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The Geobattery Concept: A Geothermal Circular Heat Network for the Sustainable Development of Near Surface Low Enthalpy Geothermal Energy to Decarbonise Heating

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Decarbonisation of heating represents a major challenge in efforts to reach Net Zero carbon emissions, especially for countries that rely heavily on the combustion of carbon-based fossil fuels to meet heating demand such as the United Kingdom. In this paper we explore the use of near surface low enthalpy geothermal energy accessed via commercial and domestic heat pump technology. These resources may become increasingly important in decarbonisation efforts but, while they are renewable, their sustainability is contingent on appropriate management. Here, we introduce a new geothermal circular heat network concept, known as a "geobattery," which redistributes recyclable heat from emitters to users via elevated permeability pathways in the subsurface and offers a platform to manage shallow geothermal resources. If successfully implemented the concept has the potential to provide low carbon, resilient, low-cost heating that is sustainable both in terms of heat pump performance and the shallow geothermal resource. We demonstrate the concept based on the cooling requirements of a case study data centre with existing high energy use and the potential to inject the generated heat into elevated permeability pathways in the shallow subsurface. We show that thermal recharge under these conditions has the potential to arrest subsurface temperature declines associated with closely spaced borehole heat exchangers, ensure the long-term sustainability of shallow geothermal resources for generations to come, and play an important role in the decarbonisation of heating.

Keywords: sustainability, geothermal energy, net zero, borehole heat exchangers, circular heat network, mine water geothermal

INTRODUCTION

Decarbonisation of the heating sector is a significant challenge in the drive for Net Zero. Globally, energy use in buildings contributes 17.5% of all Greenhouse Gas (GHG) emissions—more than the entire transport sector (www.ourworldindata.org, 2021). In the United Kingdom over 40% of energy is used for space heating, while it is over 50% in Scotland (www.gov.scot, 2019). The

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source of this heat is principally natural gas, then oil, contributing to about 34% of the overall GHG emissions of the country (BEIS, 2019). The United Kingdom has committed to reaching Net Zero carbon emissions by 2050 through the 2019 Climate Change Act amendment, with a target of 2045 in Scotland.

While progress is being made to decarbonise electricity production in the United Kingdom, until very recently decarbonisation of heat has not seen the same level of investment or research and development. The United Kingdom is a good Case Study for bold heat decarbonisation innovation projects as the UK Government announced plans to prevent the installation of new fossil fuel-based heating systems after 2025, while also committing to rapid development of heat pump installations to up to 600,000 per year by 2028 (UK Government, 2020b). There is increasing investment in R&D programmes around decarbonising heat e.g., (www.ukri.org, 2021) as well as the UKGEOS Glasgow site that is specifically designed as a field-scale research laboratory for mine water geothermal schemes (Monaghan et al., 2021).

Shallow geothermal energy is a resource capable of providing low-carbon solutions to decarbonising heat for both domestic and commercial properties. Lund and Toth (2021) report a 54% increase in global geothermal heat pump installations between 2015 and 2019 and a doubling of countries where geothermal heat pumps are installed since 2000. Local scale examples include ground source heat pumps (GSHPs) and borehole heat exchangers (BHEs), while aquifers and abandoned coal mines represent opportunities for more district, or even city, level schemes (Gluyas et al., 2020; Farr et al., 2021).

The theoretical geothermal potential of the shallow subsurface is often considered to be extremely large i.e., simply calculating the heat-in-place in a subsurface volume leads to large values of energy. However, not all this energy is technically, economically, or sustainably extractable, and developing particular sites may be subject to potential barriers (Rybach, 2015; Bayer et al., 2019; Casasso and Sethi, 2019). Heat pumps, such as those coupled to BHEs or mine water systems, are highly efficient, typically producing 3–4 $\mathrm{kW_{th}}$ for every 1 kW of electrical input. The "additional" energy (to raise 1 kW to 3–4 $\mathrm{kW_{th}}$) is gained by cooling the surrounding area, and usually considered freely supplied. The problem is that the "free energy" accessed in the subsurface is principally energy which has been naturally stored over geological time (over thousands of years in a dynamic system with changing climate) and has very low recharge rates (e.g., ~0.063 $\mathrm{W/m^2}$ in the United Kingdom) compared with extraction rates of ~18 $\mathrm{W/m^2}$ required to meet the heat demand of an average UK house (OFGEM, 2016; OFGEM, 2021b).

A key notion we explore here is that geothermal energy is a renewable form of energy but not necessarily a sustainable one. Its sustainability is contingent on its proper management. Sustainability of shallow geothermal resources can be considered from an operational performance perspective i.e., constant BHE temperatures and energy production (Signorelli et al., 2005; Rybach and Eugster, 2010), or from a resource perspective that ensures that geothermal energy exploitation does not result in excessive thermal drawdowns that mean BHEs need to be switched off to allow the ground to recover. Borehole heat exchangers are an established and mature shallow geothermal technology, widely installed across Europe and considered to provide a low carbon solution to heating and cooling demands (Rybach and Sanner, 2000; Signorelli et al., 2005; Rybach and Eugster, 2010; Bayer et al., 2012, 2019; Casasso and Sethi, 2014; Rivera et al., 2017; Walch et al., 2021). Commonly, sustainability assessments of BHEs consider the engineering performance of the BHE and demonstrate steady borehole wall temperatures and consistent heat pump coefficient of performance values (COP) (Signorelli et al., 2005; Rybach and Eugster, 2010; Casasso and Sethi, 2014; Walch et al., 2021). BHE's do not extract water and therefore rely on conduction as the heat transport mechanism, but groundwater flow can have a significant impact on subsurface temperatures (Casasso and Sethi, 2014; Rivera et al., 2015; García-Gil et al., 2020; Abesser et al., 2021).

Sustainability assessments based on performance, however, do not consider the original concept of sustainable development of "…meeting the needs of current generations without compromising the needs of future generations" (Brundtland and Visser, 1987). Thermal recharge to a single BHE is thought to take at least as long as the operational lifetime of the BHE (Rybach and Eugster, 2010), and when BHE arrays are considered, recharge times increase dramatically (Signorelli et al., 2005). This indicates that once the resource has been exploited, it can no longer be considered safeguarded for future generations and the owners of the property served by the BHE will need to replace their heating system while the ground recovers. In this paper, we consider sustainability within the framework of ensuring the availability of the resource for future generations i.e., without the need to turn off the BHE to allow the resource to recover.

There is increasing evidence from both modelling and field studies to suggest that rapid development of the shallow geothermal resource *via* closely spaced BHEs could lead to thermal interferences and reductions in subsurface temperatures that cause decreases in heat pump efficiencies in heat-demand dominated schemes (Vienken et al., 2015; Casasso and Sethi, 2019; Meng et al., 2019; Vienken et al., 2019; Abesser et al., 2021). Even "local" systems need to be considered and monitored at the district and/or city scale to enable effective management of the subsurface thermal regimes (Epting et al., 2017; Mueller et al., 2018; Bayer et al., 2019; García-Gil et al., 2020). Intriguingly, García-Gil et al. (2020) report an example in Zaragoza, Spain, in which the groundwater flux had the positive (and accidental) effect of transferring rejected heat from a cooling-dominated BHE system down gradient to a heat-only BHE extraction system. The authors term this a "nested BHE system" and it raises the possibility that, with careful planning, design and management, groundwater flux could be harnessed to transfer stored heat to BHEs further downstream within a district-scale scheme.

BHEs are a form of electrification of heat, transferring demand from the gas network, which, in the United Kingdom, currently accommodates an order of magnitude higher seasonality than the electricity grid and has the capacity to match extremely fast ramp up speeds associated with daily heat demand patterns (Wilson and Rowley, 2019; Gluyas et al., 2020; Mouli-Castillo et al., 2021; Scafidi et al., 2021). Therefore, as the proportion of renewable electricity generation increases, thermal energy storage and demand side response will become increasingly important to minimize the impact on a renewables dominated electricity grid (UK Government, 2020a; Revesz et al., 2020; Scottish Government, 2021a).

In the United Kingdom, abandoned mines are being considered for both geothermal renewable heat and thermal energy storage as approximately 25% of housing and businesses overlie legacy flooded coal mines (Banks et al., 2009; Banks et al., 2019; Gluyas et al., 2020; The Coal Authority, 2021). Key advantages of mine water geothermal schemes include the elevated flow rates e.g. up to 150 L/s at Dawdon mine, United Kingdom (Bailey et al., 2013), elevated mine water temperatures e.g., on average 17˚C for Scottish coal fields (Gillespie et al., 2013), potential socio-economic regeneration of disadvantaged areas (Gluyas et al., 2020; Kurek et al., 2020), and CO_2 savings when replacing fossil-fuel based heating and cooling systems (e.g., ~65% savings at Heerlen, Netherlands, and ~39% savings at Barredo, Spain (Verhoeven et al., 2014; Peralta Ramos et al., 2015). Todd et al. (2019) provided a theoretical estimate of the sustainable heat production from abandoned coal mines in Scotland and the wider United Kingdom and concluded that, although a large amount of energy is present in these systems, they could sustainably provide approximately 2–8% of Scotland's annual domestic heat demand and 1–5% of the United Kingdom domestic heat demand respectively.

Gluyas et al. (2020) produced a theoretical estimate of the thermal energy storage in United Kingdom mine water systems of 32 TWh based on raising the entire estimated mine water volume by 10˚C. Some of this thermal energy could be provided by harnessing the estimated 46 TWh per annum recyclable heat currently expelled to the atmosphere from a wide range of sources in the United Kingdom, e.g., industrial processing (food, drinks, cement, ceramics), and data centres, to create a geothermal circular heat network (Albert et al., 2020; Gluyas et al., 2020). However, the elevated transmissivities of mine workings mean they are atypical storage complexes because the thermal resource is advected away from the storage site (Fleuchaus et al., 2018; Pellegrini et al., 2019).

This creates a paradox in which mine water geothermal systems could become more sustainable with thermal energy storage (and an important energy store), but some of the key benefits they provide (increased transmissivity and groundwater flux) are not compatible with the traditional sense of underground thermal energy storage.

These benefits do, however, raise the possibility of a novel approach that builds on the observations of García-Gil et al. (2020) and transforms the liability of groundwater flux for thermal energy storage into a key component of a subsurface energy transfer and storage system that we term a "geobattery." At the centre of the concept is the creation of a geothermal circular heat network harnessing recyclable heat to recharge shallow geothermal resources *via* a transmissive subsurface pathway such as legacy mine workings. We focus on ensuring the long-term sustainability of closely spaced BHEs to facilitate the rapid growth of this technology in the United Kingdom to meet its Net Zero ambitions.

In this concept paper we first discuss the heat balance and sustainability of BHEs in a heat-demand dominated climate, before introducing the key components of the geobattery and how strategic recharge could minimize subsurface temperature decline, safeguarding shallow geothermal resources for future generations and avoiding potential negative environmental impacts. We then present a case study near Edinburgh in Scotland, discuss the potential advantages of this technology and the challenges to overcome to maximize its potential.

GEOBATTERY CONCEPT

The Geothermal Heat Balance in Heat-Demand Dominant Climates

The general warmth of the ground is a consequence of the absorption of the heat flux and has been established over thousands of years. The temperature of the near surface is controlled principally by two main sources of heat which have been stored over geological time; solar radiation and the inherent heat flux from the Earth's hot core to the surface. Climate variations clearly have a secondary influence and recently, urban settings are seeing an anthropogenic signal known as the Urban Heat Island Effect (Benz et al., 2015; Rivera et al., 2015; Bayer et al., 2019). The seasonal solar flux controls the temperature of the near surface [~10–20 m depth (Rybach and Sanner, 2000; Rybach and Eugster, 2010)], with warmer seasons seeing heat energy conduct downwards into the near surface, and during colder seasons heat is lost from the surface. Within most of the United Kingdom the overall seasonal heat flux lost from the surface equates to the geothermal heat flux normal to the Earth's surface of ~0.063 W/m^2. This flux is driven by a general geothermal gradient of the order of 3˚C/100 m increase in depth. There are regional variations dependent on local geological and hydrogeological conditions, but the average value given expresses a reasonable initial estimate of the amount of sustainable heat available. On warm sunny days the direct solar insulation (incident radiation) can be as much as 100 W/m^2, but after the various reflection and cooling processes occurring within the upper soil layers, the seasonal average equates to a cyclical amplitude of around 8 W/m^2 for meteorological data from the Glasgow area, but a yearly

