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The role of regulation in geothermal energy in the UK

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ABSTRACT

Geothermal energy is a constant, reliable source of energy which has the potential to play a key role in decarbonisation of the heating of buildings in the UK. At present it is underutilized, making up just 4.5 per cent of renewable energy used in the UK, and a significant reason for this is the lack of clear regulatory framework for addressing the environmental impacts and supporting private investment. This article identifies the environmental and financial risks of both shallow and deep geothermal energy and analyses if, how, and to what extent they are addressed in the current regulatory regime. It finds that regulation of the environmental impacts is piecemeal and recommends reform of the regulatory regime to cover all geothermal energy systems and operations. This article also finds that the current regulatory framework fails to address the significant upfront costs of both shallow and deep geothermal energy operations or the potential for depletion of the geothermal resource on which they depend. It highlights the need for a regulatory regime that protects geothermal energy resources from overabstraction and balances the interests of multiple users, and for financial incentives to encourage growth of both the shallow and deep geothermal energy industries.

1. Introduction

Greenhouse gas emissions from the heating of buildings (commercial buildings, public buildings and homes) are currently the second largest source of emissions in the UK (after transport), making up 23 per cent of UK emissions, with homes comprising the largest proportion. Decarbonisation of the heating of buildings can make a significant contribution to reducing the UK's carbon emissions and is essential to meeting its obligation to achieve net zero carbon emissions by 2050 (HM Government, 2021a). Geothermal energy is the heat stored beneath the Earth's surface. It can be used to provide heat or for the generation of electricity and is therefore one of the energy sources available to achieve net zero. Where a heat pump is required to increase the temperature of the abstracted geothermal heat, the amount of carbon savings depends on the electricity mix for running the heat pump and its efficiency, but studies have shown that significant carbon emission savings can be made by using ground source heat pumps (which use shallow geothermal energy) rather than conventional heating systems (Saner et al., 2010; Bayer et al., 2012). Deep geothermal energy can be used to produce electricity as well as to provide heating, and although the greenhouse gas emissions vary depending on the geological conditions and technology and procedures used (Menberg et al., 2016), geothermal power plants generally produce fewer carbon emissions than those that use fossil fuels (O'Sullivan et al., 2021).

Geothermal energy is a predictable, constant, and reliable source of energy that, unlike other renewables such as wind and solar, is unaffected by weather or seasonal variations (Glassley, 2015). It has been estimated that the UK has sufficient accessible geothermal resources to meet its current heating requirements for approximately 100 years (as well as 9 per cent of England's and 85 per cent of Scotland's annual electricity requirements) (Gluyas et al., 2018; Abesser et al., 2020). In 2021, geothermal energy (shallow and deep combined) made up just 4.5 per cent of renewable energy used in the UK (Department for Business, 2021), and the many risks involved in the abstraction and use of geothermal energy – directly related to the lack of both a clear regulatory framework and measures to encourage and support private investment - are considered significant factors behind this underutilisation (Abesser et al., 2020; Garcia-Gil et al., 2020a; Tsagarakis et al., 2020).

Whilst there have been some studies and reviews of the regulation of geothermal energy in both the UK and other jurisdictions (Garcia-Gil et al., 2020a; Tsagarakis et al., 2020; Haehnlein et al., 2010), the attention it has received to date does not reflect its potential importance in light of the social desirability and policy salience of achieving net zero. In response to this, this article interrogates the ways in which the

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environmental and financial risks are currently regulated in the UK, with the view to identify ways in which the regulation of geothermal energy could be improved to facilitate industry growth. Section 2 gives an overview of shallow geothermal energy, summarises the key the risks related to it, and examines if, how, and to what extent there is regulation in place to address those risks. Section 3 does the same in relation to deep geothermal energy. Section 4 makes a number of recommendations for strengthening regulation of both shallow and deep geothermal energy and discusses the regulatory reforms needed to do implement these recommendations. It also discusses the use of a less formal approach based on the development of industry standards and codes of practice. The article argues that whatever approach is taken to the regulation of geothermal energy, there is a clear need for financial incentives to encourage the use of both shallow and deep geothermal energy.

A couple of preliminary points should be made, however. First, the article does not purport to provide a comprehensive overview of all the potential risks or regulatory controls in place. Instead, its aim is to provide the foundations for future work on the importance and feasibility of scaling up the abstraction and use of geothermal energy, particularly deep geothermal energy. Second, the topic of geothermal energy has received little attention from law and regulatory scholars in the UK. As a result, the article aims to scope the regulatory conditions under which abstraction of geothermal energy operates with the aim to provide a starting point for further discussion. In this context, the article seeks to complement existing work, which has focused on the governance and policy aspects of shallow geothermal energy (Garcia-Gil et al., 2020a; Tsagarakis et al., 2020; Haehnlein et al., 2010). Third, it must also be noted that the regulatory attention and knowledge base underpinning the exploration of deep geothermal energy are changing rapidly. As a result, the recommendations regarding deep geothermal energy are somewhat speculative in nature, reflecting a commitment to considering a wide range of regulatory options in the attempt to engage with deep geothermal energy.

2. Shallow geothermal energy

2.1. Abstraction and use of shallow geothermal energy

In the UK, shallow geothermal energy is generally considered to be that found in the first 500 m below the Earth's surface (Abesser et al., 2020). Through the use of heat pump technology, shallow geothermal energy can be abstracted from the ground to provide heating and hot water to buildings (Garcia-Gil et al., 2020a). Such systems are commonly referred to as ground source heat pumps or ground source heating systems. Shallow geothermal energy abstraction systems operate using either an open-loop or closed-loop system (Stober and Bucher, 2021). Open-loop systems abstract groundwater through a borehole, transfer the heat from it, and then reinject the water back into the ground through a second borehole (Garcia-Gil et al., 2020a). More rarely, they can involve the abstraction of surface water and/or the discharge of water into a surface water body (Ground Source Heat Pump Association). Closed-loop systems involve a pipe or pipes being buried in the ground. A heat transfer fluid is then circulated through the pipes and heat exchangers are used to transfer heat from the ground to the heat transfer fluid. The heated transfer fluid is then carried to the surface where the heat is abstracted from it and the cooled fluid pumped back into the ground. (see Fig. 1)

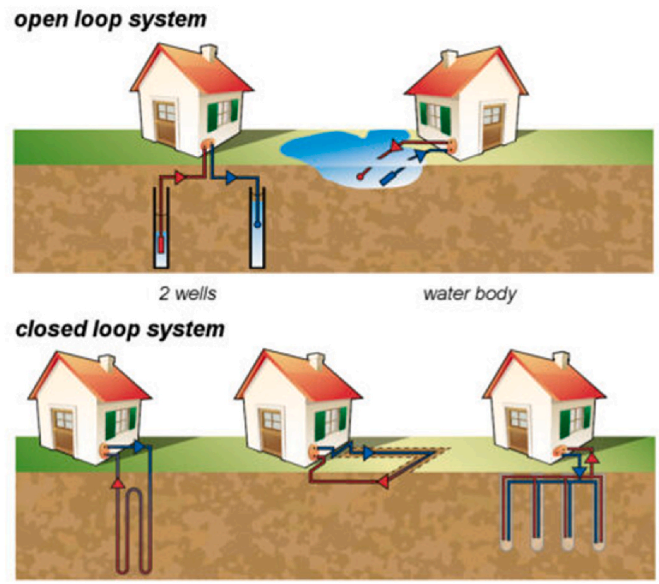

Fig. 1. Open and closed-loop shallow geothermal energy abstraction systems (adapted from ITB Climate, GETS System Options (ITB Climate, 2022)).

