Barriers and enablers to dual use of transportation tunnels for heating and cooling decarbonisation

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Abstract

The potential to source thermal energy from buried infrastructure such as tunnels and metro stations may offer significant potential to support the decarbonisation of heating and cooling and reduce costs associated with dedicated drilling for traditional ground-sourced systems. However, this remains a niche approach with few commercial schemes globally, partly due to high initial costs, long payback periods, technical uncertainties, and the need to minimise construction risk and delays. To help address these challenges, this study examines the energy resource potential, technical and economic challenges, and how these can be overcome, for tunnels beneath Manchester and Crewe that were proposed as part of the HS2 Phase 2b railway construction. A worthwhile thermal resource is established along with enthusiasm for use of the energy by the infrastructure developer and by third parties in the vicinity. The economic case is set out which establishes financial viability but with significant uncertainty based on future market conditions. This demonstrates the need for a supportive future policy environment to encourage uptake of all available heat sources.

Keywords chosen from ICE Publishing list

Tunnels & tunneling, Energy, UN SDG 13: Climate action, District heating, Buried structures, Energy geotechnics, Infrastructure planning, Sustainability, Sustainable development.

1. Introduction

The challenge of decarbonising heating and cooling will be subject to competing demands for low carbon / environmental energy sources (Baruah et al., 2014; Eyre and Baruah, 2015). Power-to-heat technologies such as heat pumps will place demands on the electricity grid which will also need to supply sufficient green electricity to enable the shift to electrified transport (HM Government, 2020). Meanwhile, civil engineers are ever more aware of the need to reduce environmental impacts from infrastructure and seize opportunities to support decarbonisation efforts (Howells, 2023).

Subsurface infrastructure assets such as building foundations, tunnels, metro stations and wastewater systems can be used for heat capture and storage alongside their primary function (Lagoeiro et al., 2019; Meibodi and Loveridge, 2021). So-called *energy geostructures* act as underground heat exchangers. Subject to suitable operational temperature limits, this can facilitate underground storage of waste heat from cooling during summer, and subsequent extraction of that heat from the ground in the winter to provide heating. Energy geostructures can also support heating and cooling decarbonisation through enabling access to ground and environmental thermal energy sources which would otherwise be technically or economically inaccessible (Loveridge et al., 2022). Because they can avoid the need for dedicated drilling and special purpose ground heat exchangers, energy geostructures can offer opportunities to reduce the capital costs for accessing shallow geothermal energy (Anis Akrouch et al., 2020; Loveridge et al., 2020; Lu and Narsilio, 2019). Energy tunnels are one type of energy geostructure which involve embedding heat transfer pipes in the linings of tunnels, typically during construction, to extract thermal energy from the earth around the tunnels and from within the tunnels themselves (Adam and Markiewicz, 2009; Franzius and Pralle, 2011).

Despite the opportunities presented by energy tunnels, they remain a novel approach with operational projects limited to small-scale test developments. Most trials have involved

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Tunnel Boring Machine (TBM) construction with plastic heat transfer pipes within pre-cast concrete tunnel lining segments (Figure 1) requiring pipe joints as segments are connected. A design example from Crossrail in London (which was never built, see below) given in Figure 2. Completed trials include the Stuttgart-Fasanenhof urban railway in Germany and the Jenbach (Franzius and Pralle, 2011) and Lainzer (Adam and Markiewicz, 2009) tunnel projects in Austria. Pipework installation in these cases runs to tens of metres, whilst a reasonable energy capture requires around 500m-1km length of tunnel activation. Following a trial section, a commercial project is under consideration with 15.7km of tunnels and metro stations of the Torino Metro Line 2 extension acting as sources and customers for thermal energy (Barla and Insana, 2023).

In the UK, attempts have been made to develop projects during Crossrail and in Phase 1 of High Speed 2 (HS2), both in London (Legg, 2014, p. 2; Nicholson et al., 2014a), but neither has proceeded to construction. The work presented in this study brings together existing state of the art knowledge on feasibility of energy tunnels with lessons learnt from those two projects, and a novel socio-economic assessment for energy tunnels beneath Manchester and Crewe as part of the previously planned HS2 Phase 2b. Together this helps illustrate the steps required to unlock this solution for wider uptake.

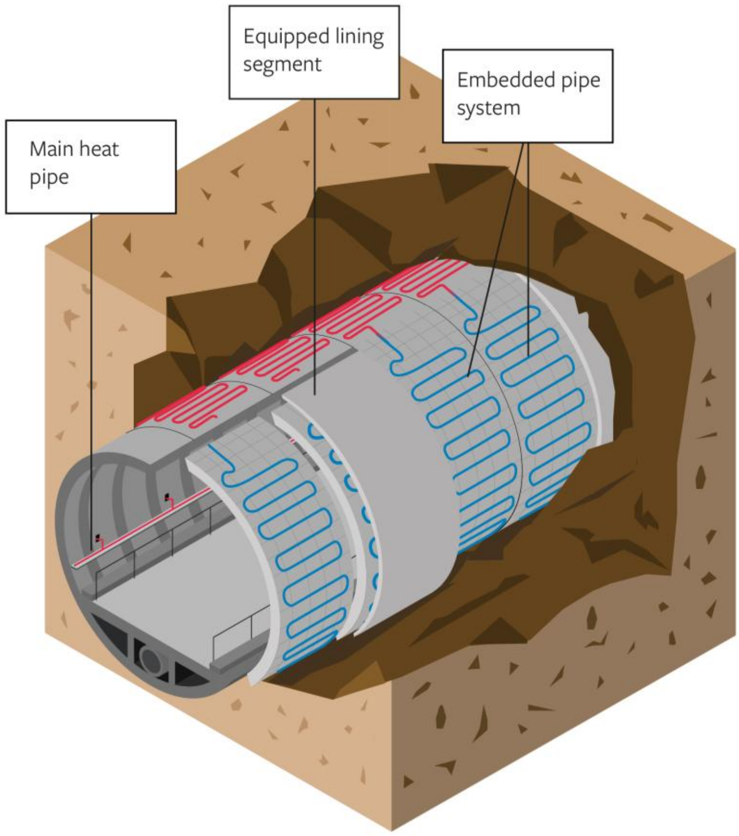


Figure 1 Schematic representation of a tunnel segmental lining equipped as ground heat exchanger