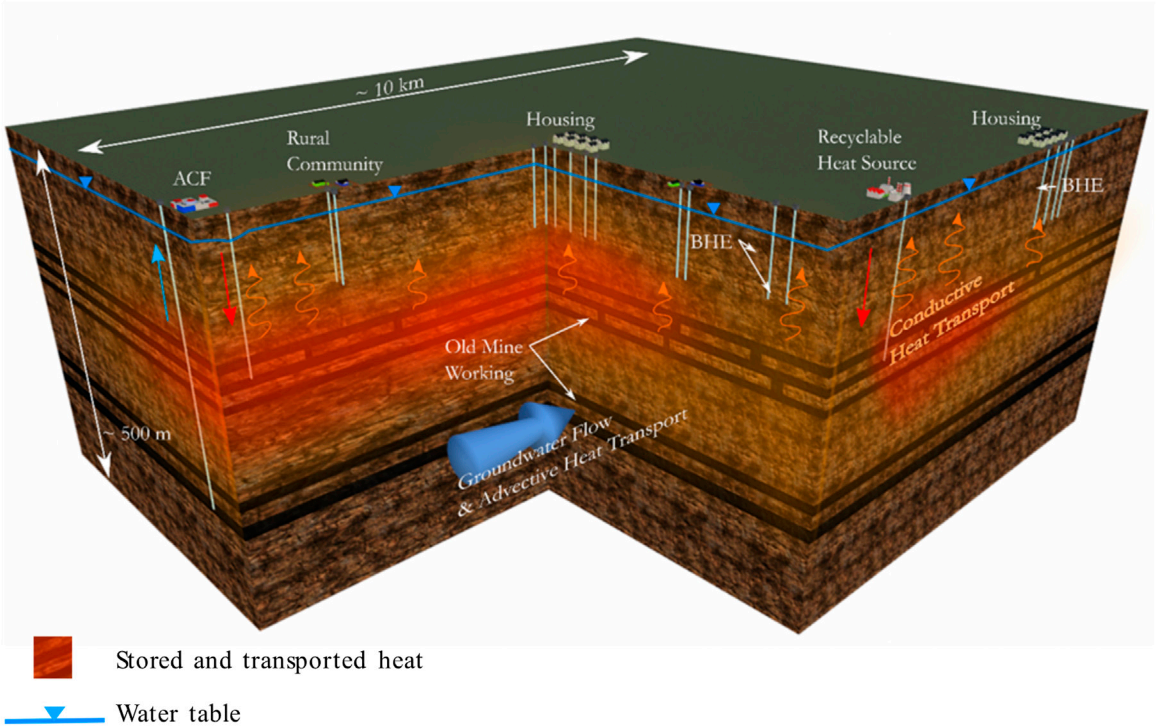

FIGURE 1 | A schematic diagram of the geobattery concept showing the recyclable heat source (Advanced Computing Facility – ACF) that is extracting water to meeting the cooling load, and reinjecting the water into shallow mine workings that act as the transport pathway. Multiple heat users are located down gradient of the heat sources. Heat extraction is via borehole heat exchangers, either in arrays or in small clusters for smaller communities. Heat is advected within the mine workings and conducted towards the shallow geothermal resource to improve sustainability.

balance of −0.063 W/m^2. Significantly more and the surface would be a lot warmer, significantly less and the surface would be a lot cooler. Extraction of heat at a rate greater than 0.063 W/m^2 will lead to ground cooling, as the stored energy is being removed in addition to the sustainable heat flux.

According to the UK's Office of Gas and Electricity Markets (OFGEM), the medium typical domestic consumption value (TDCV) (used here as a proxy for annual heat requirement of a standard house) is of the order of 12,000 kWh/year (OFGEM, 2021b). This equates to a heat demand of ~1.4 kW per house, or ~18 W/m^2 assuming an average property spatial footprint of ~78 m^2 (OFGEM, 2016). Supplying this by capturing only the geothermal heat flux of 0.063 W/m^2 leads to an area (footprint) for sustainable geothermal heat recharge of ~5 United Kingdom acres (~20,000 m^2) per house i.e., >250 times the average property spatial footprint. For this preliminary analysis we do not consider the heat demand of multi-property buildings such as flats in which population density and heat demand may be much higher. Although this analysis considers only conductive recharge, Abesser et al. (2021) and Meng et al. (2019) confirm that, even when considering additional thermal recharge from groundwater flow, increasing the spatial density of ground source heat pumps particularly in urban/semi-urban environments will lead to depletion of the thermal resource and unsustainable extraction of geothermal energy i.e., "heat mining."

The "geobattery" concept therefore aims to harness recycled or renewable heat to thermally recharge this shallow geothermal resource via legacy mine workings or other permeable aquifers and transport it to end users. The aim is to produce a balanced and sustainable low/very-low enthalpy geothermal resource capable of sustaining ultra-low carbon heating to thousands of homes and businesses. A key component of this concept is to use the subsurface as a transport medium from the heat source to a multitude of potential users kilometres down gradient. **Figure 1** shows a conceptual model of the geobattery, connecting heat producers and heat consumers via a subsurface transfer pathway. We identify three key components:

- Readily available heat source(s)
- Suitable subsurface hydrogeology
- Heat users

A geobattery system could harness heat from three different potential heat sources. Firstly, excess heat could be supplied by data centres, waste incineration plants, and other industrial processes in the vicinity of the geobattery, and secondly, primary heat from renewable generation such as solar thermal, a technology that is currently being tested in Bochum, Germany (Hahn et al., 2018) and has recently gained funding from the UKRI (www.ukri.org, 2021). A third potential heat source is from excess renewable electricity that could be converted to heat for storage, particularly as storing heat is cheaper than storing electricity (Elliott, 2016).

In **Figure 1** we have chosen to include a data centre (the Advanced Computing Facility, ACF) as the excess heat source for the geobattery, and represent the subsurface heat transport pathway as an abandoned mine system as we will introduce a case study that targets this heat source and subsurface hydrogeology. Nevertheless, the concept could equally apply to shallow aquifers with significant groundwater fluxes as part of a smart balanced energy network (e.g., Revesz et al., 2020). Abandoned mine workings can sustain significant groundwater fluxes due to the elevated permeabilities created by the extraction of the coal and the subsequence collapse of overlaying strata creating fracture networks in addition to any remaining void space (Younger and Robins, 2002). They are currently being considered as potential renewable heat resources in their own right, and it should be noted that development of a geobattery would not preclude the use of target mines as traditional mine water geothermal heat resources. In fact, a geobattery could be seen as a complementary technology as additional heat injected into the mine would also serve to improve any potential open-loop mine water heat resource. Careful design would be needed to ensure successful integration of the two systems.

Advective heat transport is dependent on a multitude of factors including mine geometry, void geometry and material properties, connectivity, and flow rates (Loredo et al., 2017) and requires site specific investigations to accurately assess. Nevertheless, open mine voids and connected fracture networks represent preferential flow paths in the subsurface and can be expected to facilitate heat transport over kilometres in short timescales (~weeks to months) thus, enabling thermal recharge to the subsurface at a significant distance away from the heat supply source. **Figure 1** shows the advective heat flux transporting heat within the mine workings, raising the temperature of the mine itself and creating an increased geothermal gradient for conductive heat transfer towards the shallow geothermal resource.

For the geobattery concept we have assumed a heat extraction technology of borehole heat exchangers located in the near subsurface. We have focussed on this technology for several reasons. Firstly, BHEs are a commercially mature technology that have seen widespread deployment in other countries and are a suitable for both retrofit in urban areas and primary installations for new developments due to their low areal footprint (Walch et al., 2021). This makes them attractive and a likely technology to be implemented if the United Kingdom shallow geothermal resource is to be rapidly developed. In addition, heat extraction in this way does not involve producing mine water, avoiding all the associated complications that can bring e.g., geochemical precipitates (Bailey et al., 2013; Banks et al., 2019; Banks et al., 2009), uncertainties associated with drilling into mine workings at depth (especially pillar and stall mine workings) (Walls et al., 2021), or the need for a fluid abstraction license (Abesser et al., 2018; Monaghan et al., 2021). However, in the United Kingdom there are currently no regulations or licensing with respect to BHE deployment. This means that a rapid rise in installations could cause significant heat mining, particularly as there is currently no requirement to even register the location of the installation, potentially leading to unintended thermal interactions (Abesser et al., 2018). We therefore focus on BHEs to investigate whether sustainable geothermal utilization could be achieved with this "off-the-shelf" technology in heat-demand dominated climates when combined with a geobattery.

A Generic Example

To demonstrate the sustainability of heat extraction from a BHE with and without a geobattery, we develop a 2D finite element fluid flow and heat transport solution in OpenGeoSys (Kolditz et al., 2012) to simulate thermal drawdown through time considering recharge from a mine water system. These results are then used to determine the benefits of a geobattery system through improving the sustainability of the resource by ensuring its availability for future generations. The model consists of 4 boreholes located 30 m apart at 40–90 m depth with continuous extraction of −1,500 W for a period of 40 years (to match the average household heat demand described earlier). This duration is longer than the typical 20–30 years design lifetime for a heat demand dominated BHE, and also does not consider how heat demand might vary in the future, but is used to evidence the potential advantages of a geobattery system.

For the reference model we simulate a mine that is situated 30 m directly below the BHEs. The mine is modelled with a porosity of 10%, a specific heat capacity of 1,200 J/kgK, and a thermal conductivity of 0.31 W/mK within the ranges reported in the literature (Herrin and Demirig, 1996; Waples and Waples, 2004). The surrounding rock mass is assumed to consist of Carboniferous coal measures which are known to be very heterogeneous and heavily deformed such that they may not be horizontally bedded at a given site. We therefore calculate an effective thermal conductivity for the Carboniferous sequence from the Lower limestone to the Scottish Coal Measures both parallel and perpendicular to the stratigraphic units based on effective thermal conductivity data presented by Busby (2019). These values are 2.217 W/mK and 2.164 W/mK, respectively. For this simplified model we take a rounded average of 2.2 W/mK and 10% porosity.

Thermal diffusivity (m^2/s) for the saturated medium is calculated within the model from:

$$\alpha = \frac{\lambda_r (1 - n) + \lambda_w n}{\rho_r c_r (1 - n) + \rho_w c_w n} \tag{1}$$

where c is the specific heat capacity (J/kgK), λ is the thermal conductivity (W/mK), ρ is the density (kg/m^3), and n is the porosity (−). The subscripts w and r refer to the water and rock respectively. Here we assume a density of 1,000 kg/m^3 for the fluid and an isotropic density of 2,500 kg/m^3 for the rock, a fluid

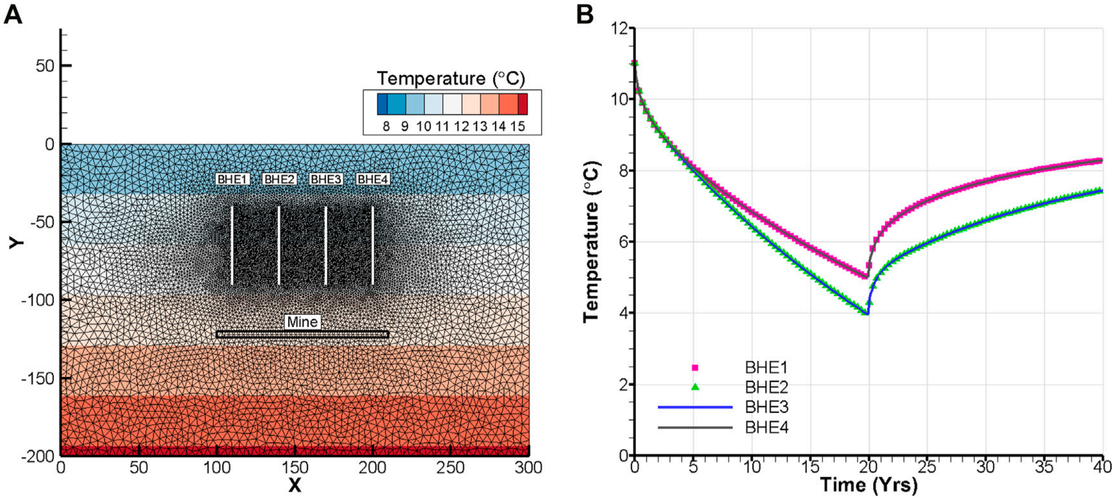

FIGURE 2 | Model configuration **(A)** and BHE temperatures for the BHE array for a 20 years operation period and 20 years recovery **(B)**. Temperatures are calculated as the average over the BHE length. The symmetry of the generic model means that BHE1 and 4, and BHE2 and 3 produce the same results. Thermal recovery is initially rapid after the BHEs are switched off due to the high thermal gradients in the vicinity of the BHE, but the rate of recovery gradually reduces through time and full recovery is not achieved after 20 years.

thermal conductivity of 0.6 W/mK, and specific heat capacity of 4184 J/kgK and 1,200 J/kgK for the water and rock respectively. This results in a thermal diffusivity of 6.54 × 10^{-7} m^2/s.

Each borehole extracts heat for a single house which is assumed to have a total area available for heat extraction of 900 m^2, corresponding to an area 30 m thick, 15 m either side of the BHE. This estimate aims to be a middle ground between semi-urban areas where spacing may be closer (e.g., Signorelli et al. (2005) simulate 7.5 m spacing and Walch et al. (2021) consider 5 m spacing for longer BHEs), and rural locations where BHE spacing could be much larger.

Typical design lifetimes of BHEs are in the region of 20–30 years, after which the BHE may be turned off to allow ground temperatures to recover through natural thermal recharge. **Figure 2A** shows the BHE configuration in relation to the mine and **Figure 2B** shows the BHE temperatures, calculated as the mean over the BHE length, for 20 years operation and 20 years recharge. The results show a thermal drawdown of 7.08°C for BHE2 and 3, and 6.05°C for BHE1 and BHE4. The difference is caused by the larger volume for thermal recharge accessed by BHE1 and BHE4 that are on the edge of the array. After the BHE extraction is stopped, temperature recovery is initially very rapid due to higher thermal gradients in the vicinity of the BHE but the rate then gradually reduces through time. After 20 years recovery in our model there is still a thermal deficit of 2.73°C and 3.58°C for BHEs 1 and 4, and BHE2 and 3 respectively. This shows that BHEs are a renewable technology but, under these conditions they cannot be considered operationally sustainable because they require turning off to recover the resource for future generations.