2.2. Risks and barriers relating to shallow geothermal energy

The main **environmental risks** associated with the abstraction and use of shallow geothermal energy relate to changes in the temperature of the subsurface and adverse impacts on the quality of groundwater.

Ongoing abstraction of shallow geothermal energy (using either an open or closed-loop system) will reduce the temperature of the ground or groundwater from which it is abstracted. This risk increases where there is a high density of abstraction systems (Garcia-Gil et al., 2020a, 2020b; Vienken et al., 2019). Temperature changes in groundwater can result in changes to physical properties, chemical reactions, microbiology, and the interaction between these. This can have adverse environment implications and affect the quality of drinking water (Haehnlein et al., 2010), although studies have indicated that the changes produced by moderate temperature changes in non-contaminated water may be acceptable (Griebler et al., 2016; Brielman et al., 2009). Further risks of interference with drinking water arise during installation works, particularly in contaminated areas, as they can lead to mobilisation of contaminants (Garcia-Gil et al., 2020a).

Open-loop shallow geothermal energy systems carry a number of additional risks. The reinjection of groundwater carries a risk of contaminating groundwater and increases the risk of producing undesirable temperature changes if the water reinjected or discharged is at an altered temperature (Garcia-Gil et al., 2020a; Brielman et al., 2009).

The initial upfront **costs** of installing a shallow geothermal energy abstraction system may constitute a barrier to their wider use. The government's Build Back Greener strategy states that the cost of installing a ground source heat pump can be up to £10,000 and is significantly more than a gas boiler (HM Government, 2021b), and there are conflicting reports as to whether or not they are cheaper to run (Ground Source Heat Pump Association; HM Government, 2021b). The cost of installing a shallow geothermal energy extraction system (and the lack of availability of funding) has been found to be a reason behind people in the UK deciding against them (Bleicher and Gross, 2015). Furthermore, the performance and efficiency of a shallow geothermal energy system may be impacted by a reduction in the temperature of the ground or groundwater caused by the continued abstraction of heat by the system itself or by other nearby shallow geothermal energy systems (Garcia-Gil et al., 2020a, 2020b; Haehnlein et al., 2010), and in extreme cases this can result in complete failure of the system's integrity (Kupfernagel et al., 2021).

2.3. Regulation of shallow geothermal energy

It has been reported that one of the main reasons why homeowners install shallow geothermal energy systems is a desire to invest in environmentally friendly technology (Bleicher and Gross, 2015) and that incidents of significant environmental damage allegedly caused by shallow geothermal energy systems have impacted on their uptake

(Fleuchaus and Blum, 2017). A robust regulatory regime in which the potential environmental impacts of shallow geothermal energy systems are adequately addressed is therefore essential for industry growth. Currently, there is no bespoke regime for the regulation of shallow geothermal energy. It is regulated primarily by the Environment Agency through the water abstraction and discharge regulatory regimes and by local authorities through the town and country planning regime.

2.3.1. *Regulation of the environmental risks*

Any **open-loop** shallow geothermal energy system that involves the abstraction of more than 20 m^3 of water a day will require an abstraction licence from the Environment Agency (Water Resources Act, 1991a). This licence will specify the amount of water that can be abstracted, as well as the means by which it can be abstracted (Water Resources Act, 1991b). The Environment Agency also has broad discretion to include additional licence provisions if it considers it appropriate to do so, as well as the ability to refuse an application for a licence where it considers it necessary or expedient (Water Resources Act, 1991c). This enables the Environment Agency to protect water resources from the adverse impacts of open-loop shallow geothermal operations, for example by requiring measures to be taken to prevent contamination during installation works. It could also be argued that the Environment Agency's duties regarding conservation of water resources and their dependent flora and fauna (Environment Act, 1995) requires it to use the provisions of an abstraction licence to ensure that the abstraction does not cause a reduction in the temperature of the water source that would have an undesirable environmental impact.

However, the ability of the Environment Agency to protect the quality of groundwater from the risks presented by open-loop shallow geothermal energy systems under the water abstraction licensing regime is constrained by the fact that it only applies to those shallow geothermal energy systems that abstract more than 20m^3 of water per day. It gives the Environment Agency no regulatory powers to address the cumulative impacts of small open-loop systems that abstract less than this.

An alternative means by which the Environment Agency can regulate open-loop shallow geothermal energy systems is through the environment permitting regime, under which those systems that reinject to groundwater or discharge to surface water may require an environmental permit (Environmental Permitting (England and Wales) Regulations, 2016a). The Environment Agency will use permit conditions, emissions management plans, and environmental management systems to manage the impacts and risks associated with both the reinjection or discharge specifically and the system in general, including by specifying the equipment to be used and setting emission limits where necessary (Environment Agency and Department for Environment, 2021a; Environment Agency and Department for Environment, 2021b; Environment Agency, 2021). This gives the Environment Agency the power to manage some of the impacts of open-loop shallow geothermal energy systems on the quality of ground and surface water, including the power to refuse permission for systems in contaminated areas, to control what is contained in the reinjected or discharged water, and to impose temperature restrictions and thresholds to ensure that the reinjection or discharge does not result in undesirable temperature changes in ground or surface water. (This also applies to any undesirable temperature increases that may arise through the use of an open-loop shallow geothermal energy system in reverse to provide cooling services.)

These powers are, however, limited by the fact that the environmental permitting regime contains an exemption from the requirement for a permit for some groundwater open-loop ground source heating systems. In order to be exempt, there must be nothing added to the water discharged and the system must not be on a contaminated site. There are also requirements regarding the proximity of the system to water abstraction points and the temperature of the water discharged (which must not exceed 25 °C and must not vary by more than 10 °C compared to the aquifer from which it was abstracted), and any system that discharges water with an altered temperature must be within certain volume limits (Environmental Permitting (England and Wales) Regulations, 2016b). Whilst these requirements do go some way to ensuring that those systems that risk altering the temperature of the ground or groundwater or contaminating groundwater are subject to regulatory oversight by the Environment Agency, it is not clear whether the temperature thresholds and requirements regarding distance from abstraction point have a sound scientific basis (Haehnlein et al., 2010). It is also the case that the Environment Agency's current position is to not require an environmental permit for open-loop heat pump systems for domestic properties that discharge to surface water provided that they discharge to the same surface water body from which they abstract and no cleaning products are discharged (Environment Agency and Department for Environment, 2022). This means that the potential for such systems to cause temperature changes in the surface water is not addressed.

Closed-loop shallow geothermal energy systems do not involve the abstraction of ground or surface water. They are therefore outside of the remit of the Environment Agency's regulatory powers under the water abstraction regime. Similarly, they do not involve the discharge of water to ground or surface water and therefore fall largely outside the environmental permitting regime. That being said, the category of activities covered by the environmental permitting regime includes those that involve the discharge of heat to surface water without the need for there to be any water discharged (Environmental Permitting (England and Wales) Regulations, 2016c). This means that closed-loop surface water systems fall within the regulatory remit of the environmental permitting regime if they risk increasing the temperature of surface water, in which case the Environment Agency can exercise its powers to regulate the environmental impacts of the system in the same way as open-loop geothermal systems that discharge to surface water. However, the environmental permitting regime does not cover the discharge of heat to groundwater where there is no discharge of water (Environmental Permitting (England and Wales) Regulations, 2016d) and closed-loop shallow geothermal energy systems are therefore entirely outside the environmental permitting regime.

