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The need to regulate thermal interference between mine water geothermal systems: a UK perspective

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Abstract: Mine water geothermal (MWG) technology can provide substantial amounts of decarbonized heat and is gaining traction in the UK with several active projects. However, the lack of regulations concerning potential subsurface thermal interference is hindering wider adoption. Using the GEMSToolbox modelling tool, we examined a generic room and pillar coal mine to assess the impact of thermal interference between adjacent MWG systems. The modelling quantifies the thermal interference occurring between two operators sharing a contiguous water body within a mine block. High water abstraction rates and smaller distances between the MWG wells increase the risk of significant interference, which worsens the longer the systems operate. We introduce the 'heat extraction ratio' to quantify thermal interference, defined as the ratio of heat produced with two users present compared with a single user. This metric can aid regulators in establishing acceptable levels of thermal interference between MWG systems. Drawing on regulations from geothermal energy-producing countries, ground source heat pump guidelines and UK oil and gas laws, we propose two potential policies for managing MWG thermal interference. The first policy requires unitization when thermal interference exceeds a certain threshold, and the second policy disallows additional systems if they would breach the regulatory threshold.

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The UK is legally bound to reduce its greenhouse gas emissions to net zero by 2050, as set out in the Climate Change Act 2008 (as amended by the 2050 Target Amendment Order 2019). Heating is responsible for 23% of the UK's emissions (BEIS 2021) and mine water geothermal (MWG) heating is an opportunity to decarbonize some of the space heating sector. The UK has an estimated 23 000 disused coal mines (Gluyas *et al.* 2020), often considered a liability, but they are also an opportunity, to help supply the heat demands of the 25% of homes and businesses located in coal-mining areas (Gluyas *et al.* 2020).

There are currently only a few operating MWG systems in the UK, including Nest Road and Abbotsford Road operated by Lanchester Wines, and a scheme operated by Gateshead Council (Banks *et al.* 2022; Coal Authority 2024). These three lie within the Gateshead Council area in NE England. In addition, there is a research facility, UK Geoenergy Observatory, in Glasgow, Scotland (Monaghan *et al.* 2022) and a scheme being built in Seaham, County Durham, NE England.

However, a lack of clear regulations has been identified as a deterrent to investment in geothermal energy (Goodman *et al.* 2007; Manzella *et al.* 2018). In the UK, heat is considered a pollutant (Abesser *et al.* 2018) or a physical characteristic (McClean and Pedersen 2021), but is not an ownable resource. This means that the operators of a geothermal scheme cannot guarantee that the heat resource they are using will remain available to them over the lifetime of the geothermal operation. There is a danger that it might be appropriated or disturbed by another operator located too close by.

To implement a coal MWG system in the UK, a mine water heat access agreement must be acquired from the Mining Remediation Authority to access the flooded and abandoned coal mine workings, but this does not guarantee any heat. A water abstraction licence is also required from the appropriate environment agency (Natural Resources Wales, NRW; Northern Ireland Environment Agency, NIEA; and, in England, the Environment Agency, EA) (Water Resources Act 1991, Chapter 57; Water (Northern Ireland) Order 1999, SI 1999 No. 662 (NI)). However, in Scotland, under General Binding Rule 17 (GBR 17) of The Water Environment (Controlled Activities) (Scotland) Regulations 2011 (CAR), an abstraction licence is not required if the water is re-injected into the same geological formation after being used for geothermal energy extraction.

When granting a water abstraction licence, the licensing authority can limit the amount of heat to be extracted, but this can only be done to protect ground or surface water from a change in temperature that would negatively harm the environment, not to prevent thermal interference between geothermal systems (McClean and Pedersen 2023). If the owner of an abstraction licence experiences a reduction in the amount of water they can abstract because of the permitting of further abstraction licences, they may be able to claim damages, but this does not apply to a reduction in heat (McClean and Pedersen 2023).

An obvious potential problem of having multiple operators extracting heat from an interconnected mine system is the possibility of a rapid depletion of the heat available and/or one system extracting the cold water re-injected by another. However, it is also important to consider the opposite; if mine water heating is to contribute to the UK's energy mix, mine water systems should not be artificially spaced out, wasting potential heat resources. For example, previously the Mining Remediation Authority rules only allowed one geothermal system per mine block (Coal Authority

2022). A mine block is defined as a mine or set of mines that are hydrologically disconnected from the surrounding mines. This disconnection may be complete, or there may be a limited hydraulic connection but not enough to let water levels between the adjacent blocks equalize (Coal Authority 2018). These blocks can be tens of square kilometres and there have been MWG schemes that have operated at <10 l s^{-1} (Walls *et al.* 2021). Such a scenario would not draw significant quantities of heat from the mine block, and if a second system was not allowed in a such a mine block, a huge volume of heat could potentially be underdeveloped. The current Mining Remediation Authority approach is to consider new applications on a case-by-case basis (Mining Remediation Authority, pers. comm., 20 February 2025).

The aim of this paper is threefold: (1) we review international geothermal regulations and regulations from other industries; (2) we quantify the thermal interference between two mine geothermal heating systems; (3) we combine these results to suggest policy options for regulating thermal interference between mine water geothermal heating systems. This is applicable to the UK and other countries with heat extraction schemes in room and pillar coal mines.

Regulatory context

Whereas the UK does not have a regulatory regime for considering the needs of multiple operators in one geothermal resource (Abesser and Walker 2022), other countries have a longer history of commercial geothermal energy extraction and currently produce more geothermal energy, and as such, in most cases, have developed regulatory regimes. These regulations may be instructive for the UK to develop its own geothermal regulations. Likewise, there are examples in the oil and gas industry, which also deals with a valuable fluid that can flow from one area to another and does not respect human surface infrastructure or licensing blocks (Kemp 2013). Ground source heat pumps (GSHPs) have grown in popularity in Europe, with 2.19 million GSHPs installed as of 2023 (European Geothermal Energy Council 2023). Regulations specifically for GSHPs (which often are separate from other geothermal regulations) can also provide insight, as heat interference between increasingly densely packed GSHP systems is a growing problem (Belliardi *et al.* 2022).

Oil and gas unitization rules in the UK

Unitization in the oil and gas industry refers to organizations with the right to extract petroleum in a reservoir co-operating to operate the reservoir. It is common around the world, including in the UK. The purpose of unitization is to decrease economic and physical waste, and to ensure that the operators all receive their ‘fair share’ (Asmus and Weaver 2006).