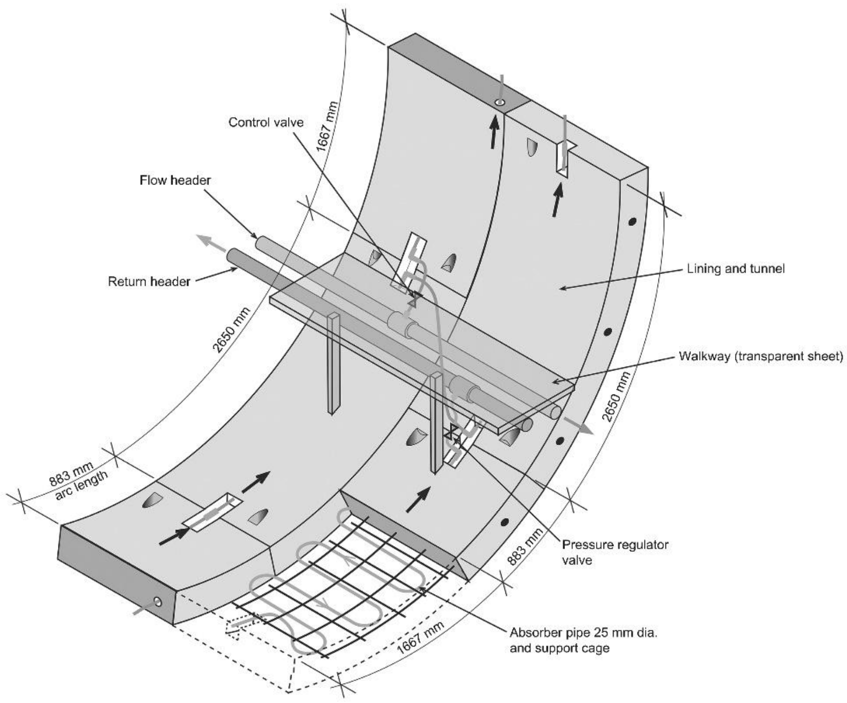


Figure 2 Schematic of tunnel energy system showing embedded pipework and flow/return pipes in the tunnel (Nicholson et al., 2014a)

1.1 HS2 case study and study scope

HS2 is the UK's new high-speed rail line from London towards the north-west, and Phase 1 is currently under construction from London to Birmingham. Phase 2 between Birmingham and Manchester was due to be built by 2035. The project Client, HS2 Ltd, has committed to be net zero carbon in operational and construction by 2035 (timeframe under review) (HS2 Ltd, 2022a). Separately, the HS2 energy strategy commits the institution to generate heat and power for facilities onsite wherever possible (HS2 Ltd, 2020, p. 2). Additionally, HS2 Ltd has a strategic goal to be a good neighbour and protect the natural environment (HS2 Ltd, 2022b). In pursuit of these commitments, HS2 Ltd was keen to explore the potential for thermal energy capture from Phase 2b assets, from Crewe to Manchester.

Although not currently planned to proceed, Phase 2b of HS2 was to include new stations at Manchester Airport and Manchester Piccadilly as well as twin-bored running tunnels under Crewe and separately from the south of Manchester to termination at a new Manchester Piccadilly high speed station (HS2 Ltd, 2022c). Tunnels at Crewe and Manchester were proposed to be 8.8m and 7.5m in diameter, supported by precast segmental linings, and 6.8km and 12.8km in length, respectively (MWJV, 2022, 2021).

A team from the University of Leeds collaborated with HS2 Ltd, working to identify the most suitable locations for the use of tunnel-sourced thermal energy (Section 2), to gain an initial idea of the scale of the thermal resource (Section 3), and learn practical lessons from past UK projects to support future project delivery (Section 4). The research also included an exploration of how the tunnel heating and cooling could be used internally by the railway operator or transferred externally via heat networks (Section 5), the economic, business and carbon case (Section 6), and delivery models for how such a project could be realised (Section 7). Section 8 goes on to discuss the implications of this study in the wider policy landscape, highlighting changes that would benefit both transport and energy objectives, while Section 9 presents the study conclusions.

2. Scope for geothermal activation from subsurface assets

Initial asset identification was undertaken considering all options for thermal capture against route plan and profile maps (HS2 Ltd, 2022d; Loveridge et al., 2022) with results shown in Table 1. Availability of detailed design information required for thermal resource analysis limited further consideration to geothermal activation of the tunnel linings only. Station boxes and foundations can offer significant additional opportunities for accessing thermal resource in the same fashion as the tunnels and this approach is being deployed in the case of Torino Metro. As such, this was recommended for consideration once station design information is available.

Table 1 Potential assets for thermal activation for HS2 Phase 2b under Crewe and Manchester

Asset type	Number	Heat source
Tunnel lining, accessed via 6 ventilation shafts, 4 tunnel portals	16.18km length / 447,047m^2 area	Train operations, ground thermo-hydrogeology
High speed station	2 stations	Waste heat from station, ground thermo-hydrogeology via foundations and station boxes
Depots	2	Ground thermo-hydrogeology via building foundations
Cutting and embankment retaining walls	26	Ground thermo-hydrogeology via thermal activation of walls
Transformer stations and electrical management sites	12	Waste heat from electrical equipment
Surface and subsurface water management, e.g. culverts, ponds	6	Water source via heat pump

For geothermal activation of the tunnel linings, a suitable point to bring thermal energy to the surface is typically required. In addition, the length of heat transfer pipe which could feasibly be installed is limited by pumping energy costs which can become excessive. In this case thermal activation was kept within 500m of ventilation shafts and tunnel portals (Figure 3). In addition, the shafts themselves can also be thermally activated. This amounts to an activated length of tunnel of 16.18km and ground contact surface area of 447,047m^2 for thermal assessment, covering both tunnels and shared ventilation shafts.