There are proposals to address this anomaly by amending the environmental permitting regime to cover the discharge of heat to groundwater without the need for there be a discharge of water (Department for Environment, Food and Rural Affairs, 2021a). However, running alongside this are proposals to introduce a set of exempting conditions for closed-loop ground source heat pumps to mitigate the increase in bureaucratic burden and cost to operators and the Environment Agency resulting from bringing closed-loop geothermal energy systems within the environmental permitting regime (Department for Environment, Food and Rural Affairs, 2021a). DEFRA's justification for this is that the exempt ground source heat pumps are low risk, and the draft exempting conditions include limits on the proximity of the ground source heat pump to wetlands and watercourses and a requirement not to mobilise contaminants. They do not, however, include any temperature thresholds, meaning that those closed-loop ground source heat pumps that risk causing undesirable temperature changes to groundwater will be exempt from the requirement for an environmental permit (provided they comply with the other exempting conditions).

The **town and country planning regime** provides local authorities with some powers to regulate the environmental impacts of shallow geothermal energy systems. When determining an application for planning permission for a shallow geothermal energy system, the local authority will take account of the environmental impacts of the proposed system and has wide discretion to refuse planning permission or make it conditional upon measures being put in place to address the impacts (Town and Country Planning Act, 1990a). The local authority can therefore ensure that measures are taken to prevent the proposed system from mobilising contaminants (for example, by refusing planning permission for systems in contaminated area) or otherwise adversely impacting the quality of groundwater, including through conditions that require measures to be taken to prevent an undesirable change in the temperature of the ground or groundwater.

The ability of local authorities to manage the impacts of shallow geothermal energy systems is, however, significantly limited by the fact that ground source heat pumps for domestic premises constitute permitted development, as do those for non-domestic premises where the area of excavation/surface area covered does not exceed 0.5 ha and there is only one system within the curtilage of any one premises (Town and Country Planning (General Permitted Development) Order, 2015a). This means that these systems do not require an application to the local authority for planning permission and there is therefore no opportunity for the local authority to require measures to be taken to address their impacts (unless it has issued a direction to remove the permitted development rights (Town and Country Planning (General Permitted Development) Order, 2015b)).

2.3.2. Regulation of the financial risks and barriers

Where a shallow geothermal energy system requires a water abstraction licence, the **Environment Agency** can impose limits on the amount of heat that is abstracted with the water. This may help ensure sustainable abstraction rates and mitigate the impact on performance and efficiency that one shallow geothermal energy operation has on another. However, the purpose of limiting the amount of heat abstracted must relate to protection of the groundwater from a temperature change that would have an undesirable impact on the quality of the groundwater ecosystem. Similarly, the environmental permitting regime enables the Environment Agency to impose temperature restrictions and thresholds on discharges to prevent temperature changes that would have an undesirable environmental impact, but it does not give it the power to impose such restrictions and thresholds with the purpose of preventing a temperature reduction that would impact the efficiency of the system or other nearby systems. In any event, what powers the Environment Agency has to prevent a reduction in the temperature of shallow geothermal energy resources apply only to those caused by systems that require an abstraction licence and/or environmental permit.

The wide discretion that **local authorities** have regarding what they take into account when determining planning applications (Springer v Ministry of Housing, 1970) means that they can take account of the impact that a proposed shallow geothermal energy system may have on other systems in the area. It would therefore seem that a local authority is able to regulate the amount of heat abstracted to ensure that the system for which planning permission is being sought does not have a detrimental impact on other shallow geothermal energy systems. However, the local authority should not take into account the economic viability of the system for which planning permission is being sought (Walters v Secretary of State for Wales, 1979) and therefore ought not to regulate the amount of heat abstracted so far as it relates to the system's own performance and efficiency. In any event, it is questionable whether local authorities have the expertise needed to manage heat abstraction.

Members of the public considering installing a shallow geothermal energy system may wish to assess the risk of interference from other systems in the area. They can obtain copies of abstraction licences, environmental permits, and planning permissions relating to other systems from the Environment Agency and local authorities (Water Resources Act, 1991d; Environmental Permitting (England and Wales) Regulations, 2016e). However, a significant number of shallow geothermal energy systems fall outside the water abstraction, environmental permitting, and planning regime and a comprehensive record of shallow geothermal energy systems is not currently available.

The **owner** of a shallow geothermal energy system that has an abstraction licence has the right to claim damages from the Environment Agency if it grants any further abstraction licences that derogate from the owner's right to abstract the amount of water specified in its licence (Water Resources Act, 1991e). However, this right to damages does not apply where the further abstraction licence(s) interferes with the amount of heat available. Any redress that the owner of a shallow geothermal energy system may have for interference with the amount of heat available is therefore largely through the tort of nuisance. Compliance with the terms of any licences and permits granted by the Environment Agency and local planning authority will not provide a defence to such a nuisance claim, but there are a number of factors that limit the utility of nuisance as a means of regulating competing rights to shallow geothermal energy resources. Fundamentally, nuisance is concerned with balancing competing property rights. It is therefore only applicable to geothermal resources if they are privately owned and, as discussed below, the question of ownership of geothermal resources, particularly those that are 300 m or more below the surface, has not been conclusively answered (McClean and Pedersen, 2021). Furthermore, multiple factors can affect the temperature of shallow geothermal energy resources and shallow geothermal energy systems (Bidarmaghz et al., 2021) and it may be difficult to prove the requisite causal link between the reduced performance of the claimant's system and the alleged nuisance.

3. Deep geothermal energy

3.1. Abstraction and use of deep geothermal energy

Deep geothermal energy is generally considered to be that which is at depths of over 500 m (Abesser et al., 2020), the temperature of which increases as a function of depth (Gluyas et al., 2018). It can be used for the generation of electricity or as a heat source for high-temperature district heating networks (Stober and Bucher, 2021). Like shallow geothermal energy, deep geothermal energy can be abstracted using either an open or closed-loop system. (see Fig. 2)

3.2. Risks and barriers relating to deep geothermal energy

There are a number of potential **environmental impacts** of deep geothermal energy abstraction and use. The drilling and construction work can result in noise pollution (Shortall et al., 2015; DiPippo, 2015), alterations to the soil (DiPippo, 2015), adverse impacts of the water through blowout (DiPippo, 2015), habitat disturbance (Shortall et al., 2015), and adverse visual impact (Shortall et al., 2015; DiPippo, 2015). As with shallow geothermal energy abstraction systems, there is also the risk that installation of the abstraction system will connect contaminated zones and aquifers (Shortall et al., 2015).

The operation of deep geothermal energy abstraction systems can lead to air pollution (Shortall et al., 2015) and additional noise pollution (Shortall et al., 2015; DiPippo, 2015), and the quality of water can also be adversely impacted by effluent and leakage (DiPippo, 2015; Kruszewski and Wittig, 2018). Once constructed, the visual impacts of a direct use deep geothermal energy operation are relatively minor,

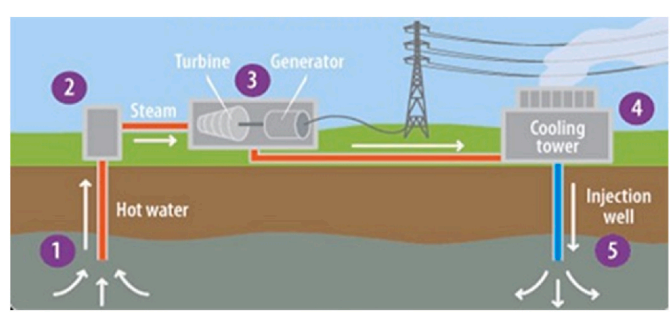

Fig. 2. Deep geothermal power plant (reproduced from EPA, A Student's Guide to Climate Change (Environmental Protection Agency, 2022)).

comprising a borehole covering not much bigger than a manhole.[1] The long-term visual impacts of a geothermal power plant will vary depending on factors such as the size and type of system being used and the properties of the geothermal resource, but they are generally smaller than in relation to a conventional electricity generation power plant, wind-turbine, solar thermal power tower, or nuclear plant (DiPippo, 2015). Nevertheless, the visual impacts are likely to be a concern for those living in the area and regulating deep geothermal energy operations in a way that addresses this concern and keeps alterations to the landscape to a minimum is important for ensuring public support.