We consider thermal recharge from a geobattery concept to compare the sustainability of continuous extraction from a BHE array over a 40 years period with and without artificial thermal recharge. **Figure 3** presents the temperature change results from two scenarios—with and without geobattery recharge for 40 years. In a first scenario, heat recharge is only provided through a constant geothermal heat flux of 0.063 W/m^2 entering the model at the bottom and coming out at the surface (i.e., yearly balance of cyclical solar flux), maintaining a natural geothermal gradient of 0.031°C/km. In a second scenario, a geobattery system is modelled as a constant 30°C heat source within a mine gallery located below the BHEs. In this scenario, heat extraction from the BHEs (that have an initial temperature of 11.02°C calculated from the average over the length of the BHE) starts simultaneously with the storage of heat within the mine gallery, where heat is assumed to be uniformly distributed within the whole gallery (i.e., ignoring the effects of heat advection within the mine). Over time, the diffusion of heat from the mine towards the borehole permits, in the absence of groundwater flow, the provision of additional heat recharge to the heat extraction area. The amplitude of the heat recharge to the boreholes therefore depends on several parameters, such as the distance between the geobattery to the heat extraction system, any time lag between the onset of heat storage and heat extraction from the BHEs, the thermal diffusivity of the ground, and on the presence of advective heat transfers induced by regional groundwater flow.

The temperature time-series displayed in **Figure 4A** presents the average temperature over the borehole length in BHE2 and indicates that in the considered scenario, the effects of heat storage in the mine reach the central BHEs after ~2.5 years. After 20 years of operation, the presence of a geobattery system reduces the total temperature drawdown ΔT from −7.06°C to −4.71°C at BHE2 and 3 and from −6.02°C to −4.72°C at BHE1 and 4, relative to a scenario without the geobattery. After 40 years thermal drawdown in the non-

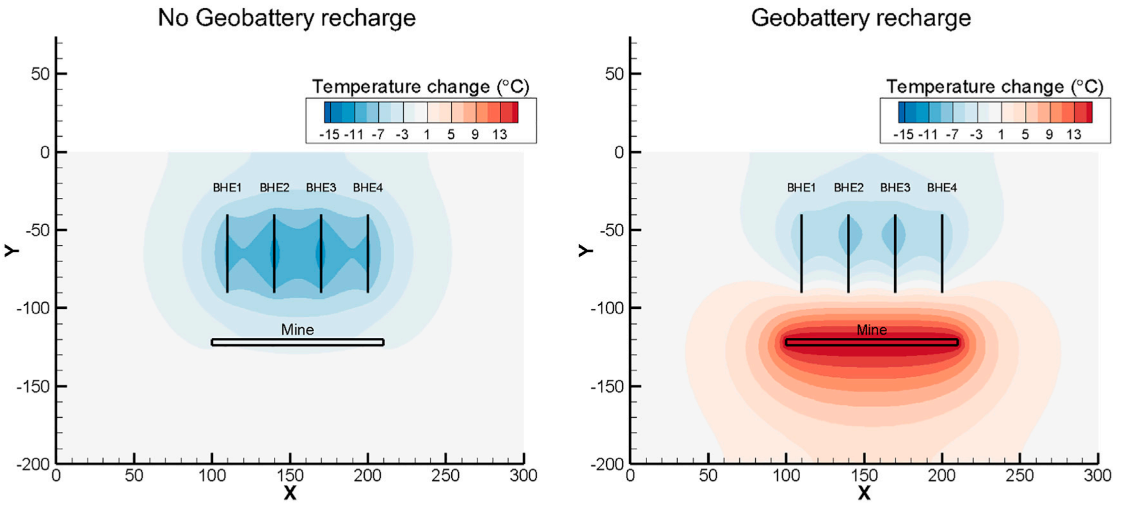

FIGURE 3 | Temperature footprint induced by constant heat extraction from 4 BHEs at a constant rate of –1,500 W for 40 years in a scenario without geobattery **(A)** and with geobattery **(B)**, corresponding to a 30°C heat store in a mine gallery.

geobattery model produces potentially uneconomic temperatures of 0.37°C in BHE2 and 3, and 2.25°C in BHE1 and 4 (ΔT of 10.65°C and 9.77°C respectively). However, thermal recharge from the geobattery limits thermal drawdown resulting in temperatures of 5.07°C in BHE2 and 3, and 6.09°C in BHE1 and 4 (ΔT of 6.95°C and 5.93°C respectively).

Thermal drawdown is largest at the two central BHEs because the volume available for heat extraction is limited by the presence of the other BHEs. BHE1 and BHE4 have additional recharge from storage from the surrounding rock mass. The reduced thermal drawdown of the geobattery model indicates that the presence of a constant heat store in the vicinity of BHEs increases the longevity of heat extraction technologies by creating a sustainable heat resource in the ground.

Quantifying the Benefits of the Geobattery

Figure 4A shows how the geobattery modelled in the example above results in economically viable ground temperatures even after 40 years of operation. It highlights how the use of ground source heat pumps without the geobattery might lead to very low temperatures (~1°C in our example after 40 years). These temperatures could result in environmental issues, in extreme cases leading to a freezing of the ground in the vicinity of the BHE, which could be considered an ultimate operational limit for BHEs. These results also compare favorably to the limited lifetime model of the BHEs presented in **Figure 2**, ensuring that temperatures in BHE2 after 40 years of operation are higher than after 20 years of operation without a geobattery. Although these results indicate clear benefits of improving the longevity and sustainability of the resource as well as reducing the impact of thermal interferences, it is important to develop further quantitative metrics for the evaluation of the geobattery for the user i.e., the benefits over and above those already presented by BHE-supplied heat pump systems.

We perform an analysis using the temperature from BHE2 modelled above as input to the heat pump system. The target heating system temperature is assumed to be 78°C, which is recommended for central heating systems with gas boilers in the United Kingdom. However, we also include a sensitivity analysis with the heating system temperature ranging from 20°C to 80°C to cover most of the end use cases depending on the building stock it is used to heat e.g. in a modern well-insulated house with underfloor heating the heat pump can supply heat at a lower temperature (and therefore higher coefficient of performance (COP)) than a poorly insulated house that uses wall-mounted radiators to distribute heat. We calculate the maximum heat pump COP using the inverse of the Carnot Efficiency (**Eqs 2**, **3**).

$$COP_{ideal} = \frac{1}{\eta_{th,rev}} \tag{2}$$

where $\eta_{th,rev}$ is the Carnot Efficiency (Çengel and Boles, 2011)

$$\eta_{th,rev} = 1 - \frac{T_c}{T_h} \tag{3}$$

where T_c is the temperature of the cool reservoir and T_h is the temperature of the hot reservoir. We assume that the ratio of the theoretical maximum COP to actual COP is 50% (η). This gives us the estimated actual COP for our heat pump (**Eq. 4**).

$$COP_{actual} = \eta COP_{ideal} \tag{4}$$

Figure 4B indicates that the amount of work required from the compressor of the heat-pump supplied by BHE2 (centred above the recharged mine) will decrease over time compared with a system without the geobattery. In the case studied, after 40 years, the geobattery could reduce the amount of work required by 10% compared with a user of a heat pump in an area not served by the geobattery. These savings are likely to be lower in some of the other wells modelled or in cases where the BHE is not directly above the heat source, but these differences are a function of the distance of the BHE from

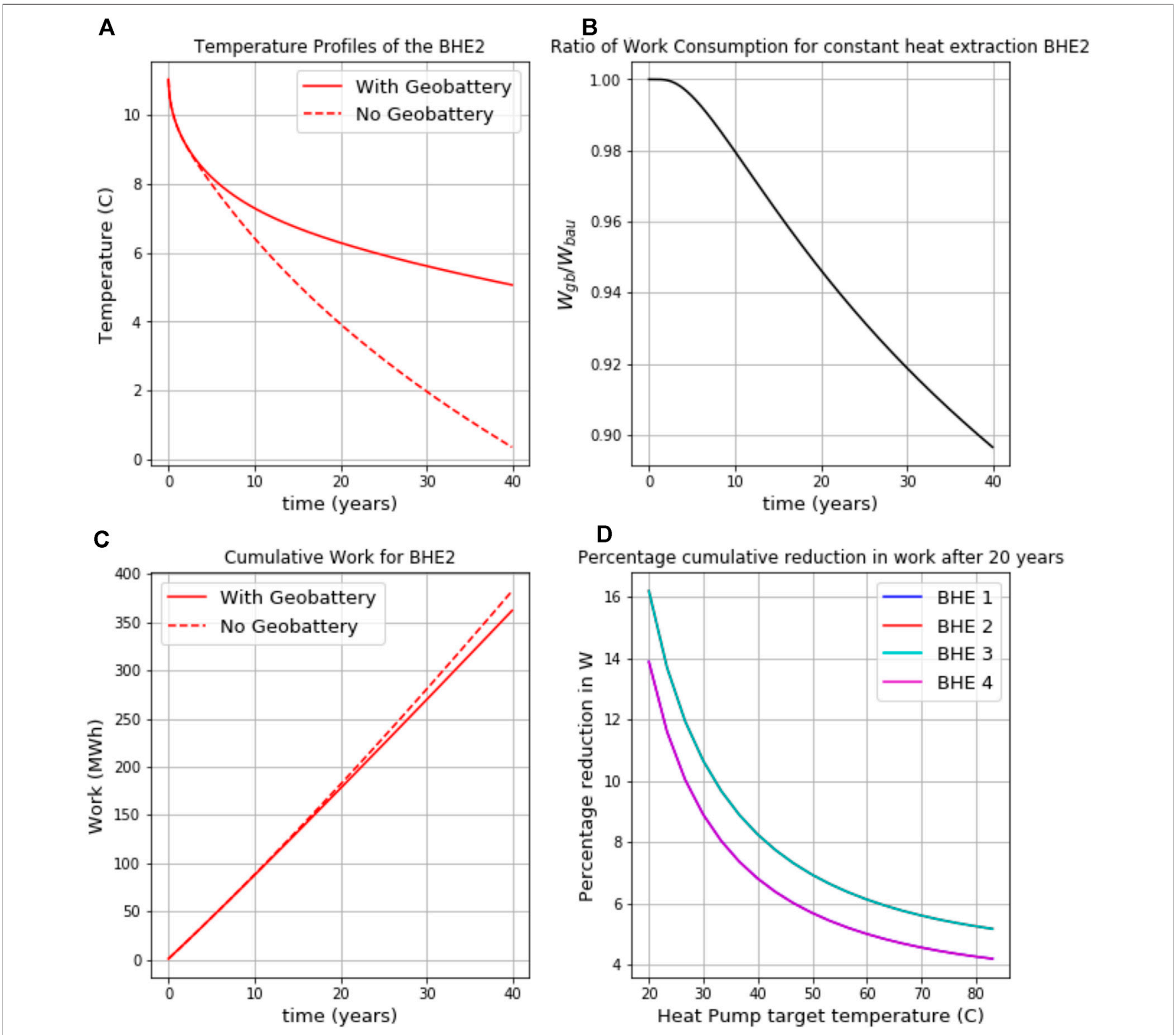

FIGURE 4 | Summary of geobattery benefit analysis. **(A)** illustrates the change in BHE temperature over 40 years with and without the geobattery providing heat recharge. **(B)** illustrates the ratio of compressor work required by the heat-pump to meet the target temperature of 78°C, with and without the geobattery. Temperature inputs from the first top-left graph are used. **(C)** uses the work consumption of a heat pump with and without geobattery to determine the cumulative use over 40 years. This assumes the 1.5 kW heat production from the BHE as per the modelling example above. **(D)** the sensitivity analysis indicating the percentage reduction in the cumulative work consumption after 40 years of use for different heating system temperatures, and for each of the four boreholes considered in the model.

the recharged mine, which could be carefully considered when designing an integrated system.

The benefits of the geobattery over the lifetime of the project in terms of cumulative work by the heat pump are presented in **Figure 4C**. Indeed it is important to understand what benefits are to be had when considering the entire period of operation of the system. The graph indicates the cumulative work required by the compressor over the lifetime of the system i.e., 40 years. We see that over time the savings in work required by the heat replenishment from the geobattery will start to add up. We note that this cumulative reduction in work saved is not drastic and that would not lead to significant cost savings to the end user. Although the geobattery provides means of maintaining the original efficiency of the system its true value lies in maintaining the ground temperature at environmentally sustainable levels, enabling the continued supply of heat after 40 years (or more) compared with the limited lifetime model portrayed by **Figure 2**.