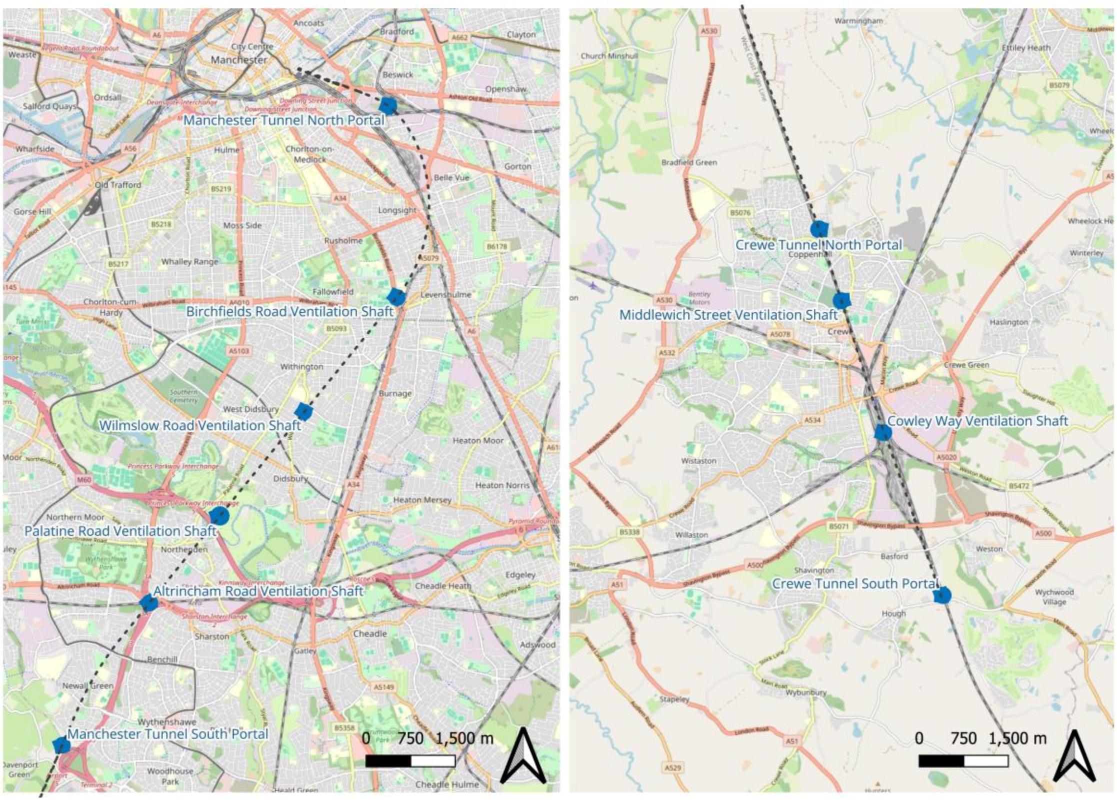


Figure 3 Maps showing route and shaft locations for the proposed Manchester and Crewe tunnels. Tunnel routes obtained from HM Government / HS2 Ltd (2025)

3. Assessment of thermal energy availability from subsurface assets

The design charts of Dornberger et al (2020) and Di Donna & Barla (2016) were used to estimate heat transfer rates per unit area of the tunnel lining. In addition to the ground thermal conductivity, both charts require understanding of the initial ground temperature, which was assumed to be 10-12ºC (Busby et al., 2011). The charts by Dornberger et al

(2020) focus on the impact of the tunnel internal conditions and additionally require tunnel air temperature and air-to-lining heat transfer rates as input variables. Meanwhile those of Di Donna & Barla (2020) focus on the influence of groundwater, requiring a groundwater flow rate (Darcy velocity).

3.1 Ground thermal and hydrogeological conditions

The ground conditions vary along the length of the proposed route, including sequences of glacio-fluvial deposits and/or glacial till overlying Triassic bedrock of the Mercia Mudstone or Sherwood Sandstone Groups. Evidence from thermal response testing (TRT) finds that glacial tills and Mercia Mudstone can be assumed to have a thermal conductivity of approximately 2 W/mK (Banks et al., 2013). The quartz-rich Sherwood Sandstone would be expected to have higher conductivity, and 3 W/mK was adopted based on laboratory scale testing (Boon et al., 2021). However, field scale conditions also include advective heat transfer due to groundwater flow with effective thermal conductivities in TRTs being as much as 5 W/mK (Banks et al., 2013). Possible groundwater flow rates in the Sherwood Sandstone were estimated based on regional groundwater contours which give a hydraulic gradient of 0.02 to 0.05 m/day, from published aquifer properties (Allen et al., 1997; BGS, 2010). Hydraulic conductivities are potentially highly variable with typical values in the range 0.2 to 2 m/day, but with high flow horizons potentially exceeding 10 m/day. Groundwater flow rates (Darcy velocity) could therefore routinely be up to 0.04 m/day but could easily exceed 0.2 m/day at some horizons.

3.2 Internal tunnel conditions

A heat transfer coefficient is used to describe the overall heat transfer between the tunnel air and the tunnel lining, according to the air temperature and wind speed (Peltier et al., 2019). A review of published evidence suggested a constant conservative lower bound value of 5W/m^{2}K is appropriate (Di Donna et al., 2017; Nicholson et al., 2014b, 2014a;

Peltier et al., 2019). This would be representative of a tunnel airflow of less than 1 m/s. Airflow of only 5 m/s could lead to heat transfer coefficients of 20 to 30 W/m^2K.

The tunnel air temperature is likely to be elevated with respect to both the surrounding ground and the outside ambient air temperature (Di Donna et al., 2017; Smith, 2015; Thompson, 2015a, 2015b). Calculations for the tunnel ventilation design for Crossrail and HS2 Phase 1 tunnels suggest temperature ranges between 20°C and 35°C depending on the time of year, train frequency, proximity to stations and rolling stock design (Nicholson et al., 2014b, 2014a; Smith, 2015; Thompson, 2015a, 2015b). Since the deign charts use discrete values of tunnel air temperature, 25°C was used in the method of Dornberger et al (2020) and 21°C in the approach of Di Donna & Barla (2016).