If the UK Minister (for Energy Security and Net Zero, as of January 2025) decides that any section of a licenced area is part of a single oilfield that contains other granted licences, the Minister can order that the licensees in the affected field co-operate to extract the petroleum. The Minister can do this as it is in the national interest to ‘secure maximum ultimate recovery of petroleum and in order to avoid unnecessary competitive drilling’ (The Petroleum (Current Model Clauses) Order 1999, SI 1999/160).

Although this national interest supersedes the need for fairness (Asmus and Weaver 2006), the regulations state that the unitization should be fair and equitable (The Petroleum (Production) (Landward Areas) Regulations 1995, SI 1995/1436). However, the North Sea Transition Authority, previously the Oil and Gas Authority, states that the final decision to accept or reject a field development programme will be based on the plan producing the maximum economic recovery of oil and gas (North Sea Transition Authority 2018). If there is no wastage, the government will not force the licensees to unitize, even if that leads to unequitable extraction between licensees (Asmus and Weaver 2006). The UK does not consider petroleum to be privately ownable until it has been extracted, as all rights to unextracted petroleum are vested in the Crown (Gordon 2015; North Sea Transition Authority 2018). Therefore, issues of fairness cannot be enforced while the petroleum remains in place within the reservoir (Asmus and Weaver 2006; North Sea Transition Authority 2018). Although the UK Government has the power to enforce unitization, this power has not been exercised, although the existing regulations have led to many voluntary unitizations (Gordon 2015).

Review of national geothermal regulations in 11 countries

The use of mine water geothermal heating is not prevalent enough around the world (Chu *et al.* 2021) for there to be many laws or regulations that directly deal with thermal interference in MWG. However, the problem of heat sharing is relevant to multiple types of geothermal technologies, including GSHPs and deep/high temperature geothermal energy. For example, if a company is targeting a permeable fault structure for open-loop power production and a rival company targets the same fault structure further downstrike there will be similar issues of heat resource degradation to those a mine water geothermal system would experience. Regulations from various countries were investigated in this study. Although a comprehensive review of global regulations was not the objective, a selection of countries was chosen based on their geothermal energy production and regulatory frameworks. The analysis focuses on the top seven geothermal-producing countries as of 2022 (Richter 2023): the USA, Indonesia, the Philippines, Turkey, New Zealand, Mexico and Kenya.

Additionally, regulations from several other countries were reviewed because of unique regulatory approaches or noteworthy geothermal developments. Iceland was included as it is renowned for its extensive geothermal energy utilization. The Netherlands was examined for its well-developed regulatory framework and successful implementation of mine geothermal systems (Verhoeven *et al.* 2014). Poland, with its numerous operating coal mines, presents significant potential for mine geothermal projects post-closure. Czechia was also analysed because of its interesting regulatory structure.

The countries’ regulations can be classified into three categories:

(1) regulations do not mention competing usage;
(2) regulations mention competing usage but do not provide a framework for dealing with it;
(3) regulations provide a framework for competing usage.

Regulations do not mention competing usage. Neither Indonesia nor Kenya mention competing usage or thermal interference in the Law of the Republic of Indonesia No. 21 of 2014 about Geothermal or the Energy Act (2019) of Kenya, respectively. In Turkey, multiple licences can be found over one geothermal reservoir as the licencing areas do not relate to the geothermal reservoir being exploited (Aydin *et al.* 2020), so the thermal interaction problem is not addressed. This has resulted in significant amounts of thermal interference between wells (Aydin *et al.* 2020).

Regulations mention competing usage but do not provide a framework for addressing it. In Czechia using ‘dry heat’ (from the Earth) for ‘industrial purposes’ requires a permit under the Mining Activity Act. When applying for this there must be documentation proving the settlement of conflicts (Szalewska 2021), although no further detail on how to settle the conflicts has been given.

To explore for a geothermal resource in Iceland, a Prospecting Licence must be granted by Orkustofnun (National Energy

Authority), and then, to use the resource, a Utilisation Licence is required. Conditions can be attached to the Prospecting Licence if there are concerns about interference with pre-existing exploitation. A Utilisation Licence can be rejected or have conditions attached if the Minister (responsibility delegated to Orkustofnun) is concerned about pre-existing use of the resource, with Article 17 of the Act on the survey and utilization of ground resources (1998) (No. 57/1998) stating: 'In granting utilisation licences care should be taken that … account is taken of any utilisation already begun in the vicinity. If the Minister is of the opinion that the applicant for a utilisation licence does not meet these requirements, the Minister may refuse to grant the licence or insert special conditions in the licence.'

The Netherlands Mining Act (Wet van 13 oktober 2022 tot wijziging van de Mijnbouwwet 2022, Stb 2022 438) states that an application for a geothermal search area, start-up permit and follow-up permit may be rejected if there is a geothermal energy search area allocation, a geothermal energy starting permit or a follow-up geothermal energy permit that already applies to the area in question. When applying for a search or start-up permit, the applicant must estimate any temperature or pressure interference with other geothermal projects. This demonstrates that thermal interference is considered in the Dutch system, but the law does not state when this thermal interference will or will not be acceptable.

The Geothermal Service Contract of the Department of Energy (2019) in the Philippines states that the developer will 'Have a free and unimpeded use of Geothermal Resources within the Contract Area in view of the Geothermal Operations, Additional Investments and New Investments in regard of which, the DEPARTMENT (of Energy) shall ensure that rights, privileges and other authorizations it may grant to third parties will not defeat or impair such use'. The obligation is on the Philippines Government to ensure that any licence that is issued does not have an impact on prior use.

Regulations provide a framework for competing usage. The Polish Geological and Mining Law (2011) covers licensing for the extraction of thermal waters. Article 30 states that the 'concession' must include 'the area within which the intended activity is to be pursued', and Article 29 1a states that the concession granting authority will refuse to grant the concession if there is already a concession for the same type of activity in the same area. If the concession area includes the whole area that water and heat are extracted from and the areas cannot overlap, then that should theoretically mean that there is no thermal interference between adjacent systems.

Mexico, New Zealand and some parts of the USA all provide for unitization to manage multiple operators in one geothermal reservoir. In Mexico this comes from the Geothermal Energy Law of Mexico (2014), which states that the Secretariat of Energy has the responsibility to resolve disputes arising from the interference of granted concessions. If the Secretariat determines the joint operation is required to avoid damage to third parties, enforce national security, serve public interest, ensure efficient use of the geothermal resource and/or avoid environmental damage, the involved parties are required to come to an agreement for joint operation. If after 90 days the parties do not agree, the Secretariat will determine the joint operating agreement.