The final graph in **Figure 4D** shows how much work has been saved cumulatively after 40 years of operation for all four

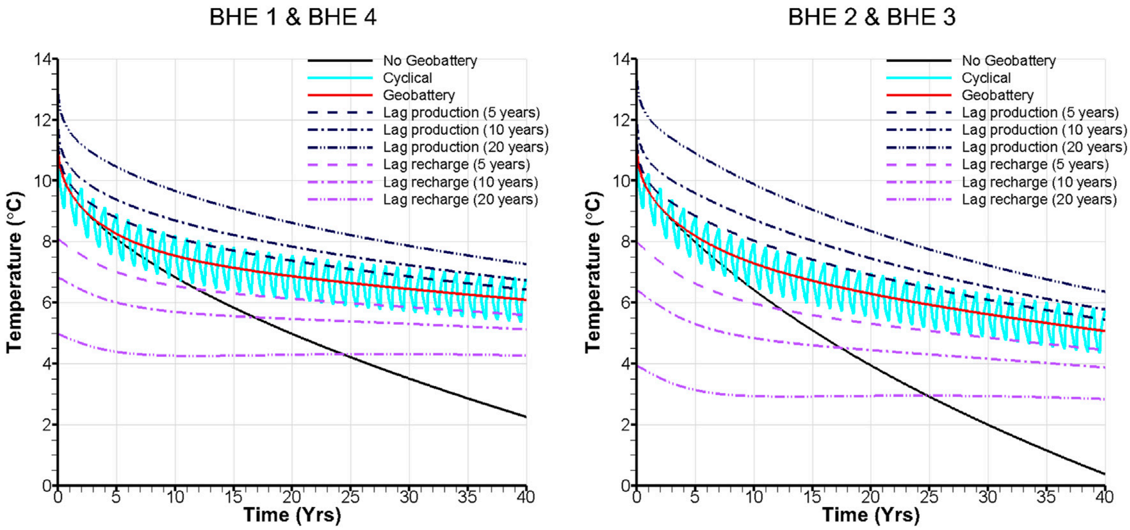

FIGURE 5 | Modelled temperatures at the BHEs for different scenarios of geobattery development. In the reference model the BHEs are arranged symmetrically above the mine so BHE1 and 4, and BHE2 and 3 have the same response. The solid black line represents the base reference model with no geobattery, while the red line includes thermal recharge from a geobattery. The dashed dark blue lines represent the pre-heating models and the dashed purple lines represent the pre-extraction models. Also shown is the sinusoidal cyclic extraction model (light blue) verifying the annual mean heat extraction approach.

BHEs considered in the model above. We indicate how the system would perform as a function of the central heating system temperature that the heat pump has to deliver. For reference, current advice in the United Kingdom for a boiler central heating system is to set the temperature at 78°C. However, modern heat pump installations such as the ones installed in new builds could operate at lower temperatures, for example 50°C. In such cases, as much as 7% of the total work required over 40 years of operations could be saved by the user. This is particularly important in the context of reducing demand on a renewables dominated electricity grid and also achieving Net Zero because a major way to reduce carbon emissions is by reducing energy usage.

Non-Concurrent Geobattery Effects

In our model we simulate the annual heat demand of a typical UK house over a year supplied by constant heat extraction through the year. In reality, BHEs thermal loads vary on the daily scale and by the seasons (Rybach and Eugster, 2010; Walch et al., 2021). As we are interested in the long-term effects of heat extraction on subsurface temperatures we also consider a scenario with sinusoidal heat loads (similar to Walch et al. (2021)) based on annual heating cycles of 8 months heating, 4 months recharge. **Figure 5** shows results for BHE1 and 4 (left), and BHE2 and 3 (right) of the reference model and multiple non-concurrent geobattery scenarios discussed later in this section. It can be observed (light blue line in **Figure 5**) that the cyclical heat production with intermittent recharge causes an annual variation in subsurface temperatures, but that these do not alter the overall impact of recharge from the geobattery (i.e., compared with the reference model with geobattery—red line in **Figure 5**).

Banks, (2016) and Banks et al. (2019) indicate that the timing of a mine water heat development with respect to the infrastructure development (new houses/municipal buildings etc.) is of vital importance to the successful development of the resource. There may be a mine water heat resource available but it needs to be considered right at the start of a new development plan e.g., Seaham Garden Village close to Dawdon mine water treatment scheme (The Coal Authority, 2021). The geobattery concept aims to supply heat to shallow geothermal resources at a much larger scale than a single development and as such will not be developed at the same time as all infrastructure development. To determine the impact of temporal offset between geobattery development and BHE installation we use our generic model to investigate two further scenarios—one in which the housing or infrastructure development occurs before the geobattery is developed (dashed purple lines in **Figure 5**), and one in which the development occurs after the geobattery is fully operational (dashed dark blue lines in **Figure 5**). The first scenario is applicable to a situation where BHEs have been installed as part of a rapid drive for decarbonisation of heat while the geobattery is developed to support this, and the second scenario is representative of new developments built to access the sustainable heat supply provided by the geobattery in a similar fashion to the inward investment and development at Heerlen, Netherlands (Verhoeven et al., 2014). For each scenario, three different time lags have been considered—5, 10, and 20 years before/after the geobattery development.

Figure 5 shows the temperatures at all BHEs for each of the considered scenarios; the reference model with no geobattery, the reference model with geobattery including annual average and cyclic heat demand, pre-heating of 5, 10, 20 years, and pre-geobattery BHE extraction of 5,10, 20 years. The geobattery clearly has a beneficial effect on the BHE temperature but this varies depending on the time of the geobattery development with respect to BHE installation and the relative location of the BHEs.

For the reference case with no thermal recharge from the geobattery (black lines on **Figure 5**) the BHE temperature continues to decline over the 40 year period until reaching 2.25°C in BHE1 and BHE4, and 0.37°C in BHE2 and BHE3. Thermal decline is slowed down after ~2.5 years if the geobattery is concurrent with the BHE development (red lines on **Figure 5**). For all BHEs the geobattery tends towards steady temperatures sometime after the 40 years period modelled here, with greater thermal drawdown related to the BHE position within the array e.g., 40 years temperatures in BHE 1 and 4 are ~6°C and ~5°C in BHE2 and 3. The continued, but very gradual decline in temperatures suggest an almost balanced system in which the BHEs are extracting the close to the same energy as can be supplied by the geobattery. As might be expected the BHEs on the edge of the array see a reduced rate of decline as they benefit from a larger potential thermal resource volume. It should be noted that the model presented here is a simplified generic model to demonstrate the potential of the geobattery concept. Additional factors such as different injection temperature or different thermal diffusivity will influence the thermal recharge capacity of the geobattery.

The scenario that represents a later development after the geobattery is operational (pre-heating) (dashed dark blue lines in **Figure 5**) results in elevated starting temperatures for the BHE installation, which then follow a similar trend of steep initial reduction in temperature before approaching a steady state. The two main parameters controlling BHE temperatures are the length of pre-heating and the proximity to the recharge location i.e., the longer the pre-heating stage and the more central the BHE over the mine, the higher the initial temperature. However, lower temperatures after 40 years of operation for the central BHEs (2 and 3) compared with the edge BHEs (1 and 4) indicate that, although the geobattery recharge improves sustainability, it does not fully mitigate the impact of thermal interference.

For the case in which the BHEs are installed prior to geobattery operations (dashed purple lines in **Figure 5**) the results indicate that the geobattery is able to limit further temperature decline in all BHEs. For all BHEs, there is an initial continued decline in temperature as the heat from the mine is conducted towards the BHE. As the effects of heat injection from the mine propagates, the rate in temperature decline reduces, especially in BHE1 and 4. The longer the BHE extraction period pre-geobattery, the lower the final temperature, but the more steady the modelled temperature. This is because larger thermal gradients between the mine and the BHE result in a more significant contribution to the BHE temperatures. As such, the 20 years lag model indicates that for all BHEs, subsurface temperatures could be stabilised over the modelled time duration, albeit at a lower temperature than other modelled scenarios. For all scenarios with the geobattery the general trend indicates that the long-term BHE temperatures converge towards a steady value implying that a geobattery could ensure sustainability of the shallow geothermal resource for future generations.

The "Lag recharge" model results are further visualized as temperature recovery profiles in **Figure 6** to demonstrate the potential for the geobattery technology to act as a mitigation technology if BHE installations cause significant heat mining in areas where a geobattery could be developed.

Thermal recovery is defined as the ratio of BHE temperature at a given time compared with the initial BHE average temperature (11.02°C). Our modelling indicates that the geobattery offers considerable benefit in all cases by reaching long-term stable BHE temperatures. As might be expected, the sooner thermal recharge occurs the greater the operational temperature, but there is a larger relative benefit of thermal recharge with increasing time lag between heat extraction and recharge.

Additional Scenario Impacts

An important consideration is that the thermal energy from a recyclable source such as the Advanced Computing Facility (ACF) may not be consistent due to different usage patterns and routine maintenance requirements, which is one reason that this potential thermal resource is not suitable for direct usage. Reduced usage of the ACF will influence the rate of fluid injection but not the temperature, while maintenance could stop injection altogether. To assess the impact of a worst-case maintenance scenario on geobattery performance, we consider the reference case and include a period of 1 month each year in which the mine temperature is reduced to the original ambient temperature. This could be considered a worst-case scenario in which background groundwater flow instantly cools the mine back to initial conditions. **Figure 7** shows that there is a minor reduction in the thermal recharge for each BHE resulting in a reduction in BHE temperature after 40 years of ~0.5°C and 0.7°C for the lateral and central BHEs respectively and that, unsurprisingly, the impact is greatest at the BHE directly above the thermal recharge/discharge. It does not significantly affect the long-term sustainability of the BHEs, however, when considered in this context. A further scenario of interest, given the complexity of mine water flow and potential heat transport, is the impact of the spatial location of the BHE with respect to the heat source i.e., the mine. **Figure 8** shows the impact of the geobattery on BHE temperatures when the mine is laterally offset from the array. In this model BHE4 is closest to the mine and is positioned directly above it, and BHE1 is the furthest from the mine, offset by a distance of 90 m. In this case the geobattery offers a decrease in thermal drawdown for each of the BHEs but the impact is minor for BHEs that are offset from thermal recharge location.

CASE STUDY—MIDLOTHIAN, SCOTLAND

In our generic model, we demonstrate the clear potential to ensure sustainability of the shallow geothermal resource, as

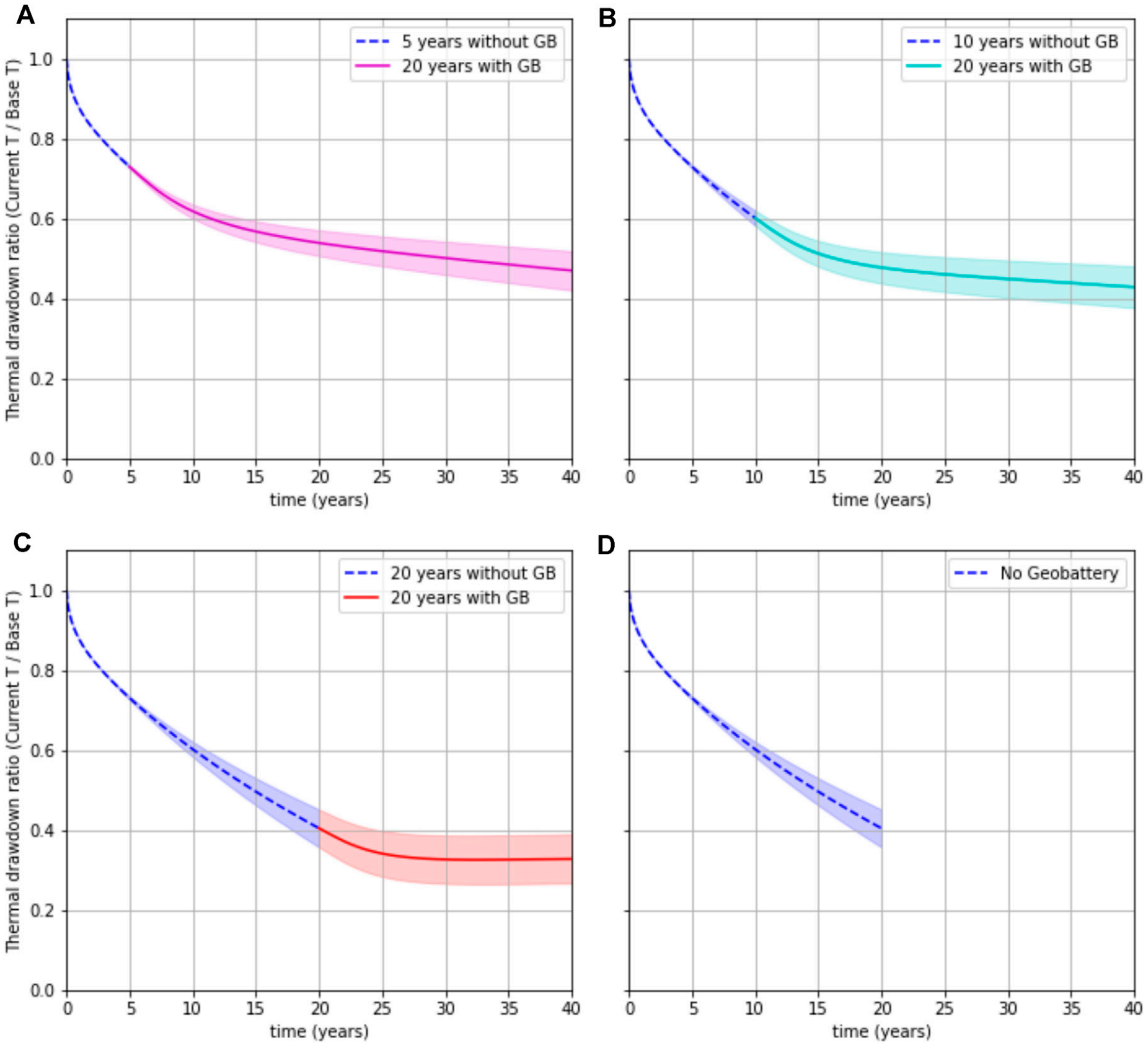

FIGURE 6 | Analysis of the recharge potential to BHEs installed at different times prior to 20 years of geobattery operation. **(A)** 5 years of extraction, **(B)** 10 years of extraction, **(C)** 20 years of extraction, **(D)** no further extraction—BHEs in this configuration are not sustainable. The envelope of the results for all four BHEs are represented by the shaded areas with BHE1 and 4 (at the edge of the array) defining the top boundary and BHE2 and 3 (in the centre of the array) delimiting the lower boundary.

exploited by BHEs, through thermal recharge of an abandoned mine. Here we show the concurrence of the three main geobattery components at a case study location in Midlothian, Scotland (**Figure 9**), bringing together potential recyclable heat source(s), connected abandoned mine workings, and the potential users. **Figure 9** shows the location of the Midlothian Coalfield mine workings in Scotland (hashed polygons in **Figure 9**) with the case study mine workings highlighted in red (geobattery) and purple (coolth store). The base map shows the current population centres that a potential geobattery could serve and also highlights the Shawfair development (green polygon), which is another potential large development in the area located above mine workings where a geobattery could also be developed.