3.3 Heat transfer rates per unit area of tunnel lining

Each set of design charts has been produced for specific temperature differences between the heat source (the undisturbed ground temperature) and the sink (the heat transfer fluid temperature). Table 2 summarises four main scenarios depending on the ground, groundwater flow and tunnel internal conditions. The resulting heat transfer rates are shown in Figure 4. Based on this, two conservative choices were taken forward for analysis: 12 W/m^2 (Scenario 1) for cases without significant groundwater flow or tunnel air movement, and 25 W/m^2 (Scenario 2) where one of these two phenomena was present. In reality, if both groundwater and tunnel air movements are significant, then values in excess of 30 – 50 W/m^2 could be possible. Despite this higher potential, conservative assumptions regarding heat transfer rates were applied to ensure a robust investment feasibility study.

Table 2 Assumptions for tunnel heat transfer coefficient calculations

Description	Mudstone or Glacial Till	Sherwood Sandstone	Sandstone with moderate groundwater flow	Mudstone or Sandstone with higher tunnel airflow
Ground Conductivity W/mK	2	3	3	2 – 3
Groundwater Flow m/s	0	0	0.5 m/day	0
Tunnel Air Temperature °C - Dornberger et al - Di Donna & Barla	25 21	25 21	25 21	25 21
Tunnel internal heat transfer Coefficient W/m²K	5	5	5	20

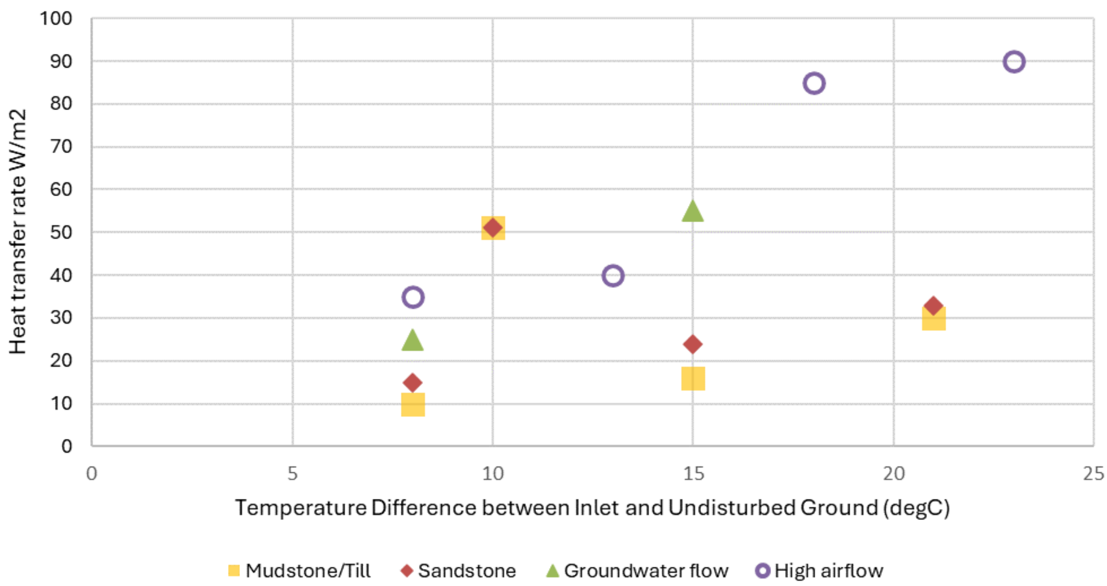


Figure 4 Tunnel energy per unit area for different conditions

3.4 Application ground and tunnel conditions to identified assets

Scenario 1 and 2 heat transfer rates were applied based on thermal activation of 500m lengths of tunnel adjacent to the four tunnel portals and from either side of the six ventilation shafts (Figure 3), as well as the shafts themselves. Table 3 sets out the range of thermal resource within each Scenario. An simplified equivalent number of houses that could be heated with the thermal resource is supplied for illustrative purposes, based on UK Government figures of average annual heat demand for a UK home (BEIS, 2021a). The thermal resource figures refer to direct energy capture only from the ground conditions and surface area of tunnel lining, without considering heat pump upgrade. The thermal resource can be used for both heating and cooling purposes, depending on future user requirements, and by doing so would increase the efficiency and overall energy availability.

Table 3 Energy availability under lower and higher scenarios applying thermal estimation to identified assets

Asset type	Thermal resource (Scenario 1)	Thermal resource (Scenario 2)	Equivalent # of homes
Tunnel Portals	3.0 – 3.4 GWh/yr	5.7 – 6.3 GWh/yr	274 – 572
Ventilation Shafts	6.3 – 7.2 GWh/yr	11.7 – 13.2 GWh/yr	574 – 1,195

4. Overcoming challenges to successful implementation

The study sought to learn lessons from previously unsuccessful attempts to implement energy tunnels in the UK, in pursuit of maximising the chance of future success. Insights from the Crossrail project were gathered via informal stakeholder engagement with construction engineers and others involved in the development. Stakeholders reported that two types of geothermal activation were attempted: (i) for the running tunnels, designs were prepared to place heat transfer pipes within the tunnel segmental linings (Nicholson et al 2014a, Figure 2); (ii) for station boxes and shafts, pipes were installed within piles and diaphragm walls, but they were not successfully connected to over station developments for active use. Of the challenges highlighted by construction stakeholders, all were considered solvable. Insights from stakeholder engagement are summarised in points 1-5.

1. **Lead time:** Issues encountered were largely due to insufficient lead time to fully incorporate the system into designs, contracts and construction practices, contributing to some of the other challenges to implementation.