In the USA there are both federal and state laws regarding geothermal energy. The Energy Policy Act of 2005 states that on federal land the Bureau of Land Management can both approve voluntary unitization agreements and compel unitization agreements (Doris *et al.* 2009). The rules for state land vary from state to state. In Utah, for example, the power to regulate geothermal resources (natural heat of the Earth from higher temperature sources, >120°C) is given to the Division of Water Rights in the Geothermal Resource Conservation Act. If the reservoir underlies multiple rights owners, each owner has the right to a proportionate amount of the resource. The Division of Water Rights can order unitization if it believes it is needed to 'prevent waste, correlative rights, prevent drilling of unnecessary wells', subject to a two-thirds supporting vote from the owners (Geothermal Resources 1982).

In New Zealand Deep Geothermal Systems (DGS) were originally operated as one consent holder systems. However, in 2006 a court case between the Waikato Regional Council and several private operators changed this. The Waikato Regional Council rules stated that for 'large takes and discharges' there should be a single consent holder to provide a single point of responsibility and control. However, the Environment Court decided that a single operator system was not the best way to regulate sustainable development and in reality there were already cases of multiple consent holders in several systems (Environment Court New Zealand 2006, Decision No. A047/2006). The Court's decision was that DGS did need to be managed in an integrated manner and provided the components required in an 'integrated management system'. This included a 'Multiple Operator Agreement' in which multiple operators must co-operate to address the efficient use of the resource, resolve conflicts and have accountability for adverse effects (Environment Court New Zealand 2006, Decision No. A047/2006). Malafeh and Sharp (2015) identified this as compulsory unitization.

GSHP regulations

Ground source heat pumps are a method of space heating or cooling that are becoming increasingly popular (Lund *et al.* 2022). Heat is exchanged with the ground using vertical borehole heat exchangers, or lateral coils of tubing, before the temperature is elevated using a heat pump. Although many countries do not have regulations regarding the prevention of thermal interference between GSHPs (Tsagarakis *et al.* 2020; Perego *et al.* 2022), some do. These are often in the form of minimum distances between the GSHP and either the property line or the next geothermal system (Haehnlein *et al.* 2010; Somogyi *et al.* 2017). Countries that have such regulations include China, Germany, Lichtenstein, Sweden and Switzerland, and the distances vary from 3 to 20 m (Haehnlein *et al.* 2010). Whether these or similar regulations apply to GSHPs and underground thermal energy storage depends on the country. In some cases, depth and/or temperature limits place these technologies under different regulatory frameworks. However, several countries have established minimum distance regulations for shallow open-loop geothermal systems. For example, Czechia, Greece and Sweden have specific requirements, with mandated distances ranging from 5 to 30 m (Haehnlein *et al.* 2010). Although there is significant work investigating thermal interference between systems (Fascì *et al.* 2019; Belliardi *et al.* 2022; Perego *et al.* 2022; De Paoli *et al.* 2023; Duijff *et al.* 2023; Stemmle *et al.* 2024), the regulations are rarely based on this work (Somogyi *et al.* 2017). The evidence base on which the regulation is based was not readily available after a literature review.

Mine water thermal modelling method

The aim of the modelling was to quantify the impact of having two MWG systems present in a mine and assess the effects of flow rate, distance and the timescale the systems operate for. These parameters are investigated because they vary between systems and can be controlled by the system operators, unlike the underlying geometric and geological characteristics of the mines.

Conceptual model

The model is configured for an open loop with re-injection geothermal heating system in a room and pillar coal mine (Fig. 1). In this set-up warm water is pumped from a deeper, warmer seam to the surface, passed through a heat exchanger and the now cool mine

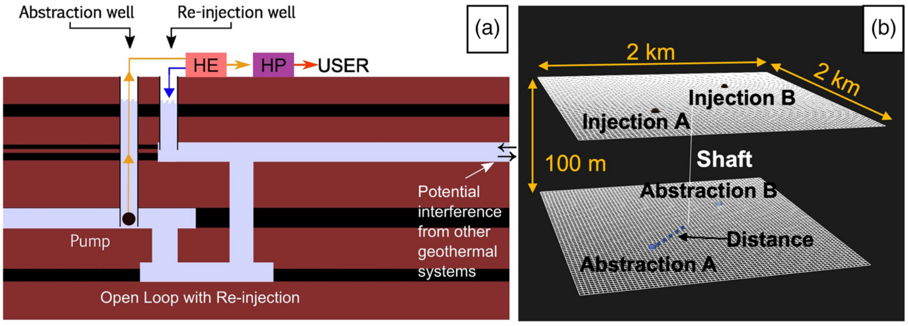

Fig. 1. (**a**) Diagram of a hypothetical open loop with re-injection coal mine geothermal system. Arrow colours indicate temperatures, where red is greater than orange, which is greater than blue. HE, heat exchanger; HP, heat pump. (**b**) Our model set-up, showing two injection and abstraction points placed symmetrically around a central shaft in a two-seam system.

water is disposed of back into a shallower seam in the mine to re-heat before being abstracted again. Room and pillar mining is a style of mining common to coal mines, where the coal is removed creating ‘rooms’, while ‘pillars’ of coal are left to act as structural supports. In the model the rooms are assumed to be open (have not collapsed or been backfilled) and provide a direct hydraulic connection between the injection and abstraction points.

For these experiments, representative synthetic mines were created, rather than using real mine maps. Each mine system has a unique geometry, but many room and pillar coal mines share similar characteristics. We created a general, geometrically simple mine system that is representative of many existing mine systems.

The synthetic mine has two seams with a single central, connecting shaft (Fig. 1), allowing water to flow between the two seams. The need for this was demonstrated by the Gateshead mine water project, which required an additional borehole to be drilled, connecting the injection and abstraction seams, to ensure a flow cell (Adams *et al.* 2023). The synthetic seams are approximately 2 km by 2 km, with 100 m vertical spacing. Further physical parameters are given in Table 1. Water is abstracted from the deeper seam and re-injected into the shallower seam. This is typical in a heating system, as the lower seam will be warmer owing to the geothermal gradient (Verhoeven *et al.* 2014; Banks *et al.* 2019; Walls *et al.* 2021). Having the injection and abstraction wells close to each other reduces the amount of surface infrastructure needed and land required. Different distances between the wells and the shaft were tested, and as the mine dimensions are limited the water flow of the systems positioned closest to the boundary will be affected by the mine edge. This limitation is applied to replicate the real-world physical constraints of a mine.