Open-loop deep geothermal energy operations carry a number of additional risks. There is the risk of overabstraction of water, which can impact on the availability of groundwater (DiPippo, 2015), have an adverse impact on flora and fauna (Environment Agency and Department for Environment, Food and Rural Affairs, 2022), and lead to subsidence (Glassley, 2015; Shortall et al., 2015; DiPippo, 2015). The reinjection of cooled geothermal water may contribute to a reduction in the temperature of geothermal resources (Stober and Bucher, 2021). There is also a risk of induced seismicity as a result of the continued abstraction and reinjection of water (Glassley, 2015; Shortall et al., 2015; DiPippo, 2015), and this risk increases for those operations that use enhanced geothermal systems (the injection of water into hot dry rock to act as an artificial carrier of heat) (Menberg et al., 2016). Deep geothermal water can contain high concentrates of potentially harmful matter, and this can have adverse impacts if it makes its way into ground or surface water during the reinjection or discharge of geothermal water (DiPippo, 2015).

Deep geothermal energy operations can also give rise to **financial risks**. The uncertainty regarding whether drilling will be successful presents a significant risk to investors (Kubota et al., 2013). Ground surface temperature, thermal gradient, and the thermal conductivity of the rock type are all factors which affect geothermal energy yield (Piipponen et al., 2022). It is difficult to accurately evaluate a deep geothermal energy resource until exploratory deep drilling has been carried out (Barbier, 2002), and it has been claimed that the exploration and drilling costs typically constitute approximately half of the total investment costs of a deep geothermal energy operation (Shortall et al., 2015; Kubota et al., 2013). Furthermore, the time it takes for a deep geothermal energy operation to be up and running means that even if the exploration and drilling are successful there is a long lead time for return on the investment costs.[2] Besides, the information gathered during exploratory drilling is often inaccurate meaning that initial assessments of the potential of a geothermal energy operation will often be incorrect or imprecise (Malafeh and Sharp, 2015). The exploration of conventional energy resources is subject to similar risks, but regulatory path dependency and the relative experience, knowledge, and in-built maturity of the regulation of conventional energy resources provides an advantage compared to the emerging geothermal energy industry[3] and further highlights the need for a regulatory regime for deep geothermal energy that mitigates the risks involved in the initial investment to enable the industry to grow.

Furthermore, abstracting heat at a rate that exceeds the recharge rate will result in depletion of the deep geothermal energy resource, and this can lead to a decline in the productivity of the operation and shortening of its lifetime (Stober and Bucher, 2021; Malafeh and Sharp, 2015; Hackstein and Madlener, 2021).

Another potential risk-factor is that the question of who owns geothermal resources has not yet been resolved (McClean and Pedersen, 2021). Geothermal energy is currently treated as an unowned resource to which everyone has access, with the Infrastructure Act 2015 facilitating this by granting the automatic right to every person to access geothermal resources that are 300 m or more below the surface (Infrastructure Act 2015a). Current industry practice is for geothermal operators exercising their rights under the Infrastructure Act 2015 to make a voluntary payment to the local community of £20,000 per horizontal well that extends more than 200 m laterally (Department of Energy and Climate Change). However, the legislation provides for the introduction of a statutory scheme for payment to the owners of land beneath which geothermal energy resources are accessed (Infrastructure Act, 2015b). Furthermore, as the economic value of geothermal energy is recognised, it may be that the state and/or landowners claim ownership of geothermal resources. There is therefore significant potential for the abstraction costs to increase in the future, depending on the ownership model put in place. In any event, if a deep geothermal energy operation requires access to, over or through other land, including the first 300 m below the surface, agreement will need to be reached with the relevant landowners, including for the payment of compensation, rent and other fees. Clarification of the issue of ownership of geothermal resources is therefore needed to provide certainty and predictability for those considering setting up a deep geothermal energy operation.

The exposure to liability for damages and losses caused to the environment, people or property presents a further financial risk to operators of deep geothermal energy operations. The operator of a deep geothermal energy operation may be liable under the law of trespass for any pollution of other land caused by the operation,[4] and under the law of nuisance or negligence for any other loss or damage suffered by third parties (Dennis v Ministry of Defence, 2003; Cambridge Water Co Ltd v Eastern Counties Plc, 1994). Statutory liability will arise under the Environmental Damage (Prevention and Remediation) Regulations 2015 for any damage to a protected species or habitat or site of special scientific interest caused intentionally or negligently by any operation (Environmental Damage Regulations, 2015). If the system has an environmental permit, then statutory liability will arise for any environmental damage caused (Environmental Damage Regulations, 2015), and if it has an abstraction licence, then liability arises for any loss or damage resulting from the abstraction (Water Resources Act, 1991f).

Geothermal operators that produce electricity face additional risks in relation to access to the electricity network. To sell their electricity, they need to connect to the electricity transmission or distribution network. The network operator may charge significant connection fees on the basis that it does not have sufficient capacity to accommodate the generated electricity without network upgrade. Governance of the co-ordination between geothermal energy generators and the transmission and distribution networks is required to ensure that this does not prevent optimal use of geothermal power (Brunekreeft, 2015; Kallies et al., 2021). Similarly, deep geothermal operators that produce heat need a customer(s) to sell this to, unless they are the sole consumer of the abstracted heat, and heat has the additional challenge of higher energy losses than electricity during transportation which can limit it to more local use (Molar-Cruz et al., 2021).

3.3. Regulation of deep geothermal energy

As with shallow geothermal energy, there is no bespoke regime for the regulation of deep geothermal energy and it is instead regulated through a number of regulatory regimes, including those relating to water abstraction and discharge of water, town and country planning, and energy.

3.3.1. Regulation of the environmental risks

As with shallow geothermal energy systems, those deep geothermal

[1] For example, Newcastle Science Central Deep Geothermal Borehole (Newcastle Helix, 2022).

[2] The World Bank estimates that a typical full sized geothermal operation will take approximately 5–7 years to develop (The World Bank, 2012).

[3] On regulatory path dependency see (Kirk et al., 2007).

[4] For example, see (Jones v Llanrwst, 1911).

energy operations that use an **open-loop** abstraction system that involves the abstraction of more than 20m^3 of water a day require an abstraction licence from the Environment Agency (Water Resources Act, 1991a). In the same way as with open-loop shallow geothermal energy systems, the Environment Agency can use provisions in the abstraction licence to manage some of the risks associated with the operation, in particular by setting limits on the amount of water abstracted to prevent overabstraction. It can also require measures to be taken to ensure that the abstraction does not otherwise have an adverse impact on the water resource concerned (Water Resources Act, 1991b), such as requiring specific measures, techniques and equipment to be used to reduce the risk of blowout, leakage, and mobilisation of contaminants. It can also include thresholds in relation to the amount of heat abstracted to prevent reduction of the temperature of the groundwater that would have an adverse impact on its quality. Ultimately, it can refuse to grant a licence for an abstraction where the adverse impacts on water cannot be adequately mitigated.