2. **Construction practices to protect heat transfer pipework:** Despite attempts to protect the heat transfer pipes within walls and piles, a number were damaged during either installation or subsequent construction activities, such that the heat available was no longer worthwhile. This issue could easily be addressed easily by better training and supervision, and clearer contractual responsibility (and potentially associated penalties) for the different civil engineering contractors to deliver a tested and commissioned system before handover.
3. **Pipework jointing following segment installation:** Some manual interventions are required to make the pipework connections following segment placement by the TBM. It was established the best approach would be for a gantry following the TBM for operatives to make the connections straight away. The responsibility for this task would need to lie with the main civil engineering contractor for the underground works.
4. **Assurance:** Assurance is needed that pipework and joints will last at least the life of the tunnel. Engagement with the supply chain suggested the polymer pipes had at least a 120-year lifespan. The system can be designed such that if any section of pipework fails, it can be quickly and permanently sealed off with no risk to the tunnel integrity and minimal impact on energy availability.
5. **Fire risk:** It is vital that the installed pipework does not increase the fire risk in the tunnels. Stakeholders felt that installation of the pipework at least 200mm from the tunnel intrados would appropriately mitigate this risk. Flow and return pipework could also be embedded in mass concrete if this was felt to be necessary.
6. **Maintenance:** Little maintenance was expected to be required within the tunnel once the system was commissioned and handed over. Circulation and heat pumps, which may require maintenance or replacement, can be placed outside of the tunnel environment for easier safe access.

5. Assessment of potential energy use in the vicinity of tunnel energy locations

A key factor for infrastructure developers considering investment in thermal activation of buried infrastructure is the benefit the investment is likely to deliver and how this will be derived. Energy use options were explored for the heating and cooling potential of the tunnel energy systems. Both on-site consumption by the rail operator or external thermal energy transfer to third-party customers were considered. Figure 5 illustrates how tunnel energy could be used by single large users, which could be internal or external, or distributed to multiple users via traditional high-temperature or newer generation ambient temperature networks featuring distributed heat pumps at each user.

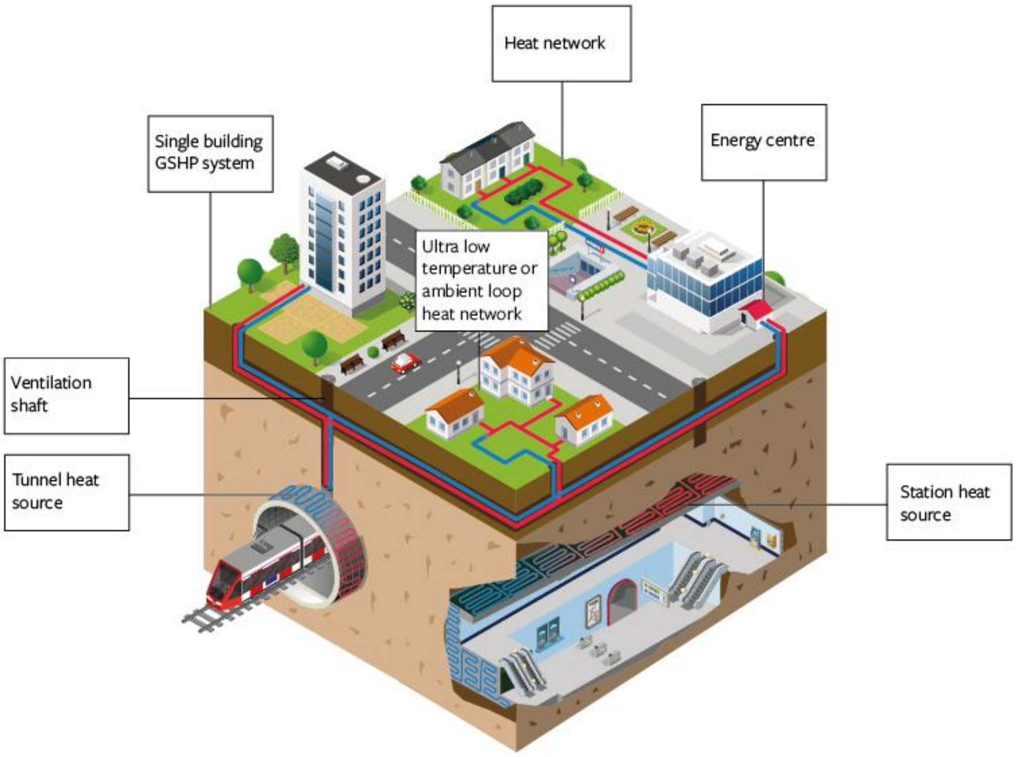


Figure 5 Tunnel energy system with different supply options

For on-site consumption by HS2 Ltd in stations and other facilities, benefit is derived through offering a source of low carbon energy for heating and cooling which would otherwise not be accessible. Given HS2 Ltd's net zero commitments, an appropriate counterfactual would be air source heat pumps (ASHPs). Like the ground source energy from the tunnels, ASHPs use electricity to drive compressors that move thermal energy from outside to where it is needed within the building, and vice-versa for cooling. Both approaches can be considered net zero compatible due to UK grid decarbonisation commitments or when connected to local renewable electricity generation. However, because the tunnels and surrounding earth are warmer in winter and cooler in summer than ambient air, and they can facilitate storage of waste heat, they can deliver greater levels of efficiency for equivalent systems (Gleeson and Lowe, 2013). This translates to lower running costs, earlier achievement of net zero carbon, and smaller demand on the UK's finite renewable electricity generation which supports system-wide decarbonisation efforts.

As an alternative to operator self-consumption in stations or other buildings, the study considered energy demand by large energy consumers including nearby hospitals, universities and manufacturing sites, as well as multiple users, including homes, via heat networks (although generally referred to as heat networks, depending on the design, they can supply both heating and cooling). Heat network development is a complex and time-consuming process, and well outside of core business of a rail operator. Therefore, in reality the ability to supply heating or cooling via a heat network depends on the current or expected future existence of a suitable network. As part of its net zero commitments, the UK government plans to implement heat network zones across England in 2025, having already been introduced in Scotland in 2021 (BEIS, 2021b, 2022a; HM Government, 2020; Scottish Government, 2021). It is expected that within heat network zones, new buildings, existing large public sector buildings, large non-domestic buildings and residential buildings which already have communal heating or are undergoing major refurbishment will be required to connect to a heat network (BEIS, 2022b). The primary aim of implementing this policy is to scale-up heat network deployment through reducing the risk to developers and their investors (HM Government, 2020).