Modelling with GEMSToolbox

The modelling tool GEMSToolbox is used (Mouli-Castillo *et al.* 2024), building on Todini and Pilati (1988), Rodríguez and Díaz (2009), Ferket *et al.* (2011) and Loredo *et al.* (2016). It is designed to be a compromise between very detailed large-scale 3D numerical models and simple analytical models. It is targeted at the feasibility stage of a project when there are few data available other than mine maps and generic rock properties to test different injection and abstraction points. Owing to the lack of available data for such projects, detailed 3D models are not warranted at the feasibility stage, when exploring the impact of parameter uncertainty on project risk is more valuable. As the model runs quickly it can be used to analyse many possible scenarios. Each run of the representative grid takes approximately 20 s on a MacBook Pro 2020, with an M1 chip. The input data used for GEMSToolbox are those of Sweeney *et al.* (2025).

The void spaces (rooms and roadways) are modelled as interconnected cylindrical pipes, interconnected at nodes (Rossman 2000). The user specifies the injection and abstraction locations and associated flow rates. This establishes a hydraulic pressure gradient and therefore flow around the mine. All water is modelled as flowing through the ‘pipes’ rather than the surrounding rock as it is assumed that the galleries have a much higher ability to transfer water than the surrounding rocks. Additionally, there is limited research on the thermal and hydraulic properties of groundwater flow in mines (Monaghan *et al.* 2025). As a result, we were unable to parameterize the water flow for input into the GEMSToolbox model.

As the water flows through the mines, heat is exchanged with the surrounding rock, owing to the temperature difference between the two, causing the mine water to warm as it moves through the system. The user sets the injection temperature, which remains fixed for the duration of the model run. The model calculates the temperature at every node, including the designated abstraction node(s) at the end of the run time. As the heat is transferred from the rock to the water, the rock face cools, creating a thermal gradient from the water–rock interface into the rock mass. Heat then diffuses towards the pipes. Because there is no external groundwater flow, no additional heat replenishment occurs within the mine.

Table 1. Physical parameters used in the experiments

Parameter	Value	Units	Reference
Thermal conductivity of the rock mass surrounding mine	2.78	$W\ m^{-1}\ K^{-1}$	a
Specific heat capacity of the rock mass surrounding mine	800	$J\ kg^{-1}\ K^{-1}$	a
Density of the rock mass surrounding mine	2500	$kg\ m^{-3}$	a
Thermal conductivity of the water in the mine	0.58	$W\ m^{-1}\ K^{-1}$	a
Specific heat capacity of the water in the mine	4186	$J\ kg^{-1}\ K^{-1}$	a
Density of the water in the mine	1000	$kg\ m^{-3}$	a
Dynamic viscosity of the water in the mine	1.0×10^{-03}	Pa s	a
Injection temperature of water	10	°C	b
Initial temperature of the rock mass surrounding the mine at the shallower seam	15	°C	b
Pipe diameter (void space is modelled as pipes)	2.25	m	c
Distance between crossroads	30	m	d, e

a, Rodríguez and Díaz (2009); b, Walls *et al.* (2021); c, Mouli-Castillo *et al.* (2024); d, Gregory (1983); e, Hartman (2002).

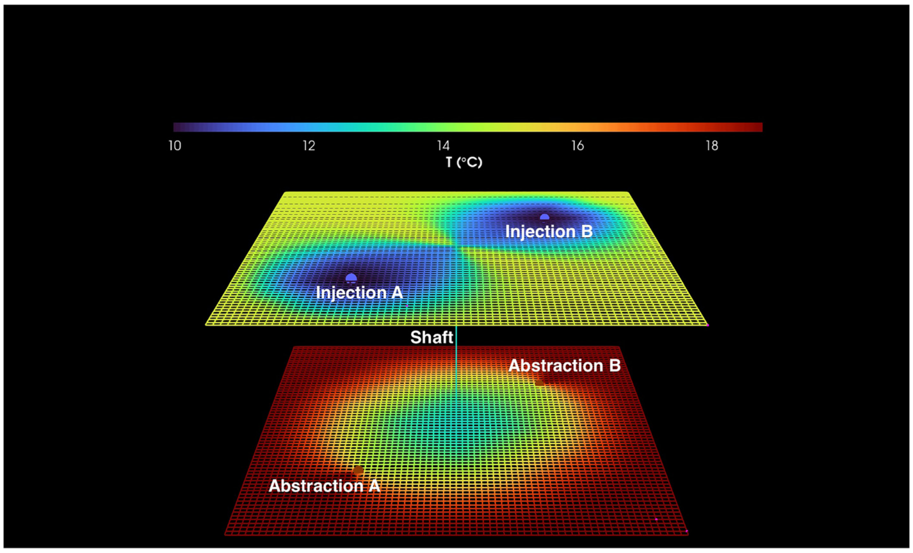

Fig. 2. GEMSToolbox model results displayed showing two systems, each with one injection and one abstraction point, with a central shaft. Vertical height not to scale. Both systems are operating at $50\ \mathrm{l\ s^{-1}}$ for 20 years and are 679 m from the shaft. The seams are separated by 100 m, the initial top seam temperature is 15°C and the bottom seam temperature is 18.76°C. The distance between crossroads is 30 m.

Quantification

The thermal power output Q (kW) produced by a system is as calculated by Preene and Younger (2014):

$$Q = q\rho_w C_w \Delta T \tag{1}$$

where q is the flow rate through the heat exchanger ($\mathrm{m^3\ s^{-1}}$), ρ_w is the density of water ($\mathrm{kg\ m^{-3}}$), C_w is the heat capacity of water ($4.18\ \mathrm{kW\ kg^{-1}\ K^{-1}}$) and ΔT is the change in temperature (amount of warming that occurs) between the injection temperature and the abstraction temperature (K) (it should be noted that ΔT, representing a temperature difference, is measured in kelvins, whereas all individual temperature values are given in degrees Celsius). Because the injection temperature remains constant throughout the model run time, a decrease in abstraction temperature will lead to a corresponding decrease in ΔT. This assumption is based on re-injection temperature requirements conceivably being set in permits or environmental regulations. The practical implication would be an increase in power requirement of the heat pump over its lifetime to maintain equivalent heat output to the end users despite a reducing ΔT. The surface pipework is assumed to be perfectly insulated, with no heat loss. Given that the abstraction temperature is taken at the model end time (i.e. if the model ran for 50 years the abstraction temperature is from the end of the 50th year), it will underestimate the actual amount of energy produced, as the abstraction temperature would have been higher in the early years.