Deep geothermal energy operations that use an open-loop system will also require an environmental permit in relation to the reinjection or discharge of the geothermal water (Environmental Permitting (England and Wales) Regulations, 2016a), and the Environment Agency can use permit conditions, emissions management plans, and environmental management systems to manage the environmental risks of the operation (Environment Agency and Department for Environment, 2021a; Environment Agency and Department for Environment, 2021b). By these means it can control noise, air, and water pollution (for example by requiring the use of specific techniques or equipment or by setting emission limits), as well as impose temperature thresholds to help ensure that the operation does not result in undesirable temperature changes. It is also the case that the environmental permitting regime only provides for the permitting of open-loop deep geothermal energy operations that reinject to groundwater if they reinject back into the same aquifer from which the water was abstracted (Environmental Permitting Regulations, Environmental Permitting (England and Wales) Regulations, 2016f). This helps reduce the risk of subsidence and seismic activity relating to open-loop deep geothermal energy operations (Stober and Bucher, 2021). Proposals to bring abstraction licensing within the environmental permitting regime (Department for Environment and Food and Rural Affairs, 2021b) has the potential to help improve the coherency of the regime for managing the amount and location of water abstracted and reinjected and further reduce the risk of subsidence and seismic activity.

Closed-loop deep geothermal energy operations do not involve the abstraction of ground or surface water and therefore do not require an abstraction licence. Similarly, they do not involve the discharge of water to ground or surface water and therefore fall largely outside the environmental permitting regime. However, as discussed above in section 2.2, there are proposed reforms to the definition of groundwater activities that will bring those that discharge heat to groundwater within the environmental permitting regime (Department for Environment, 2021a). The exemptions that have been put forward to this proposed new requirement for closed-loop geothermal energy operations to have an environmental permit do not apply to deep geothermal energy operations (Department for EnvironmentFood and Rural Affairs). Therefore, the proposed reforms have the potential to significantly increase the Environment Agency's involvement in the regulation of closed-loop deep geothermal energy operations.

Local authorities have significant regulatory powers in relation to deep geothermal energy operations. Planning permission is required for deep geothermal energy abstraction operations and any associated buildings and infrastructure (Town and Country Planning Act, 1990b). There are no permitted development rights associated with deep geothermal energy. Local authorities therefore have the opportunity to take account of the potential environmental impacts of proposed deep geothermal energy operations and the opportunity to grant planning permission subject to such conditions as they consider necessary to mitigate them (Town and Country Planning Act, 1990c). This includes through the imposition of limits on noise and air and water emission limits, requirements for the use of techniques and equipment to reduce the risk of leakage and blowout, and temperature thresholds to prevent undesirable changes in the temperature of the ground or groundwater. Local authorities can also exercise their regulatory powers to mitigate the visual impact of the operation in relation to the design (size, material etc) of any buildings and infrastructure and the use of measures such as landscaping to shield it from view. Ultimately, local authorities can refuse planning permission where the environmental impacts cannot be adequately mitigated (Town and Country Planning Act, 1990a).

One potential drawback of reliance on local authorities to address the environmental impacts of deep geothermal energy operations is that it is questionable whether they have the expertise to carry out an assessment of the risks and identify appropriate means of mitigating them. This is addressed to some extent by the Environmental Impact Assessment regime, under which planning applications for deep geothermal energy operations that are likely to have a significant adverse impact on the environment must be accompanied by a comprehensive assessment of the risks to water, air, soil, land, landscape and human health carried out by 'competent experts' (Town and Country Planning (Environmental Impact Assessment) Regulations, 2017a). However, the EIA regime only applies to those deep geothermal energy operations that fall within one or more of five specific categories set out in the legislation. These can be broadly summarised as (i) those that have a heat output of 300 MW or more, (ii) those that constitute groundwater abstraction or artificial groundwater recharge schemes that abstract or discharge 10 million m^3 or more of groundwater per year, are in a sensitive area (as defined in the legislation), or have an area of the works exceeding 1 ha, (iii) those where the area of the drilling works exceeds 1 ha, are within 100 m of controlled water, or within a sensitive area, (iv) those that produce or carry electricity or hot water and the area of the development or works exceeds 0.5 ha or 1 ha respectively or is within a sensitive area, and (v) those that form part of an urban development of over 1 ha, including more than 150 dwellings, or within a sensitive area (Town and Country Planning (Environmental Impact Assessment) Regulations, 2017b). In any event, EIA is a procedural tool aimed at ensuring local authorities take account of the environmental impacts of the proposed development and it does not require them to prevent or mitigate those impacts (Town and Country Planning (Environmental Impact Assessment) Regulations, 2017c). When deciding whether to grant planning permission for a deep geothermal energy operation, whether it is covered by the EIA regime or not, the local authority does not limit itself to consideration of the environmental impacts but must take account of all the material considerations (Planning and Compulsory Purchase Act, 2004). It may decide that the benefits of the operation outweigh any adverse environmental impacts if, for example, it will help the local economy. The only exception to this is in relation to Special Areas of Conservation (SAC) and Special Protection Areas (SPA): where a geothermal energy operation is likely to have a significant effect on such a site, the local authority can only grant planning permission if it will not adversely affect the integrity of the SAC or SPA concerned. However, even this is subject to an exception where there are 'no alternative solutions' and the local authority considers that the geothermal operations 'must be carried out for imperative reasons of overriding public interest' (Conservation of Habitats and Species, 2017). Furthermore, the government has indicated an intention to review the Environmental Impact Assessment and the Habitats Regulations in order to facilitate the planning application process (Ministry of Housing, 2020; Levelling-up and Reneration Bill, 2022; Department for Business, 2020), which may lead to a weakening of the regulation of environmental harmful development.

Conversely, the discretionary nature of local authority decision-making may result in local authorities taking an over-cautious approach to the environmental impacts of deep geothermal energy operations, particularly if there are public concerns. Many of the benefits of deep geothermal energy operations relate to their contribution to national or global renewable energy and low carbon goals and there may be few obvious local benefits. When determining a planning application, a local authority may, in exercising its discretion, conclude that the detrimental impacts of the proposed deep geothermal energy operation outweigh the benefits and refuse planning permission, and such an approach could hinder expansion of the industry.

Both the Environment Agency and local authorities are limited in their ability to ensure the **sustainable abstraction of heat** from deep geothermal resources. As with shallow geothermal energy operations, neither the water abstraction licensing regime nor the discharge permitting regime enables the Environment Agency to require measures to be taken to ensure that an open or closed-loop deep geothermal energy operation does not reduce the temperature of the geothermal resource if the objective is to prevent a reduction in the productivity and lifetime of the operation itself or other deep geothermal energy operations. Local authorities' ability to regulate the amount of heat abstracted is limited to controlling the impact of one operation on another. As such, it is largely left to operators themselves to ensure that their abstraction rates are sustainable. However, a study has indicated that reducing abstraction rates to ensure the system is operating sustainably is not as economically beneficial as more excessive abstraction over a shorter term (Hackstein and Madlener, 2021).