Heat Producers

A key component of the geobattery concept is a readily available and easily captured source of recyclable or renewable heat. In the case of a data centre, cooling is required to keep hardware operating within an optimum temperature range. Today in most data centres, IT hardware is both direct water cooled (*via* water directly traversing the computer motherboards), or air cooled with the expelled warm air being cooled through Computer Room Air Conditioning (CRAC) units. In both cases the product is warm water which is cooled largely by air-cooled radiators (some use an adiabatic process) on the roof of the data centre with some mechanical water chilling on the warmest days. However, this cooling demand may be met by a water-cooled system which could be fed by abstraction from a coolth store (in this case deeper, disconnected mine workings). The heat exchange with

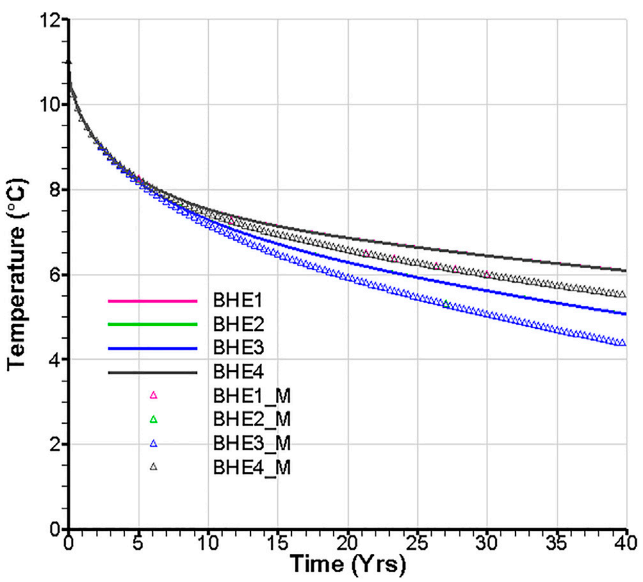

FIGURE 7 | Comparison between temperatures at BHE 1-4 considering constant thermal recharge from a geobattery (solid lines) and thermal recharge considering 1 month off for routine maintenance (triangles).

the data centre warms the mine water which is then reinjected into the shallow subsurface heat transport pathway.

For this case study, we have identified a recyclable heat source to be the Advanced Computing Facility (ACF) at Easter Bush, near Edinburgh. Currently, the ACF uses a closed-loop water-cooling system to ensure a constant working temperature for the data centre. The ACF is split into four computer rooms, each hosting equipment with slightly different thermal and cooling characteristics. For many years, inlet water temperatures on supercomputer systems were around 15˚C with outlet water temperatures of around 25˚C. Modern supercomputing technology allows systems to run at much higher inlet temperatures. Some of the systems at the ACF today run at an inlet temperature of 25˚C and we expect the next generation of system—an Exascale supercomputer—to run at an inlet temperature of 32˚C. Outlet water temperature is likely to be around 45˚C. Currently this excess heat is released to the atmosphere such that the water re-enters the cooling system at anything between 16˚C and 25˚C. The current capacity of the ACF requires a 3 MW cooling facility but is expanding to around 6 MW by the end of 2021 i.e., 6 MW of heat will be released to the atmosphere. With future development of computational facilities this could significantly increase up to 30–35 MW. An Exascale supercomputer service is expected to require 25–30 MW and existing equipment will require around 5 MW. Available power to the ACF site by the end of 2021 will be 38 MW.

Considering a modern-day cooling system with a ΔT of 15˚C, the maximum heat production/cooling system operation of the ACF (6 MW at end 2021), requires a flow rate of approximately 85 L/s. The geobattery concept could be achieved using heat exchangers between the ACF facility and the mine water facility such that the expected 45˚C water at the outlet of the cooling system exchanges heat with the mine water facility rather than the atmosphere. Mine water temperatures measured in Bilston Glen Colliery measured at 670 m depth a 15˚C (Gillespie et al., 2013). Therefore, removing 15˚C of heat (45˚C to ~30˚C) from the cooling system would raise the temperature of this mine water to 30˚C at reinjection (used as the estimated mine temperature in our modelling).

If we take the OFGEM estimated heat demand for an average house in the United Kingdom (1.4 kW), 6 MW of

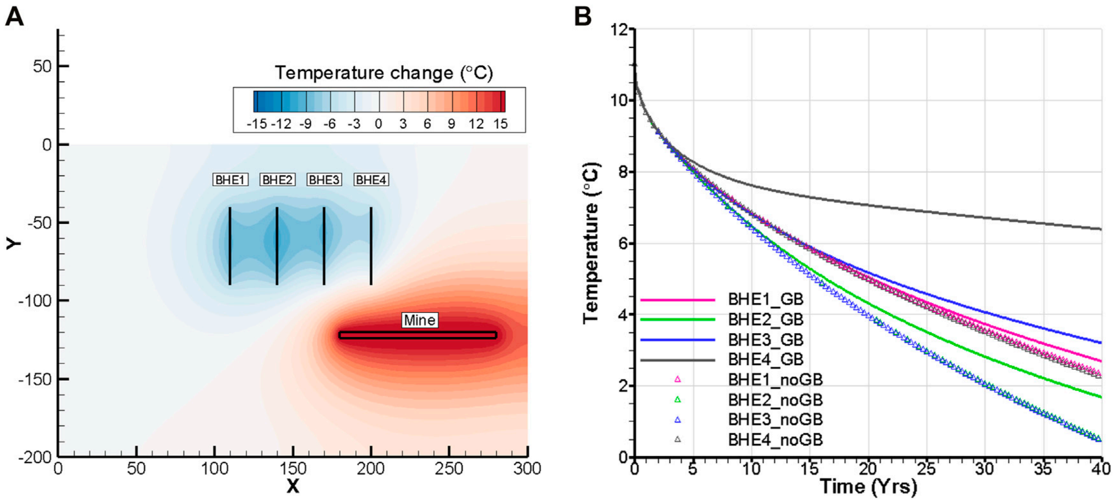

FIGURE 8 | Temperature change distribution **(A)** and comparison of BHE temperatures with the geobattery (solid lines) and without (triangles) when the BHE array is offset from the mine **(B)**. BHE4 is directly above the mine and BHE1 is offset from the mine by 90 m. The positive effect of the geobattery is still observed for BHE4 but the impact is reduced depending on BHE offset. Note, the colour-scale on the cross section is temperature change but the *y*-axis on the graph is modelled temperature.

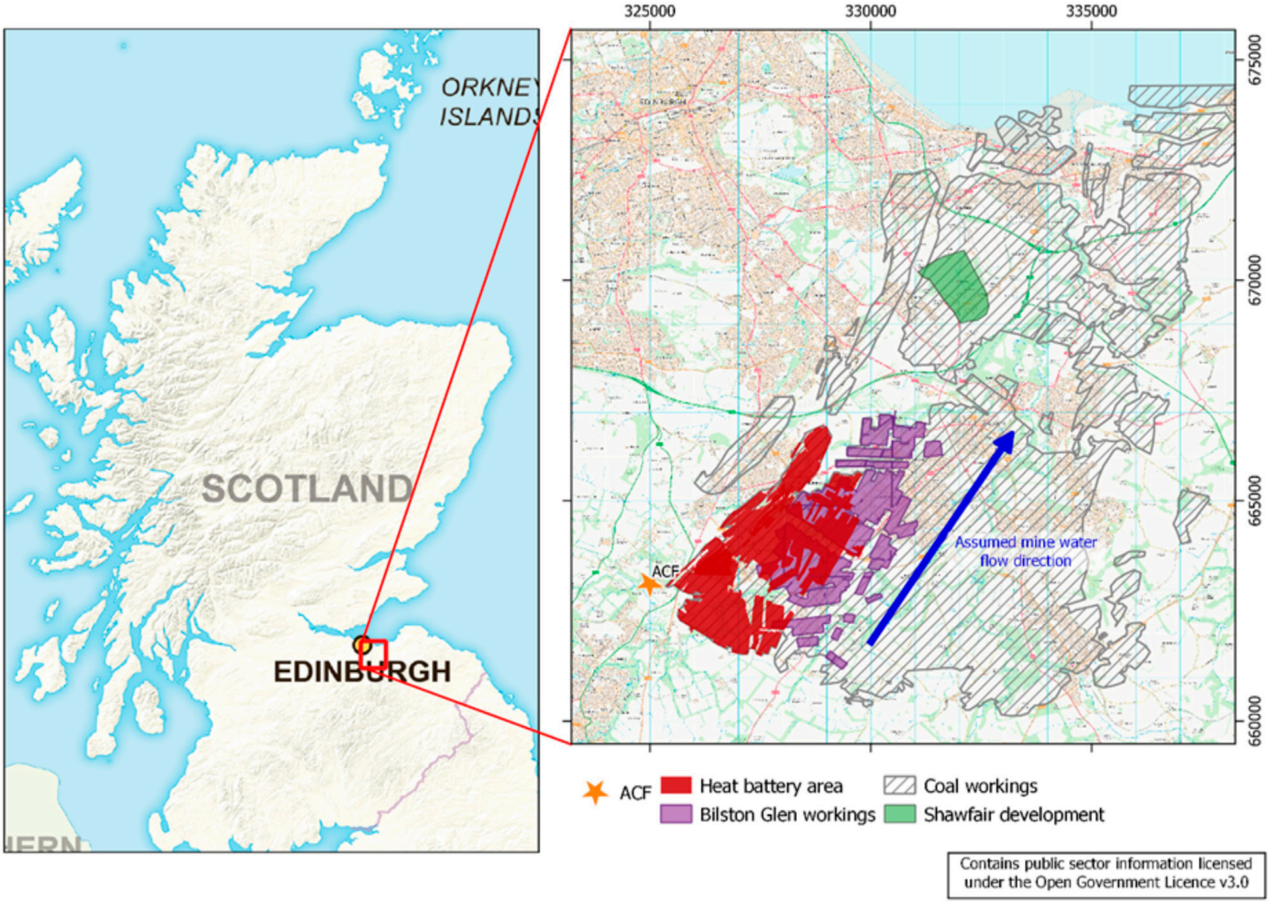

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FIGURE 9 | Maps showing the case study location. The geobattery area (red) covers mine workings from Roslin, Burghlee and Ramsay collieries. The Bilston Glen mine workings (purple) are shown separately as the potential coolth resource. The Shawfair development (green) is shown for reference of a further potential location for a geobattery.

excess heat could supply over 4,250 homes. Future expansion of high performance computing technology and capacity combined with expected reductions in heat demand through building fabric improvement, suggests that data centres could be a significant future heat resource. However, the ACF cooling demand is not constant and as such, underground thermal energy storage offers a solution to smooth out the peaks and troughs of heat generation. Although we have here focussed on an existing and readily available source of excess heat, we envisage that the geobattery concept would eventually provide opportunities for multiple low temperature heat producers, e.g., solar thermal plants, to connect into the system, much in the same way that has happened at Heerlen, Netherlands (Verhoeven et al., 2014). Further possible geobattery sites are expected to exist where heat sources are co-located with abandoned coal mine workings.

Suitable Subsurface Hydrogeology

Typically, energy storage is based on the principal that one is able to recover a high percentage of the energy that you store, whether that is in the form of compressed air, methane, hydrogen, or heat (e.g., Aquifer Thermal Energy Storage). It is generally desirable in underground energy storage systems therefore, for the injected energy to remain in close proximity to the injection site (or at least the extraction site if they are not co-located), so significant subsurface groundwater flux is typically undesirable (Pellegrini et al., 2019). However, the geobattery concept aims to transform the potential disadvantage of natural groundwater flux into a key advantage. By targeting a hydrogeological system with elevated permeability pathways e.g., a legacy coal mine, the background groundwater/mine water flux can be exploited to transport the injected heat to downstream users. We propose that the recycled heat is injected into the subsurface geobattery via a series of injection boreholes within main spine roads, which are underground roadways connecting mine workings that are expected to remain as an open void.

All energy transport, e.g., the gas network or electricity grid, inevitably results in losses from the transport system, but in this case the heat losses to the subsurface environment are part of the design—they represent energy stored that recharges BHEs. In essence, 'losses' from the transport system charge the geobattery.