To evaluate the impact on an initial system (System A) of adding a second system (System B) to a mine, the heat extraction ratio (HER) was coined. This is a measure of how much the heat energy produced by System A over the entire simulation period decreases (or increases) on addition of System B. The higher the HER value, the less interference there is between systems.

$$\text{heat extraction ratio} = \frac{Q_{AB}}{Q_A} \tag{2}$$

where Q_{AB} is the Q of System A when System B is present in the system and Q_A is the Q of System A when it is in the only system present.

To assess the impact of flow rate, distance between the central shaft and re-injection location and operating time, these parameters were varied, respectively, from 1 to $180\ \mathrm{l\ s^{-1}}$, 42 to 1018 m and 1 to 50 years. We tested scenarios where the flow rates of the two systems matched, as well as scenarios where they varied.

Each configuration was run twice to calculate the HER, once with only System A, and once with both Systems A and B.

To create a simple equation that predicts the amount of warming between injection and abstraction without the need to run the model, multiple linear regression was performed on the results of 154 model runs. For this exercise, Systems A and B always used the same flow rates.

Results

The results of a model run are displayed in Figure 2. The cold re-injected water can be seen around injection points A and B before it flows towards and down the shaft, warming up as it travels towards abstraction points A and B.

For each calculation the model is run twice, once with only one system present and once with two systems present (Fig. 3). The model provides the abstraction temperature for each system present (Fig. 2), which allows the calculation of the amount of warming that is occurring (ΔT) and the HER (Fig. 3) of System A using equation (2).

The ΔT of System A increases as the distance between the wells and shaft increases, and therefore the distance to System B also increases (Fig. 3). The difference between the ΔT values of one versus two systems also decreases with distance, demonstrating that at larger distances there is less impact on the thermal resource of System A if an additional system is added. This is reflected by the

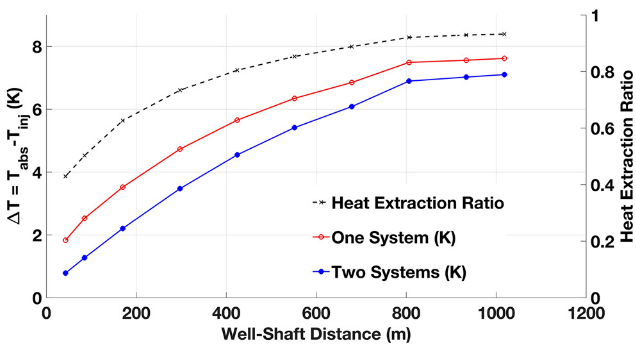

Fig. 3. The amount of System A warming (abstraction temperature – injection temperature, ΔT) at different distances, and the resultant heat extraction ratio (of System A). In this model run both systems operate at $50\ \mathrm{l\ s^{-1}}$, operating for 20 years. When there is the least difference between the abstraction temperature – injection temperature of the one-system model and the two-system model, the HER is the highest. This reflects the minimal impact of adding a second system when they are separated by the greatest distance.

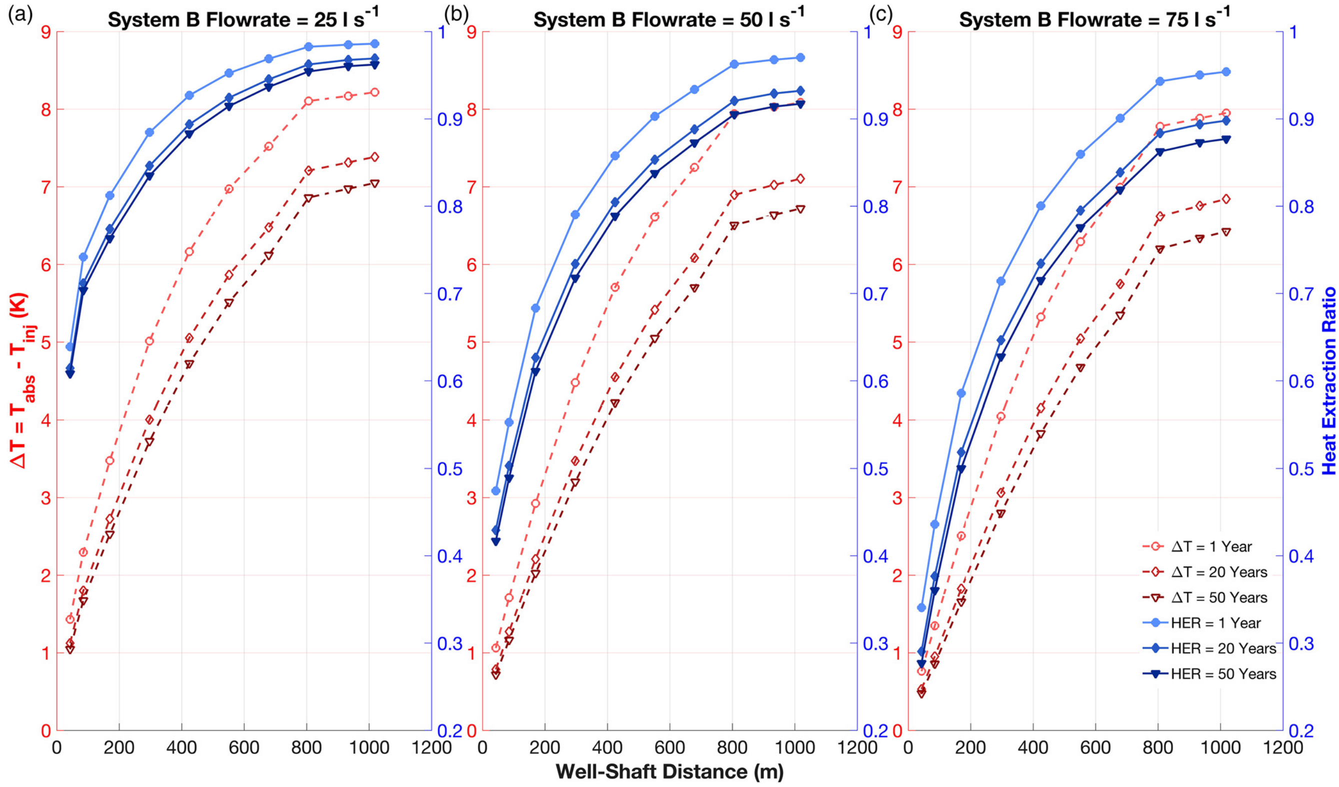

Fig. 4. (**a**–**c**) Comparison of System A warming and heat extraction ratio (HER; blue continuous lines) for different System B flow rates and operational timescales (monochromatic shades). As the distance increases, the ΔT (red dashed lines) of System A increases, showing that systems located close together will have more thermal interference (i.e. a lower HER) than those further apart. The System A temperature does stop increasing though, indicating that, eventually, increasing the distance stops being an efficient method of reducing interference between systems. The same pattern is seen for all flow rates and timescales, although shorter timescales reduce System A's temperature less, and higher flow rates require the systems to be further apart to reduce the interference. Higher flow rates have lower HERs for all timescales; the higher System B's flow rate, the more thermal interference there is, and the more heat energy System A loses. In all cases, as the distance between the systems increases the amount of heat System A loses decreases.