3.3.2. Regulation of the financial risks and barriers

In relation to the **availability of data** to help reduce the financial risks relating to the exploration phase of a deep geothermal energy operation, the Environment Agency is required to make copies of all abstraction licences, environmental permits, and applications publicly available (Water Resources Act 1991d; Environmental Permitting (England and Wales) Regulations, 2016e). Any additional environmental information held by the Environment Agency can be obtained under the Environmental Information Regulations 2004 (Environmental Information Regulations, 2004a). However, this information is only available in respect of those deep geothermal energy operations that require an abstraction licence or environmental permit and will relate to the abstraction or discharge rather than geothermal quality and characteristics of the subsurface. Furthermore, commercially confidential or sensitive information may be exempted from disclosure (Water Resources Act, 1991g; Environmental Permitting (England and Wales) Regulations, 2016g; Environmental Information Regulations, 2004b) and, in light of the competitive advantage that data gathered during the initial investigations gives operators, this exemption is likely to limit the information available. Similarly, where a deep geothermal energy operation requires planning permission, a copy of the planning application and the relevant environmental information is available to the public, including a copy of the environmental impact assessment where one was required (Town and Country Planning (Development Management Procedure) (England) Order, 2015). However, this information is held by the relevant local authority rather than in a national record. These publicity requirements may therefore provide some information that is of value to prospective operators, but they do not provide for a central, comprehensive and accessible record of the data needed to assess the feasibility and long-term performance of future deep geothermal energy operations.

With regard to deep geothermal energy operators' potential **liability for loss or damage** caused by the operation, compliance with the terms of any requisite abstraction licence, discharge permit, and/or planning permission does not provide a defence against liability under the Environmental Damage (Prevention and Remediation) Regulations 2015 or from loss or damage caused by the abstraction of water (Water Resources Act, 1991f). Neither does it provide an automatic defence to a nuisance or negligence claim (Coventry v Lawrence, 2014). The potential for liability for loss or damage caused by deep geothermal energy operations is not fundamentally different from that in relation to the petroleum and other renewable energy industries. It represents the balance that needs to be found between rights of different private individuals and between the rights of private individuals and the environment. Any increased risk that deep geothermal energy operations face as a result of uncertainty regarding its impacts are related to the nascency of the industry and should therefore decrease as the industry becomes more established.

It is clear from the discussion above that there are a number of significant financial risks relating to the abstraction and use of geothermal energy that the current regulatory regime fails to mitigate to the extent necessary to encourage the investment needed for the industry to expand. This creates a need for **government led incentives** to counteract this residual financial risk.

There are no legislative financial incentive schemes relating to the direct use of geothermal energy for heating.

The main legislative schemes relating to electricity generation from geothermal energy are Contracts for Difference (CfDs) and the Smart Export Guarantee (SEG) (Energy Act, 2013; Smart Export Guarantee Order, 2019). The CfD scheme enables large-scale geothermal power operations to enter into a contract with the Low Carbon Contracts Company (a government owned company established by the Energy Act 2013). Under a CfD, the operator will be paid a flat rate, representing the difference between the cost of generating the electricity and the market price, for electricity produced over a 15-year period. The SEG scheme requires larger licensed electricity suppliers to pay small-scale generators of low-carbon electricity for electricity exported back to the National Grid (Smart Export Guarantee Order, 2019). Unlike the feed-in-tariff scheme that the SEG scheme replaced, the export tariff is not set by the Government (and is therefore likely to be lower than the tariff received under the feed-in-tariff scheme) and the scheme does not provide the generator with a long-term contract (Cui et al., 2020; Grimwood, 2019). Furthermore, whilst CfDs and the SEG take some of the risk out of the sale of geothermal power once it has been generated, they do not address the financial risks relating to the initial exploratory and drilling phases of deep geothermal energy operations, which, as discussed above, constitute a major risk for investors. Moreover, as the CfD and SEG schemes apply to renewable/low-carbon energy in general rather than geothermal energy specifically, they do not provide any additional incentive that may be required to create a level playing field between deep geothermal energy and other renewable/low-carbon energy (Abesser et al., 2020). Neither do they address the difficulties that independent deep geothermal energy operations (ie those that are not vertically integrated into the energy market) may face in relation to being able to transport the power generated to the purchaser. Although applications for connection to the national grid or distribution network should be accepted if the relevant requirements have been complied with (ICLG, 2021), network capacity limitations may prevent the connection being accepted or connection charges could be prohibitively expensive (Burdett, 2015). The ability of the CfD and SEG schemes to incentivise investment in the deep geothermal energy industry is therefore limited.

4. Recommendations

Current regulation of both shallow and deep geothermal energy is piecemeal and demonstrates the desirability of developing a cohesive regulatory regime that covers all geothermal energy and is better targeted at the risks it presents. (see Table 1)

One possibility would be to **transfer ownership of geothermal energy** to the state and put in place a new, independent, regulator to licence abstraction of all geothermal energy. Such a licensing system could be used to manage the amount of geothermal energy abstracted from particular geothermal resources in order to ensure their sustainable use and balance the rights of multiple users, as well as to address the environmental impacts. However, the anticipated uptake of geothermal energy may not justify this and an alternative would be to amend the environmental permitting and/or town and country planning regimes so

Table 1
Summary of licensing and permitting requirements for different types of geothermal energy system.

	Abstraction licence from Environment Agency	Environmental permit from Environment Agency	Planning permission from local authority	Environmental Impact Assessment
Open-loop ground source system discharging to surface water	Yes	Yes	No	No
Open-loop ground source system discharging to groundwater	Yes	No	No	No
Closed-loop surface water system	No	Yes	No	No
Closed-loop ground source system	No	No	No	No
Open-loop deep geothermal system discharging to surface water	Yes	Yes	Yes	Depending on: - heat output - amount of water abstracted - location - size
Open-loop deep geothermal system discharging to groundwater	Yes	Yes	Yes	Depending on: - heat output - amount of water abstracted - amount of water discharged - location - size
Closed-loop deep geothermal system	No	No	Yes	Depending on: - heat output - location - size

that they can more effectively regulate geothermal energy.

One way to **include all shallow geothermal energy systems within the environmental permitting regime** would be to amend the category of energy industry operations covered by the Environmental Permitting Regulations to include geothermal energy systems and operations. (At present it only covers those energy operations that involve combustion, gasification, liquefication, or refining (Environmental Permitting (England and Wales) Regulations, 2016h). This would also be beneficial in terms of establishing minimum standards and a consistent practice as the permitting requirements for energy industry operations include reference to Best Available Techniques (Environmental Permitting (England and Wales) Regulations, 2016i). Alternatively, all shallow geothermal energy operations could be brought within the regulatory remit of local authorities by removing the permitted development rights for ground source heat pumps.

The introduction of statutory limits and requirements for **shallow geothermal energy systems** that will be granted an environmental permit or planning permission could then be used to address their risks and impacts. This could include the introduction of limits on the range of temperature changes in the subsurface that are permitted and minimum distances between shallow geothermal systems or property boundaries (Garcia-Gil et al., 2020a; Haehnlein et al., 2010). There is, however, a need for more research to be carried out before comprehensive temperature limits and distance requirements can be established (Garcia-Gil et al., 2020a; Haehnlein et al., 2010). Similarly, more effective regulation of the risk that shallow geothermal energy systems present to the quality of groundwater could be achieved by introducing more comprehensive restrictions on installations in contaminated sites and within protected areas for drinking water, obligations to carry out monitoring and leakage tests, and requirements relating to the technology used and expertise of installers.