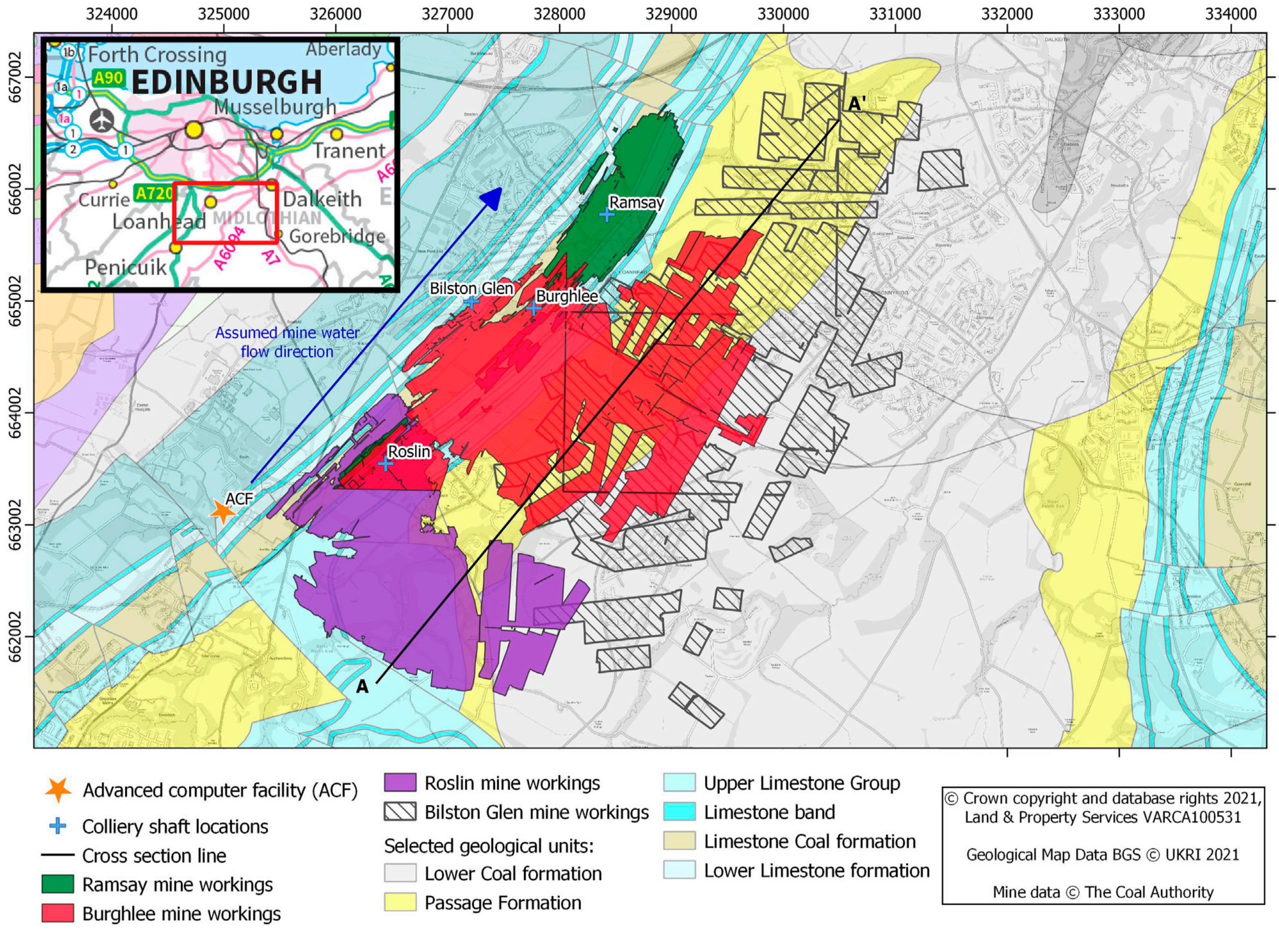

FIGURE 10 | Outlines of worked coal seams and shaft locations in the connected Ramsay, Burghlee, and Roslin mine workings. The deeper, disconnected Bilston Glen mine workings are shown in the hashed polygons. The estimated mine water flow direction is shown by the blue arrow and the NE-SW trending black line is the location of the schematic cross-section in **Figure 11**, chosen to be parallel to the flow direction.

Key to any mine water geothermal scheme is a good understanding of the subsurface in order to characterise potential flow paths. Here we have used openly available information; subsequent feasibility investigations would require detailed study of mine plans. The work below aims to demonstrate the potential for a geobattery development at this site.

The ACF excess heat source described above is located approximately 400 m southwest of historical shallow coal mine workings, part of a sequence of coals mined from the Burghlee, Ramsay and Roslin collieries (**Figure 10**). Mining began at these three collieries in the late 1800s/early 1900s and coal was extracted from the Upper and Lower limestone and limestone coal formations, all part of the Clackmannanshire Group. Mining occurred in numerous coal seams in these formations, with the main coal seams mined shown in stratigraphic order in **Table 1**. The Clackmannanshire Group comprises cyclical sequences of sandstone and siltstone beds interbedded with mudstones, limestones and coals (Ó Dochartaigh et al., 2015). The group is part of a large syncline creating a SW-NE trending valley stretching to the Firth of Forth. The Roslin, Burghlee and Ramsay collieries are located on the western side of the syncline and the worked coal seams dip steeply to the southeast, with an average dip of 46°.

The mines were closed in the late 1960s following nationalisation and a new "super-pit" at Bilston Glen took over coal production. Bilston Glen targeted deeper coals with shafts significantly deeper than the shafts at Burghlee, Ramsay and Roslin (**Table 2**). While the shallower mine workings are known to be interconnected and can be counted as a single unit, there is no evidence that they are connected hydrogeologically to the deeper mine workings from Bilston Glen. The indicative extent of mine workings from all four collieries, along the cross-section line in **Figure 10**, are shown in **Figure 11**. The depths are based on data available along the cross-section, but as the coal seams are also dipping to the south-east there will be deeper mine workings located away from the cross section. Data available indicates that workings in the Great coal seam from Burghlee and Bilston Glen are separated approximately 200 m laterally in this location. Vertically, coal seam levels in the Great coal seam

TABLE 1 | Main coal seams mined from Burghlee, Ramsay and Roslin collieries in Midlothian in the south east of Scotland, including alternative seam name.

Formation	Seam name	Alternative seam names
Upper limestone	South Parrot Splint	
Limestone coal	Mavis	Rumbles, parrot, gas
	Great	Great mid, great bottom, woodmuir smithy
	Stairhead	Diamond
	Gillespie	Upper siller willie, diver, first fireclay, johnstone, wilsontown main
	Blackchapel	Siller willie, jewel, clay, second fireclay, splint, tranent splint, bankton splint, pencaitland jewel, gillespie
	Coronation	Four foot, peacock, stinkie, third fireclay
	No. 1 Ironstone	
	Craigie	
	Lower Kaleblades	No .2 diamond, upper diamond, little splint, corbie splint, penston rough, lower diamond, corbie
	South	Four foot, peacock, stinkie, third fireclay
	North	Parrot, hauchieli, arniston parrot, blue, jewel
Lower limestone	North Greens	

TABLE 2 | Pump depths and pumping rates data from 1964 (British Geological Survey, 2021).

	Ramsay	Burghlee	Roslin	Bilston Glen
Surface level at pit (mOD)	144	137	155	152
Pump depth (mBGL)	213	366	283	752[a]
Pump depth (mOD)	−69	−229	−128	−600[a]
Level from which water pumped (mOD)	−358	−218	−116	−458
Average pumping rate (over 24 h) (L/s)	712	849	1,280	1,241

[a] *Bilston Glen pump depth unknown, this is the base of the shaft.*

(from Burghlee) are at least 60 m above the Coronation coal seam (from Bilston Glen). This suggests the Bilston Glen mine workings are not hydraulically connected to the shallower mine workings.

The Clackmannanshire group is classed as a moderately productive aquifer (Ó Dochartaigh et al., 2015) although the aquifer properties will have been significantly altered due to mining. The shafts associated with Burghlee, Ramsay and Roslin have been infilled so there is limited specific hydrogeological information available. Groundwater will preferentially flow along mined pathways and even if the mine voids have collapsed, deformation of the surrounding rock will cause changes in transmissivity (Younger and Robins, 2002; Andrews et al., 2020).

A river and two tributaries cross the coalfield area. It is unclear whether these surface water courses discharge into the mine workings. There is anecdotal evidence that they are culverted over the mined area but the condition of the culverts is unknown (URS, 2014). Robins (1988) indicates that the regional groundwater flow direction in the Midland Valley groundwater province is likely to follow the major surface divides, draining to the major rivers. In this study area, these rivers flow SW to NE. Dewatering for the mining activities will have altered the local flow paths but there is evidence to suggest the water levels have now rebounded. In the absence of specific hydrogeological data for the mined unit it is reasonable to assume, therefore, that the groundwater flow direction in this area is again aligned with the regional groundwater flow direction. Groundwater level data available from BGS (BGS, 2021) gives an indication that the groundwater gradient is from the SW to the NE corroborating the findings of Robins (1988). A hydrogeological conceptual model would be developed as part of the feasibility process for the project to ensure that the recycled heat will be transported to the identified heat users. This would include obtaining Coal Authority monitoring data (water levels and discharge flows) in the area to gain an understanding of the mine water flow direction and, should the data be of limited extent, exploratory investigation wells would need to be constructed to confirm this key assumption.

Two adits (an entrance to an underground mine), Burghlee and Roslin, were used to dewater the shallow mine workings during mining which are both reported as being filled (URS, 2014). Mine water discharge from the connected shallow mine workings would be at the lowest mine entrance which is likely to be Burghlee adit at 110 mAOD on the banks of Bilston Burn. Water quality sampling of the Bilston Burn undertaken in 2018 (Norris, 2018) indicates that there is a significant change in electrical conductivity downstream of the likely location of the Burghlee adit. Although this is a single sample point it indicates the likelihood that water levels have rebounded in these shallow mine workings. This chemistry change is upstream

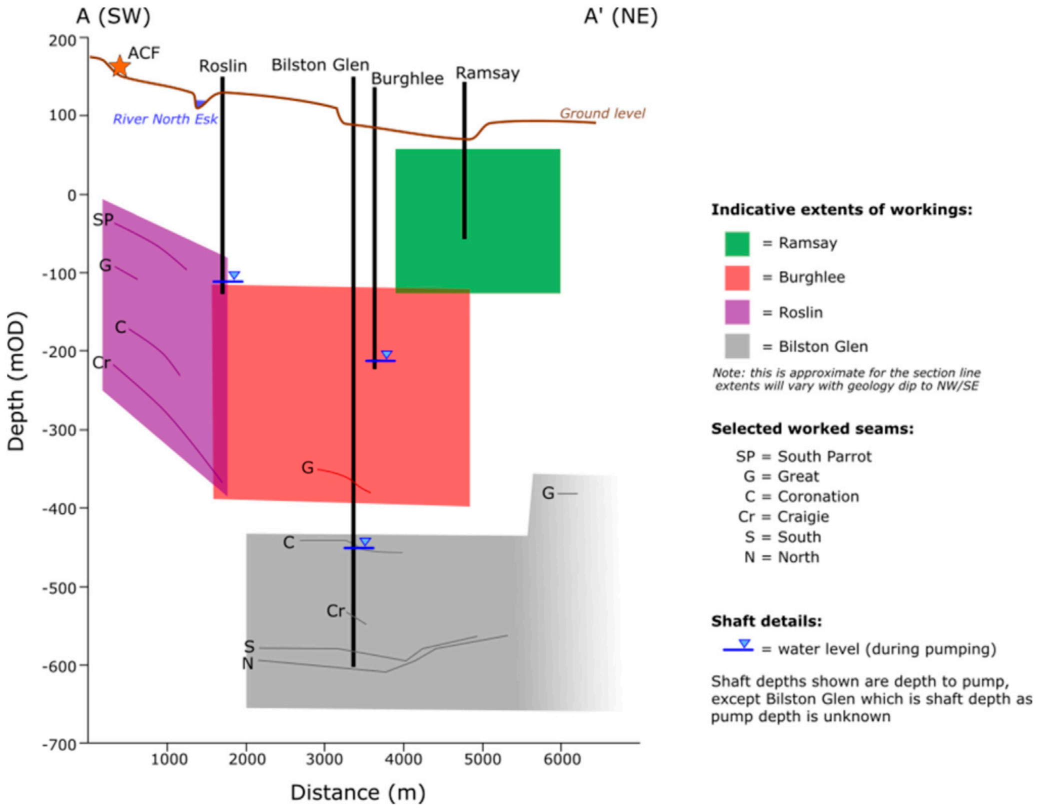

FIGURE 11 | Schematic cross section showing relative depths of mine workings and selected worked coal seams (where data are available). The location of the Advanced Computing Facility (ACF) is shown by an orange star.

of the Bilston Glen mine workings which are known to be connected to discharge from an adit at the other side of the syncline so it is unlikely to be a result of discharge from the deeper mine workings.

Sustainable Heat Available

An estimate of the sustainable heat available in the mined area can be derived following the methodology presented in Todd et al. (2019). Following the assumption that the radiative surface flux is approximately equal to the geothermal flux (otherwise the ground would be constantly heating up), the available sustainable energy can be determined from the geothermal flux over the mined area. Considering a geothermal heat flux of 0.063 W/m^2 over the mined area (~2 × 10^7 m^2 as estimated from mine plans of Burghlee, Roslin and Ramsay), the sustainable annual heat flux is calculated to be 1.3 MW. If the BHEs are spaced evenly over the entire mined area, this could provide heat for ~930 homes (based on the 1.4 kW average heat demand). However, if significantly more heat than this is extracted, or the density of BHEs is too high (e.g., on a housing development) then the resource would be over-exploited and would eventually diminish, ultimately requiring the supplied homes to change how they are heated. Although this does not take into account any additional heat inputs into the system from recharge, future heat provided by the ACF, as indicated in the section above (30–35 MW), could potentially provide >20 times the cumulative geothermal heat flux for the entire mined area.

