heating season. This implies that the repurposed KM8, in its base case configuration, could theoretically fulfill the space heating requirements of maximum 19 average dwellings, as shown in **Table 3**.

Table 3: Calculation of the theoretical number of dwellings that the repurposed KM8 could provide space heating for, assuming the base case scenario (intermittent operation) and ignoring connection to a heat network and combination with a heat pump.

Energy use per floor area (kWh/m^2 per annum)	100
UK average energy use per unit floor area (kWh/m^2 per annum)	133
Average total floor area of English dwellings (m^2)	84
Energy for heating annually (kWh)	8,400
UK average energy for heating annually (kWh)	11,172
UK average recommended hours of heating per day (hrs)	8
Number of calendar days in 6 months (d)	182.5
Predicted thermal output from KM8 (base case with intermittent operation) (kW)	146
Predicted energy output from KM8 in 6 months (kWh)	213,160
Number of dwellings that could be heated by KM8	19.08

Note, however, that heat distribution to dwellings would require connection to a heat network. Compatibility between the DBHE's output/inlet temperatures and the network's flow/return temperatures will need to be assessed, in combination with a heat pump to boost the DBHE's outlet temperature to that of the network, and a chiller to cool the return flow prior to reinjection in the well. Excluding 5th generation heating and cooling systems, modern heat networks would typically run with a difference of 20-30 °C between flow and return temperatures (e.g., 65 °C delivery /35 °C return). As shown in **Table 2**, increasing the DBHE's inlet temperature dramatically reduces the thermal output power. Note also that these calculations are for space heating only and do not account for domestic hot water use, which would represent an additional heat load.

These results show that expectations from repurposing onshore hydrocarbon wells to DBHEs need to be placed in the right context, considering the expected thermal performance and costs of the repurposed well itself, but also of the integrated surface infrastructure, and vis-à-vis potential end-users (existing or future).

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