This study considered currently available heat networks in the vicinity of extraction points, and the potential for future network development in light of heat network zoning. Local authority stakeholders implementing heat networks were engaged to explore the potential impact on tunnel heat demand. Mapping exercises explored potential energy demand in the vicinity of ventilation shafts and tunnel portal access points. Table 4 shows a summary of this work for a sample of extraction points. For each potential customer, a summary is provided of demand profile, whether internal (i.e. the rail operator) or external (i.e. transfer to a third party), whether a heat network would be required to deliver the energy, and if so, whether it is in place or expected to be under current plans.

Table 4 Sample of assessment of potential thermal energy customers and locations

Extraction location	Potential demand source	Demand profile	Internal / external	Connection type	Heat network in place
Manchester Tunnel North Portal	Mixed commercial, healthcare and residential customers	Commercial, healthcare, residential	External	Heat network	Yes
	Future over-site development	Residential & commercial	External	Heat network	No
	Trackside buildings	Commercial	Internal	Direct connection	N/A
	Medium / low density housing	Residential	External	Heat network	No
Birchfields Road Ventilation Shaft	University campus & sports centre	Commercial & residential	External	Direct connection	N/A
	Low density housing, schools x 2	Residential & education	External	Heat network	No
	Hotel	Commercial	External	Heat network	No

Extraction location	**Potential demand source**	**Demand profile**	**Internal / external**	**Connection type**	**Heat network in place**
Palatine Road Ventilation Shaft	Low density housing	Residential	External	Heat network	No
Wilmslow Road Ventilation Shaft	Hospital	Healthcare	External	Direct connection	N/A
	Medium density housing	Residential	External	Heat network	No
Middlewich Street Ventilation Shaft	Civic and municipal buildings	Commercial	External	Heat network	Yes
	Medium-density housing	Residential	External	Heat network	Reliant on expansion plans
	School, care home, crematorium	Commercial, education	External	Heat network	No
Cowley Way Ventilation Shaft	Rail station (existing)	Commercial	Internal	Direct connection	N/A
	Business park	Commercial & industrial	External	Heat network	No
	University campus	Education & residential	External	Direct connection	N/A
	Trackside buildings	Commercial	Internal	Direct connection	N/A
	Supermarket	Commercial	External	Either	N/A

Some extraction locations such as the Cowley Way Ventilation Shaft feature potential internal and external users. This is likely to make a more attractive investment opportunity, but with challenges in decisions around whether the energy will be used onsite and issues around equity of access if serving the community (Carley and Konisky, 2020). Other areas however, such as the around the Palatine Road Ventilation Shaft, feature no rail facilities for internal consumption, with primarily low-density housing and stakeholder engagement suggesting no current plans for heat network development. Without access to users via a heat network, these present a less attractive opportunity.

Stakeholder engagement with large energy consumers in the vicinity of the identified assets in both Manchester and Crewe was undertaken to assess theoretical appetite to become off-takers of heating or cooling should systems be implemented during tunnel construction. Large energy users that were engaged included two local authorities, one hospital, a university, a heat network developer, and a residential developer. This consultation found genuine interest in considering heating and/or cooling purchase in their decarbonisation plans. A summary of responses is provided here:

1. **Hospital:** The hospital stakeholder highlighted their very high year-round heating and cooling demand and associated energy costs. They were particularly interested in the cooling potential because climate change-related summer temperatures are increasing the need for cooling, with resilience lacking in current supply.
2. **Heat network:** Currently in construction, a heat network was identified in the vicinity of the Manchester tunnel north portal that will initially supply a hospital, area of new residential development and student accommodation. The stakeholder reported that they are considering a range of heat sources to support their network decarbonisation and future expansion and were keen to explore future integration of tunnel heat.
3. **Local authorities:** Support was expressed by the local authorities covering both areas of tunnel construction, although in both cases the timeframe for tunnel heat availability did not directly support their decarbonisation commitments which require earlier achievement of net zero carbon. In the Crewe area, the local authority was keen to consider integration of tunnel heat into a heat network currently in pre-construction phase. The local authority in the Manchester area identified social housing currently in the hands of a private landlord but due to be returned to the authority in the early 2030s as a potentially ideal user of the tunnel heat.

4. **Property developer:** The stakeholder acted to manage land post-construction of HS2, some of which would be subject to new areas of development above the tunnels. Engagement was motivated by potential ideal alignment of development timeframes and tunnel heat availability. Although the stakeholder wouldn't develop the land themselves, they felt there may be interest by future site developers.
5. **University:** A major university with a local campus and sports centre in the vicinity of the Manchester tunnel was engaged. The tunnel construction timeline did not align with their decarbonisation commitments, and their plan for significant redevelopment of the buildings meant that a potential heat demand could not be estimated. However, they were interested in further engagement to obtain a long-term, secure energy supply.

Overall, potential energy users were keen to continue engaging with regards to future offtake. However, it was clear that early stages of tunnel planning (i.e. with heat delivery starting from late 2030s), while necessary for overcoming technical and other challenges as noted in Section 4, likely mean little possibility of securing firm agreements at this stage. Any such agreements would likely mean little over the long timeframes involved, in any case. This timescale misalignment remains one of the greatest challenges to uptake of energy tunnels for external supply.

6. Economic, business and carbon case

As explored in Section 5, there was interest in using the tunnel heat beyond the boundary of the HS2 project. However, without detailed information about future customers and their energy demands, it is hard to determine the financial viability of this scenario. Economic modelling of internal self-consumption of heating and cooling by the rail operator was undertaken to consider the business case and financial viability where there was sufficient information to do so.

The financial case for implementing the tunnel energy system was explored through modelled costs and benefits of adopting energy tunnels connected to GSHPs compared to a counterfactual case based on equivalent energy delivery with ASHPs. This was considered appropriate given both HS2 Ltd's net zero commitments and that operation of the scheme will not take place for a further ten years or more, when use of gas boilers is not expected to be permitted (HS2 Ltd, 2022a).

A tunnel energy solution would accrue additional capital costs over and above the rail infrastructure for design, materials and installation. Benefits are primarily accrued through electricity cost and carbon savings to provide an equivalent heating and cooling demand when compared to an the ASHP counterfactual.