Heat Users

The Burghlee, Roslin and Ramsey collieries are situated to the SW of Edinburgh with multiple smaller built-up areas in between e.g., Roslin, Loanhead, and Lasswade. The groundwater flow direction identified earlier would transport the heat from the ACF through the mine workings towards these areas. **Figure 12** shows the downstream location of these built-up areas with respect to the ACF and the geobattery, highlighting the spine roadways that represent injection targets and expected zones of effective heat transport in open voids. Heat networks are already present at each end of the geobattery, at the University of Edinburgh's Easter Bush Campus (SW) and at Straiton industrial estate (NE). These would provide two existing users that this geobattery could feed into from the start while further infrastructure and BHE clusters are developed to supply the housing in the area.

Figure 13 shows the planned and committed development for both housing and economic areas for Midlothian. Land for future housing developments has been strategically allocated around the villages of Bilston and Roslin (green areas), as well as south of Bonnyrigg, in Lasswade, and around Rosewell. Furthermore, there are three new school developments close to

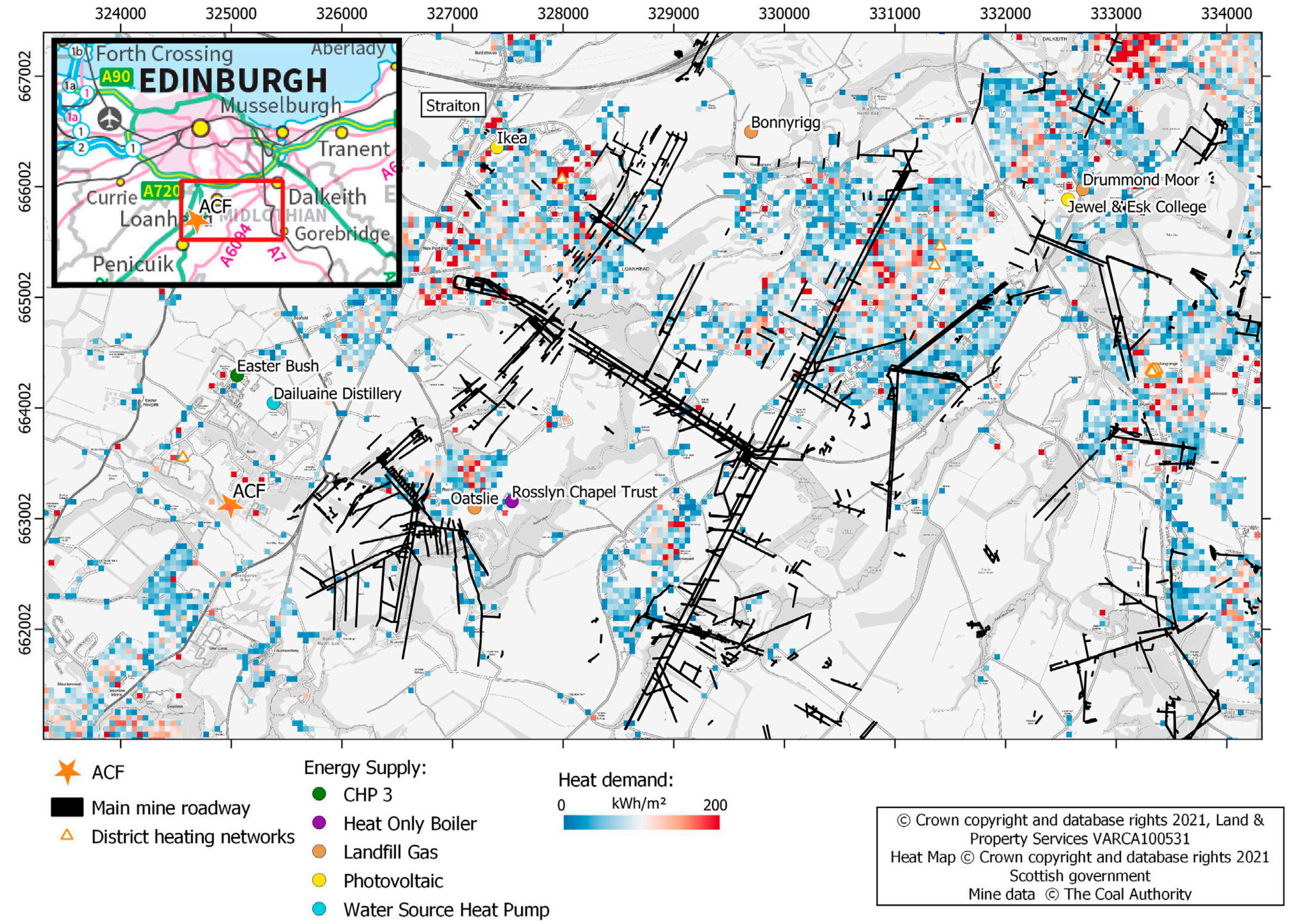

FIGURE 12 | A map of the area in which the geobattery could be developed showing the location of the spine roadways in the mine workings, the energy supply sources (excess heat sources), and the built environment in the background. Spine roadways represent target injection and transport locations for the shallow mine workings as these are most likely to remain open for effective heat transfer through the mine system. The Advanced Computing Facility (ACF) is shown by an orange star.

the geobattery area (one committed and two proposed). There are also likely to be developments nearby which are within Edinburgh City boundary and are therefore not shown on this plan. All of these potential developments could connect into the geobattery to supply low carbon heating.

DISCUSSION

The geobattery concept presented in this paper is a novel utilization of abandoned mine workings to create a balanced and sustainable shallow geothermal resource for low carbon heating, by recycling heat from cooling facilities. Building on observations of positive interferences between borehole heat exchangers as a result of advective heat transport, so-called “nested BHEs” (García-Gil et al., 2020), the geobattery specifically targets elevated groundwater fluxes as a means to transport recyclable heat down gradient to recharge shallow geothermal resources. Through harnessing recyclable heat to offset energy input for domestic or commercial space heating, the geobattery is a novel example of a circular geothermal heat network.

We show that it is possible to improve, and potentially guarantee, the sustainability of shallow geothermal resources that derive their thermal power through conduction i.e., borehole heat exchangers. Our simplified generic model considers a BHE length of 50 m from which an annual average heat load is extracted that matches the annual average heat demand of a typical UK house. BHE’s are often numerically assessed in terms of performance with respect to inlet and outlet temperatures during periods of use and intermittent periods of no heat extraction e.g. during the summer months (Piotrowska-Woroniak, 2021; Walch et al., 2021). However, from a thermal resource perspective the recharge must match the extraction to prevent heat mining and the eventual diminishing of the resource (Casasso and Sethi, 2019; Zhao et al., 2020). To test the impact of intermittency on our results, the reference model with geobattery recharge was modelled with sinusoidal heat extraction for 8 months and no extraction (geobattery

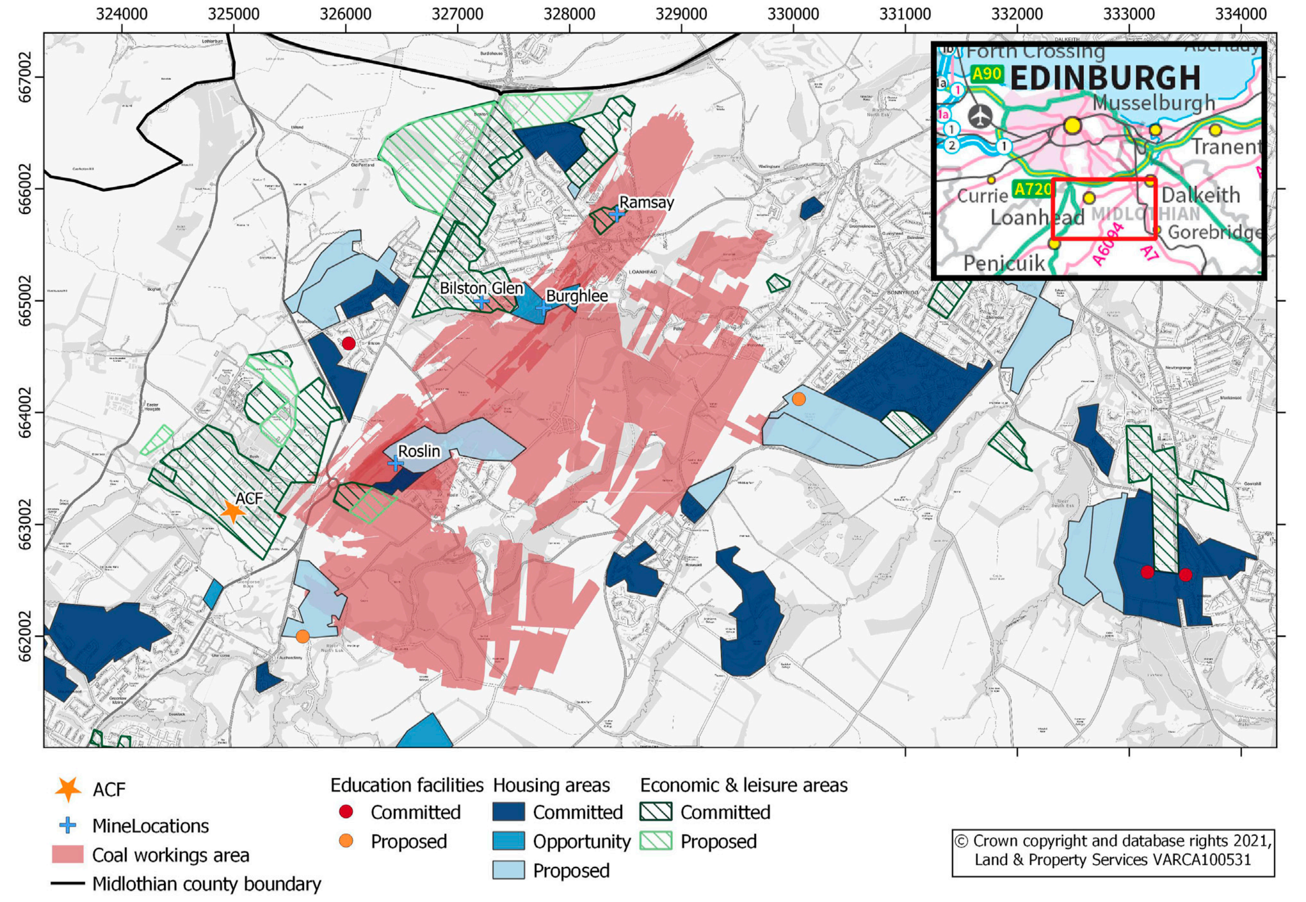

FIGURE 13 | Planned and committed developments in Midlothian near the geobattery (based on data from Midlothian Council, 2021). The Advanced Computing Facility (ACF) is shown by the orange star.

recharge) for 4 months (**Figure 5**). The results indicate that the constant heat extraction model adequately represents the temperature of the BHE.

It is important to note the model presented here is generic in order to demonstrate the geobattery concept and that there are several further assumptions made that have an impact on the results and conclusions regarding real world sustainability. These include the material properties of the subsurface, the temperature of fluid in the mine, and the distance of the BHE to the mine level. Here we estimate a thermal conductivity for a sequence of Carboniferous sediments and a constant mine temperature based on our current understanding of the geology and the potential thermal resource from an example heat source. However, variations in these values will influence the generic model results. For example, a lower thermal conductivity medium will reduce the ability for both the ground and the geobattery to supply heat to the BHE array, but if our assumption is on the low side then the sustainability gains from a geobattery could be greater than predicted by this generic model. Mine water temperatures vary across the coal fields of the United Kingdom (Farr et al., 2021), and as such the cooling demand of a data centre may produce different injection temperatures, and therefore sustainability gains, as modelled here. Alternative excess heat sources, such as waste incinerator plants or solar thermal installations may also be able to supplement injection temperatures for a geobattery, potentially increasing the sustainability gains. It may even be possible to monitor and manage the mine temperatures to optimize the thermal recharge to a BHE array. Further analysis of these variables here would not produce meaningful results because of the generic nature of the model but should be considered during feasibility assessments.

There are multiple factors affecting BHE sustainability, the most important of which are BHE length, the circulating fluid, borehole construction, and the thermal conductivity of the ground (Casasso and Sethi, 2014). Typically, one methodology to increase the density of BHE spacing is increasing BHE length, thereby reducing the thermal load per metre of BHE. This clearly comes with increased drilling costs, but we show that sustainability can be achieved through recharge from recycled heat as a means to increase BHE density while minimising BHE length. The impact of thermal recharge from the geobattery at each BHE is additionally a function of the distance between the BHE and the mine (both vertically and laterally), the location of other BHEs also extracting heat, the thermal diffusivity of the ground, and any time lag between the onset of heat extraction and heat injection.

We model an idealized situation of a constant temperature in the mine from thermal recharge of recycled heat and show that this can prevent heat mining as well as reduce the impacts of thermal interference between closely spaced BHEs. Although it only provides modest efficiency improvements in terms of thermodynamic work of the heat pumps of up to 10% (because the heat pumps can be efficient even at low temperatures), it futureproofs the shallow geothermal technology so BHEs can continue to contribute to a decarbonised heating sector for the long-term, especially if heat demand reduces in the future as a result of improved building fabric and/or warmer temperatures.