heat extraction ratio being closest to one (0.93) at the greatest distance tested (1018 m). The boundaries of the mine influence the water flow at the greatest well–shaft distances, where the injection and abstraction wells are closest to the edge. When the mine size increased from approximately 2×2 km to 4×4 km, the rise in abstraction temperature ranged from 1.11×10^{-5} to 9.7%, with the largest effect observed in systems with high flow rates positioned closest to the edge of the mine. This effect is consistent with real-world conditions, as mines are not infinite in size.

Figure 4 compares the effect of distance on the ΔT and the HER of System A, when System B is at three different flow rates (Fig. 4a–c). As the distance between System A and System B increases, the ΔT of System A increases. The steepest rate of change occurs at low distances, before the gradient starts to reduce and then flattens off, with insignificant incremental gain in temperature when the distance increases. For 1 year and a flow rate of 25 l s^{-1}, this happens at approximately 800 m (Fig. 4a). The same pattern occurs at all the flow rates (25, 50, 75 l s^{-1}) and timescales (1–50 years). These results are expected: for longer flow paths, the water can receive heat for longer from the surrounding rock, and the water temperature will asymptotically approach the rock temperature.

Figure 4 also demonstrates that increased operating times result in less warming occurring, and that without the addition of heat from an outside source the system will cool eventually, and this will occur faster at higher flow rates.

Larger distances between the systems and the central shaft (and therefore the other system) result in higher HER values, and therefore less interference between the systems. The greatest rate of change occurs at the smaller distances, but the curve flattens off as the distances increase. There is a point at which increasing the distance between the systems and the shaft is not an impactful way of reducing the systems' influence on each other. The higher the flow rates, the further away the systems need to be for this to happen.

The higher the flow rate the greater the impact on the HER and the greater the change of HER with distance.

The effect of the operating time on the HER is also displayed in Figure 4. Longer operating times result in a lower ΔT and lower HER values, meaning there is more interaction between the systems when they run for longer. The longer the systems operate for, and the higher the System B flow rate, the greater the impact on System A.

Figure 5 illustrates the relation between flow rate and operation time for a given well–shaft distance. At low flow rates, two systems can run for a long time without significant interference, but for higher flow rates, interference becomes significant sooner.

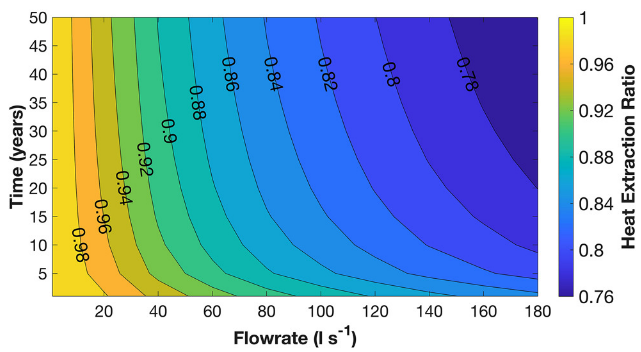

Fig. 5. Heat extraction ratio as a function of the time that two systems run for, and the flow rates used. Higher flow rates lead to a lower HER, as more interference occurs, as do increased run times, although this is more apparent at higher flow rates.

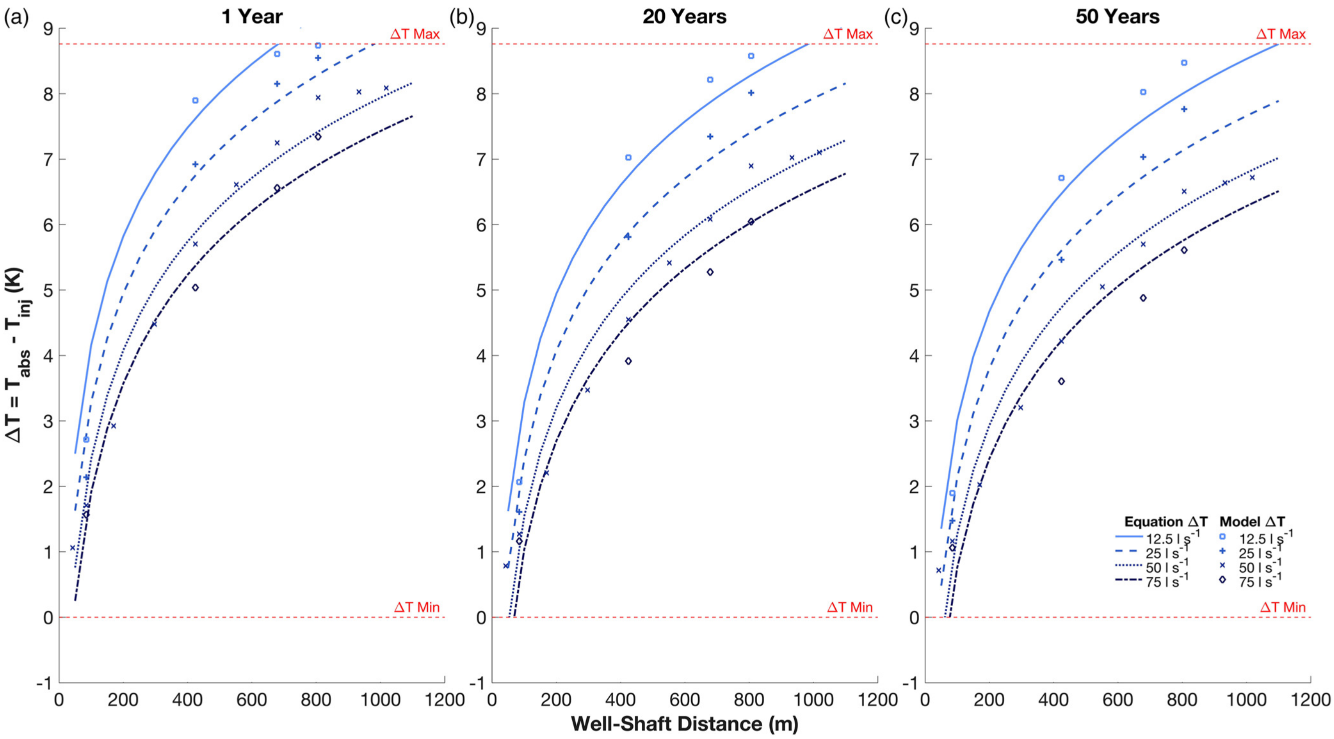

Fig. 6. (**a**–**c**) Equation predicted temperatures compared with modelling results for 1, 20 and 50 years, with Systems A and B having matching flow rates.