Cost estimates for additional design, construction and commissioning activity were based on prior work considering geothermal activation of the Northolt Tunnel in HS2 Phase 1 (Legg, 2014; Smith, 2015; Thompson, 2015b, 2015a). It is accepted that these costs would need to be updated as designs develop. However, they provided a basis for analysis to clarify whether viability on purely financial terms was at least feasible. Table 5 shows a summary of the additional costs necessary to implement the tunnel geothermal lining.

Table 5 Capital cost (CAPEX) for geothermal activation of tunnel lining for Manchester and Crewe tunnels

Tunnel	**Tunnel dimensions**	**Running tunnel length for thermal activation (km)**	**CAPEX, per km (£m)**	**CAPEX, total (£m)**
Manchester	2 tunnels, diameter 7.6m, length 12.8km, 4 ventilation shafts	10 (+131m for ventilation shafts)	1.37	13.7
Crewe	2 tunnels, diameter 8.8m, length 6.8km, 2 ventilation shafts	6 (+66m for ventilation shafts)	1.47	8.9
Total				22.6

Further to the additional expenditure required to install, test and commission the geothermal tunnel lining system, heat pumps are required to deliver heating and cooling to users. Heat pump costs vary according to system size, with figures of £800/kW for geothermal heat pumps and £483/kW for the counterfactual case of commercial ASHPs used, based on supply chain stakeholder guidance and DECC (2020). Table 6 shows total heat pump costs for the two tunnels for Scenario 1 and 2 system capacities and equivalent costs.

Table 6 Capital expenditure for heat pumps to achieve equivalent energy delivered in Scenarios 1 and 2 (S1, S2)

Tunnel	Total heat pump capacity (MW)	Equipment cost, geothermal heat pumps (£m)	Equipment cost, ASHPs (£m)
Manchester	4.5 (S1), 7.5 (S2)	3.6 (S1), 6.6 (S2)	2.2 (S1), 3.6 (S2)
Crewe	2.4 (S1), 5 (S2)	1.9 (S1), 4 (S2)	1.2 (S1), 2.4 (S2)

HS2 Ltd provided their financial appraisal model, which enabled estimation of Net Present Value (NPV), Internal Rate of Return (IRR), and discounted and undiscounted payback using HS2 and Dept. for Transport (DfT) approved assumptions, shown in Table 7.

Table 7 Business case input parameters for illustrative sample of years of operation

	2035 (first year of operation)	2040	2050	2100
Discount rate (Green Book)	3.5%	3.5%	3.5%	3%
Electricity price (real 2020 p/kWh) (Green book, Table 4, High estimate, Commercial/public sector)	15.204	14.796	14.796	14.796
Electricity emissions (kg CO_2e/kWh) (TAG databook, A3.3, Rail)	0.042	0.014	0.006	0.006

The financial model inputted the estimated geothermal solution costs evenly across tunnel construction between 2028-2033, with heat pump costs in all scenarios incurred the year before tunnel operation is expected to begin in 2035 and replaced every 20 years. Running costs for heat pump and circulation pump electricity as well as equipment maintenance are incurred from 2035 onwards. Running costs are impacted by the expected heat pump Seasonal Performance Factor (SPF), the ratio of heat delivered to electricity input over one year. For the geothermal system this was assumed to be SPF 3.0, which is a conservative assessment and could be higher with significant inter-seasonal storage of heat. For the ASHP counterfactual, all installation and equipment costs were assumed to take place in 2034 to be ready for generation in 2035, to match the heat-on date of the tunnel solution. As per the tunnel solution, energy supply and associated running costs begin from 2035, providing the same heating and cooling supply, but with a SPF 2.2. Heat pump efficiency estimates were deemed appropriate given evidence of in-situ performance for UK systems (RB&M Research, 2024).

6.1 Results of economic modelling

The tunnel solution was found to be financially viable when compared to the ASHP counterfactual in most circumstances. However, viability is particularly dependent on real interest rates (a measure of actual interest rates minus inflation). Figure 6 shows how the tunnel system returns a favourable heat generation cost that at real interest rates of below 2% (Scenario 1) and 4% (Scenario 2).

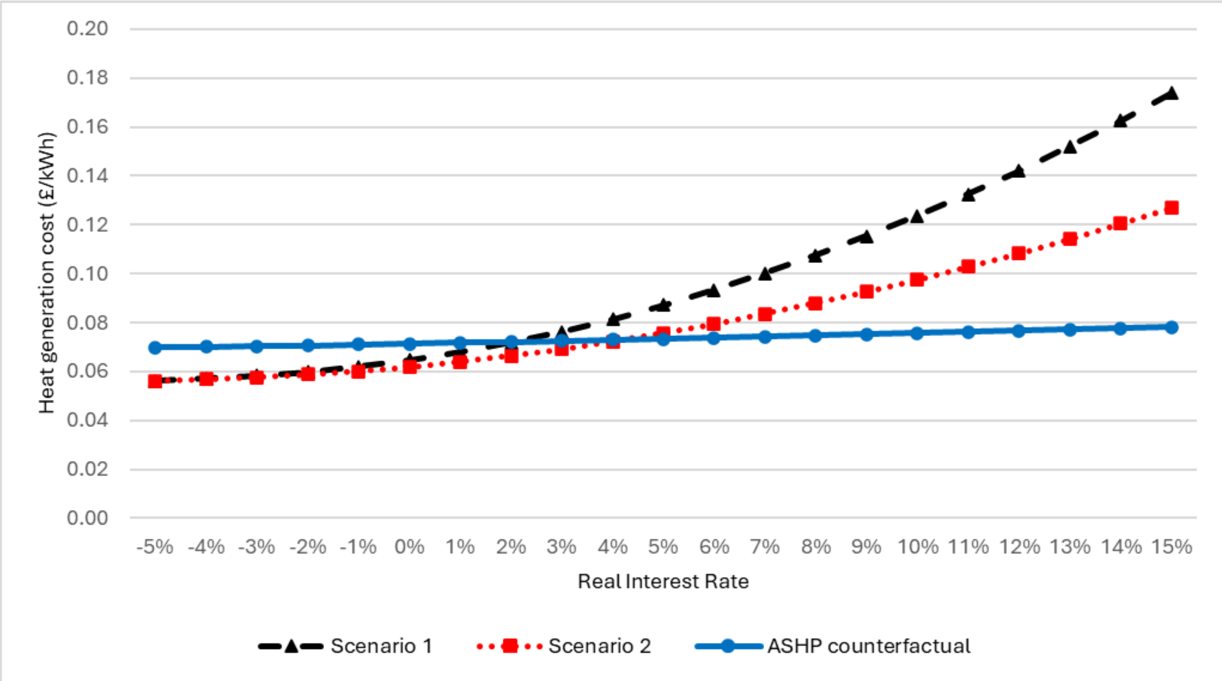


Figure 6 Real Price of Heat (£/kWh) expressed in £2024, against the real interest rate. Calculated equating NPV to zero.