The UK Government commitment to rapid heat pump deployment places increased importance on heat storage and demand side response as an integral part of minimising the impact on the electricity grid (UK Government, 2020a). This could be realised through a variety of subsurface operations e.g., underground thermal energy storage (UTES) (Gluyas et al., 2020), aquifer thermal energy storage (ATES) (Pellegrini et al., 2019), or within sophisticated integrated networks balancing energy between multiple heat resources and stores (Revesz et al., 2020). Furthermore, the Scottish Government expects an increase in value of energy storage and is considering (recently legislated for) heat networks as potential storage facilities (Scottish Government, 2020; Scottish Government, 2021a).

We suggest that the geobattery concept is as a novel utilization of the subsurface harnessing the elevated permeability of the mine workings as a heat storage and transfer network. It is therefore different to UTES or ATES as the aim is to advect heat away from the injection site, while also being distinct from mine water geothermal schemes because the thermal energy is extracted using arrays of borehole heat exchangers that do not intersect the mine workings. It should be noted however, that the development of a geobattery does not preclude the development of a mine water heat scheme that targets the mine water itself for heat extraction. In fact, thermal recharge of the mine workings would add significantly to the available heat resource for such a scheme and should therefore be developed in conjunction with the geobattery to ensure an integrated, managed system. However, as the electrification of heat is proposed to take a prominent role in United Kingdom efforts to decarbonise the heating sector (UK Government, 2020a), here we have focussed on BHEs as the heat extraction technology due to their potential for rapid deployment.

Banks et al. (2019) discussed different methods for heat exchange with mine water geothermal systems, highlighting that the yield from conduction-based heat extraction systems (e.g., BHEs) is lower than open-loop systems involving abstraction and heat exchange with the mine water. In the cases described in Banks et al. (2019) the heat is extracted from one location and then distributed at the surface, either as a low temperature input fluid for a network of decentralised heat pumps or as higher grade heat from a centralised heat pump. In contrast, the geobattery concept utilizes the mine workings to distribute the heat in the subsurface in the manner of a decentralised heat network, thereby satisfying the heat demand locally. Consequently, the system is not limited in scale by its dependence on conduction as each individual BHE extracts just the energy that is needed to fulfil the heating demand of the building to which it is connected.

Decentralised heat networks have been shown to have significant environmental benefits. Verhoeven et al. (2014) reported the concept of a decentralised mine water heat network and associated CO_2e savings of 65%, and Pratiwi and Trutnevyte (2021) conducted a life cycle comparison of different geothermal schemes in which decentralised heat networks consistently proved to have lower negative environmental impact than centralised heat pumps that then distribute higher grade heat. Much of the environmental impact of shallow and intermediate depth geothermal systems was found to be related to the surface infrastructure of a heat network and borehole drilling (Pratiwi and Trutnevyte, 2021). Although a full life cycle analysis is beyond the scope of this work, the geobattery would potentially reduce the impact associated with surface infrastructure but possibly increase the impact of borehole drilling. Such trade-offs would need to be carefully considered for geobattery development. Furthermore, the added benefit of recycling heat from industrial processes would need to be considered within a full life cycle analysis, particularly from a carbon savings perspective. Firth et al. (2019) suggest the benefit from recycling heat that is otherwise expelled to the atmosphere is from off-setting CO_2 emissions from the heat generating process rather than reducing the direct heat emissions. For direct recycling within industrial processes, Firth et al. (2019) estimate CO_2 savings could be as large as 10%–12%. The geobattery, however, would recycle heat for use by a separate user. Calculating the carbon saving benefit of the geobattery from our generic model would be heavily dependent on a range of assumptions both within the model (as above) and the wider application. For example, carbon savings will be a function of the heating technology the BHEs replace, the carbon intensity of electricity through time, the heat demand through time, and the emissions associated with the embedded costs of switching to another technology needed to replace the BHE after 30 years if it were not recharged by the geobattery. We have therefore focussed this paper on introducing the concept of the geobattery.

Key to all mine water schemes is an excellent understanding of the mine water reservoir characteristics. The mine “reservoir” can be extremely complex and depends on a wide range of factors (Walls et al., 2021). For example, Andrews et al. (2020) showed the importance of temporal evolution of mine collapse on the potential void fill architecture and the potential for that to influence the permeability of the system. Monaghan et al. (2021) identified multiple different mine facies from multiple boreholes drilled into shallow mine workings at the Glasgow Geothermal Energy Research Field Site (GGERFS) in Dalmarnock and Shawfield in Glasgow’s East End. Most mine water heat schemes aim to inject or extract from roadways that were used to transport the mined coal back to the surface remain open voids that can sustain high flow rates e.g. Barredo in Spain extracts ~100–110 L/s (Peralta Ramos et al., 2015; Walls et al., 2021), but heat and water are also drawn from the worked areas whose hydraulic and thermal properties depend on the mining technique, roof and floor stratigraphy, and the state of collapse (Monaghan et al., 2021). All feasibility studies of potential mine water heat schemes require in-depth analysis of the mine plans but, as Monaghan et al. (2021) showed, even small uncertainties in georeferencing could cause boreholes to miss targets. Furthermore, the plans may be accurate at the point of closure, but subsequent collapse and deformation may mean that areas thought to be void spaces (e.g., stalls) are no longer as transmissive as may be expected.

While the geobattery relies on interconnected mine workings to transfer heat away from the injection point, the extraction of heat using a BHE is not as dependent on specific hydrogeological conditions as a typical abstraction based mine water heat scheme. These schemes require drilling into specific roadways or high permeability areas, which increases the uncertainty and impacts a developer's business case (Townsend et al., 2020). Targeting a particular roadway is generally more difficult than determining the overall hydraulic connectivity of mine workings for a geobattery heat transfer, reducing the risk of a failed system.

Shallow geothermal resources are often considered to be renewable and sustainable sources of heat or coolth but there is increasing awareness that this is dependent on appropriate spacing and sizing to prevent thermal interferences (Vienken et al., 2015; Casasso and Sethi, 2019; Meng et al., 2019; Vienken et al., 2019; García-Gil et al., 2020; Abesser et al., 2021; Walch et al., 2021). Here we show that for conditions appropriate for a heat-demand dominated climate even a generous available land area for each property will result in heat mining. With the UK Government strategy to rapidly increase heat pump installation by 2030, failing to consider the need for recharge of the shallow geothermal resource will result in increasing demand on the electricity grid and other potential environmental issues as severe as ground freezing. The geobattery offers a method to ensure the sustainability of BHEs for the long term, helping meet our Net Zero ambitions.

A key principle in the drive for Net Zero is to ensure a just transition that "…ensures the benefits of climate change action are shared widely, while the costs do not unfairly burden those least able to pay, or whose livelihood are directly or indirectly at risk…" (Scottish Government, 2021b). The United Kingdom is an affluent country but many mining communities in the United Kingdom have suffered sustained economic downturns since the collapse of the industry, including high rates of fuel poverty, poor job quality, high unemployment, and poor health (Coalfields Task Force, 1998; Norman et al., 2014; Beatty et al., 2019). Kurek et al. (2020) showed that developing geothermal resources directly led to an improvement in many socio-economic indicators in geothermal provinces of Poland (another country with potential for mine water heat schemes), while Verhoeven et al. (2014) reported an increase in inward investment and attraction of new participants to the Minewater 2.0 project due in part to the 65% reduction in carbon emissions from the scheme. The geobattery offers an opportunity to create a circular geothermal heat network that could attract heat producing industries and stimulate the local economy in a manner that could ensure a just transition to a Net Zero economy (Scottish Government, 2021b). Through the creation of a long-term sustainable heat resource, the geobattery also has the potential to provide a locally resilient heating sector protecting customers from volatile energy prices as fossil fuels are phased out. A geobattery system may also provide a public health benefit by supplying warmer homes in areas characterized by poor public health (Norman et al., 2014). These wider benefits of a geobattery would need further quantification on a site specific basis.

Our preliminary analysis to quantify the benefits of a geobattery highlights that it should not be valued for its ability to provide small benefits in terms of daily operations, but rather for its potential to ensure the sustainability of the system in the long term, safe-guarding the shallow geothermal resource for future generations. Typically, potential financial gains in the future are considered to have less value than immediate gains in the short term, but this raises the question of how to value a geobattery system whose function ensures long-term sustainability of shallow geothermal resources, which directly contribute to reaching Net Zero emissions targets and reduce the future costs of dealing with excessive climate change. Future economic models of a geobattery would necessarily need to consider this potentially significant contribution.

While a system such as the geobattery could offer many potential advantages by recycling heat within a circular heat network and ensuring long term sustainability of shallow geothermal resources, it is, at this stage, a conceptual idea, albeit one which the authors feel warrants further investigation. To realize such a technology requires many technical, social, and economic factors to be considered. In addition to the geological complexity and corresponding hydrogeological uncertainty of mine workings, there is currently no legal framework to value heat as a resource in the United Kingdom. There are no models for heat ownership or supportive economic policies such as resource risk insurance (Dumas and Garabetian, 2018), and consequently a poorly developed heat market (Abesser et al., 2018). Currently the UK's legislation and regulations consider heat either as a waste product or with respect to its impact on groundwater quality (Abesser et al., 2018; SEPA, 2019). Some argue that this has hindered the uptake of this technology in comparison to some European countries (Fleuchaus et al., 2018; Tsagarakis et al., 2020), while Abesser et al. (2018) indicate that a regulatory framework has greatly promoted the development of shallow geothermal resources in Germany.

In the following, we initiate a discussion about the regulatory and economic requirement attached to the sustainable management of mine water heat and shallow geothermal resources. This discussion aims to spur new research and engagement on the topic. We propose that systems like the geobattery could offer a platform to facilitate a regulatory and economic paradigm shift to manage and support the sustainable use of shallow geothermal energy resources.

Because the net-energy savings between BHEs recharged or not recharged from the geobattery would be relatively minor from a user perspective and only worthwhile after 20–40 years, developing a business model centred on the added value to heat as a commodity is not feasible. One way to finance a geobattery could be operating it as a regulated service. An organisation could provide a management service to ensure the sustainability of the geothermal resource in exchange for a ‘sustainability fee’. This role would be similar to the role of current gas distribution network operators who ensure the provision of heat (as natural gas) to end-users through a network they own and manage. The sustainability fee could be recovered from the end user based on metered usage of the BHE, a model that has previously been used to pay feed-in tariffs on the UK’s renewable heat incentive scheme. Alternatively the fee could be pre-set based on the density of installed BHEs, or through the expansion of the concept of “Heat Network Zoning” to include shallow geothermal mine water geobattery systems. These zones provide guarantees to investors by making it compulsory for certain types of building to connect to heat networks within the zone (UK Government, 2021). Of course, these zones are regulated in a way that protects the consumer and by ensuring that, in the zone, district heat networks are the cheapest source of heat. Expanding the application of this concept in the United Kingdom would also align with current strategies, such as Ofgem becoming the regulator for these zones so that gas, electricity and heat are regulated by the same entity.

The preceding discussion suggests that both a regulatory and a management body would be required to guarantee the provision of heat. These entities would therefore need to have expertise in subsurface management, mine water flow and heat transport in these systems, as well as the capability to monitor and forecast heat supply and demand in the area. In the United Kingdom, the Coal Authority own and have the liability for all abandoned coal mines but do not own the water or heat in the mine and their jurisdiction ends at the mine limit. Shallow geothermal resources (not in mines) therefore fall under the remit of the devolved environment agencies but BHEs do not extract or inject fluids in the subsurface and are unregulated. The organization that could run the regulated management service of a geobattery would therefore need a remit that encompasses some aspects of both the environmental protection agencies and the Coal Authority. This could be achieved by adjusting/expanding the remits of existing bodies or by the creation of a new geothermal resource authority/agency. As an example of such a scope change, Ofgem is currently expecting to be appointed as the heat networks regulator for setting and enforcing consumer protection rules across new and existing GB heat networks (OFGEM, 2021a).

CONCLUSION

Building on field observations and modelling that indicates shallow geothermal resources exploited by borehole heat exchangers (BHEs) are not infinite and that BHEs can have both positive and negative interferences, we introduce a novel underground thermal energy storage and distribution network known as a geobattery. We propose that recyclable heat could be injected into the subsurface where significant groundwater fluxes exist, such as legacy coal mines in the United Kingdom, to transport heat from the injection site down gradient to a multitude of users in a district-scale circular heat network. We identify three main geobattery components:

- A readily available source of heat e.g., data centre, industry, renewables.
- Suitable hydrogeology to create a subsurface distribution network e.g., legacy coal mines.
- An identifiable heat demand.

Our modelling indicates that thermal recharge of a suite of BHEs from a shallow mine working results in stable subsurface temperatures that ensure the sustainability of the shallow geothermal resource for the long-term. Furthermore, we suggest that a geobattery has the potential to ensure sustainability irrespective of the relative timing of BHE installations and geobattery development. Finally, we present a case study of a potential site in Midlothian, Scotland where all three components are present.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusion of this article will be made available by the authors, without undue reservation.

AUTHOR CONTRIBUTIONS

CM, AG, and MP were responsible for the original concept. All authors then contributed to the development of the concept as is presented in this manuscript. CM, AF-H, JM-C, and MR developed scenarios and JM-C, MR, and AF-H ran simulations. AF-H wrote the first draft of the manuscript. AF-H, CM, MR, FT, JM-C, and MP wrote sections of the manuscript. AF-H, MR, FT, JM-C, AG, and AC-T contributed to figures. All authors contributed to manuscript revision and have approved the submitted version.

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CONFLICT OF INTEREST

Author AG was employed by the company ECUS Ltd.

The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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