Interference predictive model

A multiple linear regression analysis was performed to relate the ΔT to the natural logarithms of the input parameters. This provides a useful equation to predict abstraction temperatures without the need for further numerical modelling. For this analysis, both System A and System B had the same flow rate, varying from 12.5 to 75 l s^{-1}, the timescales range from 1 to 50 years and the well–shaft distance from 42 to 1018 m.

Multiple linear regression was used to find the relationship between the input parameters (distance, flow rate, time) and the amount of warming (ΔT). Natural logarithms of the input parameters were used:

$$\Delta T = \Delta T_0 + A_2 \ln(x) + B_2 \ln(q) + C_2 \ln(t) \tag{3}$$

The best fitting parameters for this system are $\Delta T_0 = -3.704$ K, $A_2 = 2.396$, $B_2 = -1.255$ and $C_2 = -0.293$; x is the distance (m), q is the flow rate ($m^3 \ s^{-1}$) and t is the time (years). These parameters give an r^2 of 0.964.

The predicted ΔT results are plotted versus the actual model runs in Figure 6. All the predicted curves start with a steep gradient, which decreases as distance increases but does not flatten off. As the distance increases, the ΔT also increases. However, at greater distances, the rate at which ΔT increases diminishes, matching the pattern of the modelled values. At longer operating times ΔT is reduced.

The results are truncated between ΔT_{min} and ΔT_{max} as this reflects the physical limits of the system; the water cannot cool below the injection temperature, or warm above the initial rock temperature.

Discussion

HER and regulatory pathways

The modelling results show that adjacent mine geothermal systems could experience negative interference, but that under the correct circumstances this can be minimized. Regulation can be used to ensure that systems are at an appropriate distance and the use of acceptable flow rates can reduce interference. The HER can be used by regulators to quantify the amount of interference between systems. A threshold value can be set, with any value below this threshold predicting an unacceptable amount of interference (Fig. 7).

The HER can be calculated without modelling the systems directly using equation (3). The use of this equation is most suitable in systems with a reasonably regular geometry. If an MWG system is already in place, then the difference between the abstraction and the injection temperature is known. The ΔT when an additional

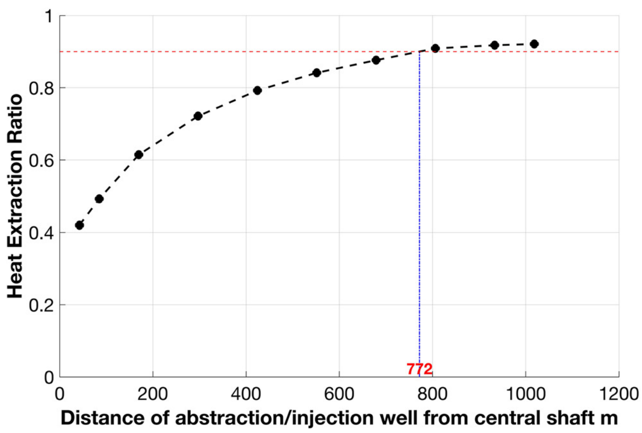

Fig. 7. Graph showing the potential to use the HER as a regulatory tool. This example uses a system with a flow rate of 50 l s^{-1} and operation time of 40 years. Using a threshold HER of 0.9 suggests a minimum well–shaft distance of 772 m. System A has an HER of 0.42, meaning it has lost almost 60% of its energy, when the two systems are 42 m from the central shaft. However, when the systems are over 1000 m from the shaft, and therefore 2 km from each other, System A's ratio is 0.92, meaning it has lost only 8% of its heat energy. Here the threshold value is at 0.9; System A cannot lose more than 10% of its heat after the addition of System B. The modelling indicates that System B should not be allowed if it is nearer than 772 m.

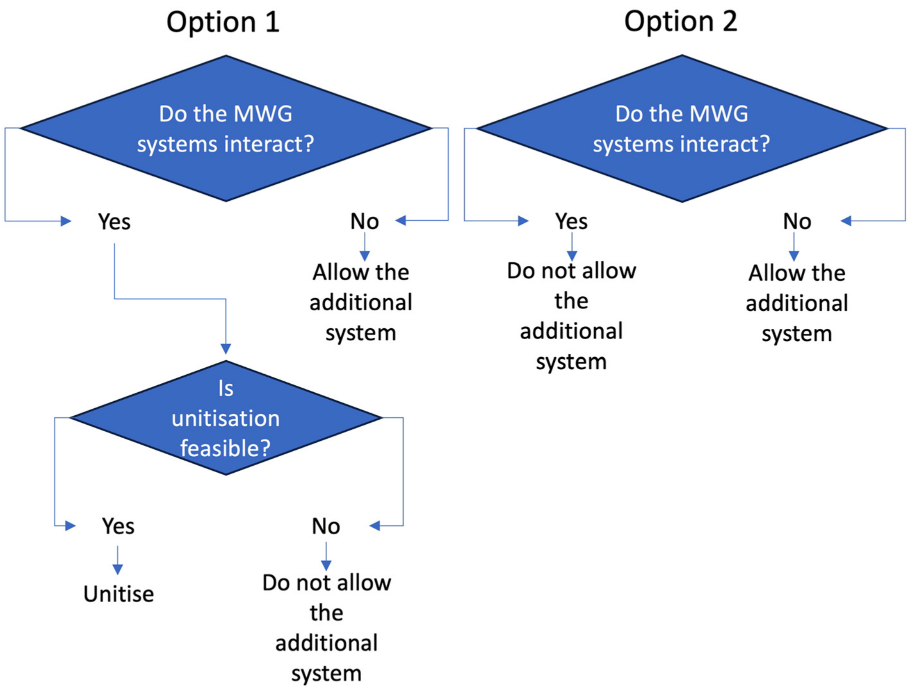

Fig. 8. Flowchart of the two suggested policy options to regulate the interference of MWG systems. 1, a unitization-based approach; 2, a simple yes or no approach.

system has been added can be estimated with the equation, and the heat extraction ratio can be calculated to quantify the impact of the additional system.