An alternative to introducing blanket restrictions for shallow geothermal energy systems regarding temperature, distance, and location, would be to include these restrictions as conditions that need to be complied with in order for the system to be exempt from the requirement for an environmental permit or to constitute permitted development. This would provide more flexibility and reduce the costs and bureaucracy in relation to low-risk shallow geothermal energy systems, whilst ensuring that the regulator has the opportunity to assess the risks relating to non-exempt shallow geothermal energy systems and require measures to be put in place to address them. However, although advances have been made in the development of models to establish the appropriate operational details (including reinjection rates and timings) in different site conditions to minimise the impact of shallow geothermal energy systems on subsurface temperatures (Vienken et al., 2019), this does not obviate the need for an assessment of the particular site conditions of shallow geothermal energy systems. In particular, account needs to be taken of any particular ecological sensitivities and the potential need for post installation monitoring (Gunawardhana et al., 2015). Careful consideration therefore needs to be given to where to strike the balance between regulatory control and minimising the bureaucratic burden on the industry and regulator.

With regard to **deep geothermal energy** operations, the diverse range of potential environmental impacts means that it would be desirable for a thorough assessment of the risks relating to each individual operation to be carried out (Shortall et al., 2015). All deep geothermal energy operations require planning permission and therefore one option would be to bring all deep geothermal energy operations within the EIA regime. This would ensure they are all subject to a comprehensive environmental assessment and that local authorities are aware of the environmental risks when deciding whether to grant planning permission. The fact that local authorities have considerable discretion regarding whether to grant planning permission and if and how any environmental implications are addressed does mean that protection of environmental interests is not guaranteed. The discretionary nature of local authority decision-making could also lead to a situation where decisions fail to give sufficient weight to national objectives, resulting in a fragmented system lacking in coherence. However, this is the same situation as for all types of development: the local authority seeks to balance environmental interests with economic and social interests. The development of planning policy and guidance relating to geothermal energy could be used to encourage consistency and guide local authority decision-making towards the determination of planning applications in a way that both encourages the use of geothermal energy and mitigates the environmental impacts thereof, along the lines of that which applies to mineral abstraction (Department for Levelling Up, 2014).

Alternatively, bringing all geothermal operations within the environmental permitting regime (as discussed above in relation to shallow geothermal energy systems) would enable the Environment Agency to assess the environmental risks of all deep geothermal energy operations and require measures to be taken to address them. Notwithstanding that regulation by the Environment Agency may provide a more robust protection of environmental interests, it may be appropriate for local authorities to continue to regulate the visual impacts of deep geothermal energy operations: managing the visual impacts and external design of development is within their expertise. Furthermore, studies have shown that dialogue with the public is an important aspect of public support for deep geothermal energy systems (Chavot et al., 2018) and the element of public participation in the determination of planning applications may therefore be beneficial in terms of ensuring that such systems are 'locally anchored' and supported by the local community.

Another gap in the regulation of both shallow and deep geothermal energy is the lack of provision for **gathering, reporting, and publishing information and data** that can be used to manage geothermal resources and better understand the risks. For shallow geothermal energy, a central record of all shallow geothermal energy systems would improve the ability of the regulator to ensure sustainable use of shallow geothermal resources and enable members of the public to find out about shallow geothermal energy systems in the area that may impact on the efficiency of their system. Reforming the regulatory regime so that all geothermal energy systems and operations require an environmental permit would enable a central record of geothermal operation to be established and made accessible to the public.

In relation to deep geothermal energy, however, such a record would not necessarily provide for a systematic and comprehensive mapping of the information that investors require in order to understand the potential and risks relating to future deep geothermal energy operations. A regime that provides for a comprehensive exchange of knowledge between the parties would be more beneficial (Ireland et al., 2021). Inspiration could be taken from the regulatory regime for the extraction of petroleum, under which licence holders have obligations to keep records and samples and provide information to the North Sea Transition Authority (NSTA) (formerly the Oil and Gas Authority) (Oil and Gas Authority Regulations, 2018; Energy Act, 2016; North Sea Transition Authority). To ensure timely access to this data and create the conditions suitable for investment, NSTA's National Data Repository discloses all reported information (North Sea Transition Authority). More ambitious still would be the development of a subsurface environmental information system that provides an interactive framework and allows data exploration within a three-dimensional environment, illustrates the interaction of multiple data sets, and displays changes to the environment over time (Rink et al., 2022). Such a regime would help reduce the financial risks relating to the initial phases of geothermal operations (and help ensure that they continue to reduce over time), as well as help increase the availability and affordability of insurance and the obtaining of funding. If the information is disseminated to the public, it would also increase the transparency of the industry and facilitate public acceptance of deep geothermal energy systems (Chavot et al., 2018).

An alternative to legislative reforms to bring geothermal energy within the formal regulatory responsibility of the Environment Agency, local authorities, or any other regulatory body, would be to develop **industry standards and codes of practice** relating to the construction, operation and decommissioning of geothermal energy systems and operations. The Ground Source Heat Pump Association has developed a number of these in relation to ground source energy systems (Ground Source Heat Pump Association) (and these could be amended to include specific provisions regarding temperature changes, distance between systems, and location within contaminated areas), but there are currently no such standards or codes of practice in relation to deep geothermal energy. This is arguably the most appropriate alternative at this early stage of the emergence of the geothermal energy industry. Whilst the use of industry standards is a form of self-regulation and therefore non-binding, it can act as a 'social control' and is a recognised form of environmental regulation. It can be an effective means of ensuring use of best practice and the meeting of certain standards within the relevant industry, particularly in relation to 'reputation sensitive companies' (Gunningham, 2009). Having a set of standards and codes of practice would also give the Environment Agency and local authorities a point of reference when determining applications for abstraction licences, environmental permits, and planning permission. Conditions requiring compliance with those standards and codes of practice could be used to make them effectively binding in respect of those geothermal operations that require an abstraction licence, environmental permit, or planning permission. The use of industry standards and codes of practice rather than a formal licensing/permitting regime may also help to prevent the time and expense of applying for the requisite licence/permit acting as a deterrent to future geothermal energy systems and operations. Standards and codes of practice also have the advantage of being relatively easy to amend to reflect the advances in knowledge and understanding that are likely to occur as the industry expands.

There are, nevertheless, disadvantages to relying on the use of industry standards and codes of practice to address the risks relating to geothermal energy. Fundamentally, such a regime does not provide for one regulator or body to have overall responsibility for the management of geothermal resources, including safeguarding resources to ensure their long-term availability. It may also be difficult to establish a comprehensive data resource for deep geothermal energy based on voluntary disclosure requirements, particularly in light of the commercial value of exploratory data. Industry standards and codes of practice would also have limited ability to address issues relating to competing users. Where one geothermal system or operation suffers a loss due to another system or operation's failure to comply with the standards and codes, for example by installing a shallow geothermal system too close to an existing system, the party that has suffered loss will need to rely on the existing, somewhat limited, avenues of recourse discussed in section 2.2.2.

Whatever approach is taken to the future regulation of geothermal energy, the development of **detailed guidance** would be beneficial. Current Environment Agency good practice guidance focuses on ground source heating and cooling systems, and there is therefore scope for the introduction of guidance covering deep geothermal energy operations and more comprehensive guidance covering shallow geothermal energy systems. Setting out what environmental impacts need to be assessed, how they should be mitigated, and to what standard would contribute to the consistency and predictability of decision-making by the regulator(s) and the development of industry good practice. Clear recognition of geothermal energy as a resource would also facilitate strategic management of geothermal resources that encourages their use but protects them from overabstraction, and clarification of ownership of geothermal resources is a key aspect of this. Recognition of heat as a resource and clarification of its ownership are also fundamental to the potential for geothermal energy systems to be used to recover and use waste heat and to store geothermal energy.

A further issue in respect of which there is need for clarification is the **distinction between shallow and deep geothermal energy** and the terminology used. Rather than referring to shallow geothermal energy systems, the Environmental Permitting Regulations refer to 'ground source heating and cooling systems' with the defining criteria being related to the size of the system, and the permitted development legislation refers to 'ground source heat pumps' for microgeneration (Town and Country Planning (General Permitted Development) Order, 2015a). The EIA legislation simply refers to 'deep drillings' and 'geothermal drilling', with no definition of either (Town and Country Planning (Environmental Impact Assessment) Regulations, 2017b), and the Infrastructure Act 2015 refers to deep geothermal energy in terms of rights granted to land at 300 m or more below the surface (Infrastructure Act, 2015a). If shallow geothermal energy systems are to be subject to less stringent requirements than deep geothermal energy operations to reflect their lower environmental risks, it needs to be clear which type of systems the different requirements apply to.

Irrespective of the introduction of regulatory or best practice measures to ensure the collation and sharing of information regarding geothermal resources and advances in technology, the fact that use of geothermal energy is an emerging industry means that there will inevitably be a residual risk due to uncertainties regarding the productivity of particular resources and the technology used to extract and use it. This uncertainty needs to be accepted and embraced, with unexpected developments acknowledged as being a fundamental part of the knowledge production process rather than viewed as failures. These developments, in what is effectively a real-world experiment, can be used to underpin the continued development of regulatory control and guidelines and should not be used as a reason for not progressing the use of geothermal energy (Bleicher and Gross, 2016; Gross, 2016).

The inevitable uncertainty does, however, mean that there needs to be **financial incentives** for investors (whether that be individual homeowners in respect of shallow geothermal energy, or industry investors in relation to deep geothermal energy). The government has introduced a number of policies and initiatives aimed at promoting the use of ground source heat pumps, such as targets for the number of heat pumps to be installed per year (Department for Business, 2020) and the Boiler Upgrade Scheme to provide funding to property owners for their installation (Department for Business, 2022). However, the targets and funding cover both air and ground source heat pumps rather than ground source heat pumps specifically. Furthermore, they lack any statutory basis and there is uncertainty as to how long the funding will be available for. There is therefore a need for the introduction of more targeted incentives that are guaranteed for long enough to allow consumers and the manufacturers of ground source heat pumps to plan with confidence.

With regard to deep geothermal energy, any data sharing would need to be supplemented by risk sharing and incentives to address the risks relating to the exploratory and drilling phases of deep geothermal energy operations, in the short-term at least whilst there would be limited information available. Current initiatives and incentives, such as the Heat Networks Investment Project and the Green Heat Network Fund, are generally applicable to renewable and low-carbon energy and their temporary nature has created uncertainty regarding the availability of the long-term support required to ensure the viability of operations (Bolton and Foxon, 2015). They therefore do little to address the particular risks of deep geothermal energy and it is unrealistic for the private sector to bear the full cost and risk of deep geothermal energy development (Yadav et al., 2022). Options for addressing this include the government taking full responsibility for the first stages of deep geothermal energy operations or the sharing of the risks involved in the initial phases between the government and the private sector (Shortall et al., 2015). There are a number of advantages to the government having responsibility for the initial phases of deep geothermal energy operations, including the government having better access to financing options and the ability to mitigate the risks relating to geological conditions by supporting investigations into a portfolio of potential sites (Shortall et al., 2015). The sharing of risks between the government and the private sector could include the use of risk mitigation funds that refund a portion of the exploration and drilling costs to the geothermal operator in the event that the desired temperature or flow rate are not achieved (The World Bank, 2012), and/or compensating geothermal operators for taking on the early risks through tax incentives, grants or soft loans, or favourable tariffs for those geothermal operations that generate electricity. Such schemes need to be guaranteed for sufficient length of time to match the long-term investment profiles of geothermal energy (Abesser et al., 2020).

Additionally, the introduction of financial incentives to encourage sustainable heat abstraction rates could be used to address the current failure of the regulatory regime for deep geothermal energy to provide long-term protection of deep geothermal energy resources (Malafeh and Sharp, 2015).

The solution to the issues that arise as a result of the liberalisation of electricity in the UK is beyond the scope of this article. So far as the issue of the ability of geothermal power operations to connect to electricity networks is concerned, there is the need to develop a regulatory regime that facilitates, through market mechanisms or otherwise, the integration of geothermal energy into the electricity system and an increase in network capacity where necessary (Kallies et al., 2021; Department for Business, 2020). There is similarly a need for the development of a regulatory regime for heat networks that facilitates their use and the integration of geothermal energy.

5. Conclusions and policy implications

Regulation of the abstraction and use of geothermal energy is needed to protect the environment and promote the position of geothermal energy in the transition to low carbon energy. Current regulation of geothermal energy through the regulation of the abstraction and discharge of water focuses on geothermal operations that use an open-loop system, and leaves those that use a closed-loop system largely unregulated. The proposed reforms to the abstraction licensing and environmental permitting regime may improve the coherence of the regulation of the environmental impacts of deep geothermal operations that use an open-loop system, but will do little to increase the Environment Agency's regulatory powers in relation to closed-loop shallow geothermal systems. Local authorities have powers to regulate the environmental impacts of deep geothermal energy operations, but they are not required to prioritise environmental interests over economic and social interests. Whilst the Environment Agency has the power to manage the abstraction of geothermal energy so far as it relates to protection of environmental interests and local authorities have the ability to take account of the impact of one system or operation's impact on other systems and operations in the area, there is no comprehensive regime for the management of geothermal resources that protects the long-term availability of geothermal energy or balances the rights of different users.

This piecemeal nature of the statutory regulation of geothermal energy supports the argument for the development of a coherent and comprehensive framework that covers all geothermal operations. This would enable the environmental implications of all geothermal operations to be assessed and regulated. Bringing all geothermal operations within the remit of one regulator, whether that be the Environment Agency or otherwise, would also facilitate the keeping of a centrally administered record of all geothermal operations and a system for monitoring and managing geothermal resources. This would not only help prevent overabstraction of heat, but also improve the expertise of the regulating authority and facilitate communication between the industry and regulator by providing a point of contact (Abesser et al., 2020).

However, an effective regulatory regime needs to strike a balance between minimising the environmental impacts and facilitating the development and effective operation of geothermal operations to incentivise exploitation of the resource. It may therefore be the case that, for the meantime, the most appropriate means of regulating geothermal energy is through the use of industry standards and codes of practice. These can be used to not only establish minimum standards and promote the use of techniques that mitigate environmental impacts, but also recognise that one geothermal operation may affect the efficiency of other nearby operations and require that new geothermal operations not be placed in close proximity to an existing one. They can also be used to establish a practice of information recording and sharing. Whilst they lack the binding nature of statutory requirements, they may be sufficient to prevent interference between geothermal operations and protect the environment whilst the industry becomes more established without the need for costly and time-consuming permitting requirements.

However, neither reform of the statutory regulation of geothermal energy or the use of industry standards and codes of practice are likely to reduce the financial risks of geothermal energy sufficiently to encourage private investment without the use of financial incentives to mitigate, in particular, the costs of installing a ground source heat pump and the initial high risks of deep geothermal energy operations.

CRediT authorship contribution statement

A. McClean: Writing – original draft, Writing – review & editing. **O. W. Pedersen:** Writing – original draft, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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