It should be noted that the models, by their nature, are simplified geometries and we recommend future work comparing the model systems with real systems to better understand variability in the predicted heat extraction ratio. The generic models presented here offer a first estimate of the interference between systems, and a more careful analysis can be achieved using tailored models, if desired. This might be particularly beneficial when mine plans deviate significantly from the regular set-up used here. Additional future areas of study would be to consider the impact of greater numbers of systems, groundwater flow and the effect of porous media, either from longwall mining or backfilling room and pillar mines.

Although the HER can be used to predict and quantify thermal interference, how to regulate thermal interference is a different question. The review of regulations indicates several possible options, ranging from not regulating interference at all, to unitization, to not allowing any interference. Having no interference regulations is likely to continue the status quo of deterring investors (Goodman *et al.* 2007; Manzella *et al.* 2018), especially as we have demonstrated that systems can interfere with each other.

As we have shown that it is possible to have systems adjacent to each other without significant negative interference, one-system mine blocks are inappropriate as this leaves large amounts of heat resource inaccessible. Although there are many potential regulatory approaches, the HER provides a quantitative basis for assessing thermal interference. Based on this, we propose two possible policy options (Fig. 8). We believe that any further recommendation with regard to how to apply the HER to a regulatory approach requires further work, such as techno-economic modelling and the addition of thermal storage and waste heat disposal.

Option 1 is a unitization-based approach, as used in New Zealand, Mexico and Utah. There is knowledge of how to regulate unitization agreements given the UK's long history of oil and gas extraction in the North Sea in which unitization is prevalent.

However, given that heat is less transportable than electricity or oil, unitization may not always be feasible. In the UK, if a renewable power company produced electricity at a site, the electricity would be sent to the electrical grid and that amount of power could then be sold to customers all over the country. Likewise, if petroleum was being produced, pipelines and/or tankers can be used to transport the product all over the world. Therefore, a unitized operation could provide power to customers regardless of their location. However, if two MWG operations unitized, this could result in increasing the abstraction and injection rates from a single site or moving the boreholes' infrastructure from the planned sites. This could result in an increased distance from the intended customers. If heat is being transferred over increased distances (Molar-Cruz *et al.* 2022), there can be significant costs in building pipes, such as obtaining appropriate permissions and excavating roads. These costs may be too great for small-scale schemes (e.g. of a few houses). However, in practice, this may not prove to be a problem, as we have demonstrated that the lower flow rates of small schemes are less likely to cause thermal interference.

Unitization may, however, be especially practical for MWG schemes associated with district heating systems where there is an inbuilt heat transfer network.

Using Option 2, without unitization, there is the potential that a pre-existing small system could prevent a much larger system from being built, which would provide decarbonized heating to a larger user base and be a more efficient use of the subsurface resource. Similar issues occur in minerals planning, and regulations have been developed accordingly.

In minerals planning the term 'sterilized' is used to refer to a situation where a surface development above or adjacent to a deposit prevents any future extraction. In this hypothetical case, it is somewhat different, as the sterilization would be by prior geothermal extraction. To prevent mineral sterilization, some countries (Austria, Czechia, Spain, Greece, Poland, Portugal, UK, Southern Australia and Maryland, USA; Wrighton *et al.* 2014; Gugerell *et al.* 2020) have implemented minerals safeguarding policies.

In the UK, these policies are the designation of mineral safeguarding areas (MSAs), which are areas of known resources, permitted reserves, quarries and infrastructure sites, and mineral consultation areas (MCAs), areas based on MSAs but including a wider buffer zone. An MSA or MCA does not mean that mineral development (the winning and working of minerals or the depositing of mineral waste; Ministry of Housing, Communities and Local Government 2014) will happen, or that non-mineral development cannot happen. An MSA or MCA requires a non-mineral developer to prove either that mineral development would not be viable or that the non-mineral development is of greater strategic importance (The Mineral Products Association and The Planning Officers' Society 2019).

A similar system could be developed for mine water geothermal areas, where regulators could have the right to refuse the installation of geothermal systems in zones that have the potential to provide large amounts of heat, to preserve that potential for future large-scale systems. Of course, to do this, there would have to be an assessment of potential mine water geothermal areas and a mechanism to decide what a suitable-sized geothermal system would be.

Interference predictive model

To allow for prediction of the ΔT and HER without modelling, multiple linear regression analysis was performed to produce a simplified equation, using the well–shaft distance, flow rate and operating time to calculate ΔT.

The physically plausible values of ΔT are between zero and the ΔT_{max}, where the ΔT_{max} is the temperature difference between the initial rock temperature and the injection temperature. The water cannot heat beyond the warmest rock temperature and cannot become colder than the injection temperature. The equation does not reflect these physical limits, and, therefore, values obtained from this equation should be truncated between zero and ΔT_{max}.

This does not affect the usefulness of the equation as values close to zero illustrate a scenario that obviously needs to be avoided, and for values close to ΔT_{max} the system is already working close to optimal.

Conclusions

Our model simulations demonstrate that thermal interference of neighbouring MWG systems can be quantified. This interference increases with flow rate, time and a reduced distance between systems. To increase confidence in the technology and therefore increase the use of mine water geothermal systems, regulation is required to manage the thermal interference. The heat extraction ratio is proposed as a novel method to quantify thermal interference and can be used to set threshold values.

We propose two policy options to regulate the thermal inference:

(1) a unitization-based approach: when an additional system would have too significant an impact on the first system present, unitization is required if feasible;
(2) a simplified yes or no approach: if an additional system would have too significant an impact on the first system present, the second system should not be allowed. If this system is used, highly prospective areas may need to be preserved for large-scale schemes.

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Author contributions **AS**: conceptualization (lead), formal analysis (lead), investigation (lead), methodology (lead), project administration (lead), validation (lead), visualization (lead), writing – original draft (lead), writing – review & editing (lead); **JH**: conceptualization (equal), formal analysis (supporting), software (equal), writing – review & editing (equal); **JM-C**: formal analysis (supporting), software (equal), writing – review & editing (equal); **JG**: writing – review & editing (equal).

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Data availability The datasets generated and/or analysed during the current study are available in the Mendeley data repository, https://data.mendeley.com/preview/bydmxh28f7?a=1e0e03f4-d906-410d-abd3-747693d985c6

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