It is difficult to predict future inflation and interest rates, and further consideration should be given to this if achieving financial viability on these terms is essential to the decision to invest. At the time of assessment, interest rates of 5.25% and inflation of 3.9% resulted in a real interest rate of around 1.3%, indicating financial viability. In fact, Bank of England and Office for National Statistics data show that real interest rates have been lower than 4% for most of this century.

A sensitivity analysis was undertaken based on the input ranges in Table 8 to assess how different factors impacted financial viability. Figure 7 shows how the future price of electricity and system efficiency have the most significant impact on payback time of the tunnel system.

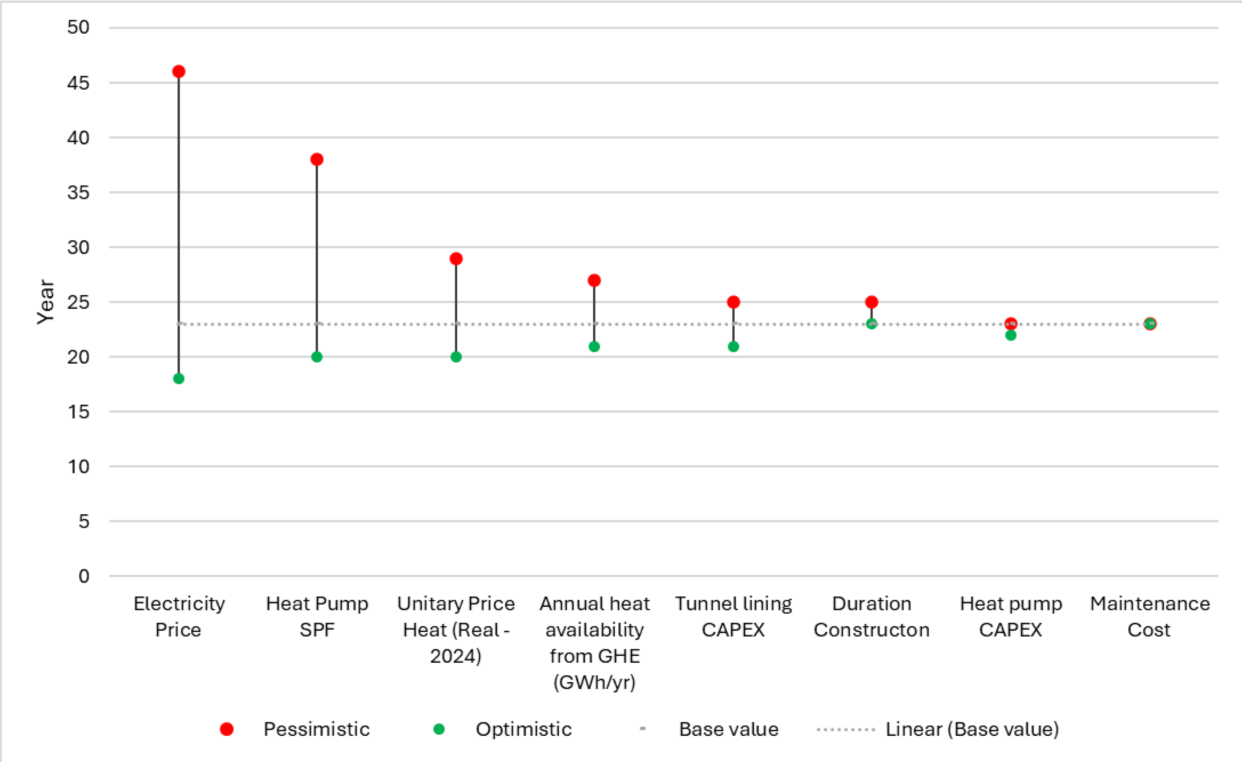


Figure 7 Sensitivity analysis of the impact of various inputs on payback time

A Monte Carlo analysis was undertaken over 20,000 simulations to consider outcomes under a range of scenarios between optimistic and pessimistic values in Table 8. Base, optimistic and pessimistic values were derived from previous projects and from HS2's own experience as discussed in the previous sections, with other data sources summarised in Table 8. The optimistic and pessimistic bounds were set at approximately ±20–30% of the base values, reflecting plausible variations based on engineering judgement and available industry data for comparable systems. Figure 8 shows that in approximately 80% of the cases the geothermal intervention generates financial value for investors.

Table 8 Input data for economic modelling sensitivity and Monte Carlo analyses

Input	Base value	Pessimistic	Optimistic	Input Data Source
Heat pump SPF	4	3	5	RB&M Research, 2024
Unitary Price of Heat (Real - 2024)	0.08 £/kWh	0.07 £/kWh	0.09 £/kWh	Prior project experience

Input	Base value	Pessimistic	Optimistic	Input Data Source
Construction duration	5 years	7 years	5 years	HS2 programme
Electricity price	22 p/kWh	30 p/kWh	14 p/kWh	Prior project experience
Annual heat availability from GHE	76 GWh/yr	54 GWh/yr	98 GWh/yr	Analysis in Section 3
Maintenance Cost	129,517 £/Yr	174,628 £/Yr	90,234 £/Yr	HS2 Phase 1
Heat pump CAPEX	£7,400,959	£10,477,669	£4,858,732	DECC (2020)
Tunnel lining CAPEX	£22,566,419	£27,079,703	£18,053,135	HS2 Phase 1

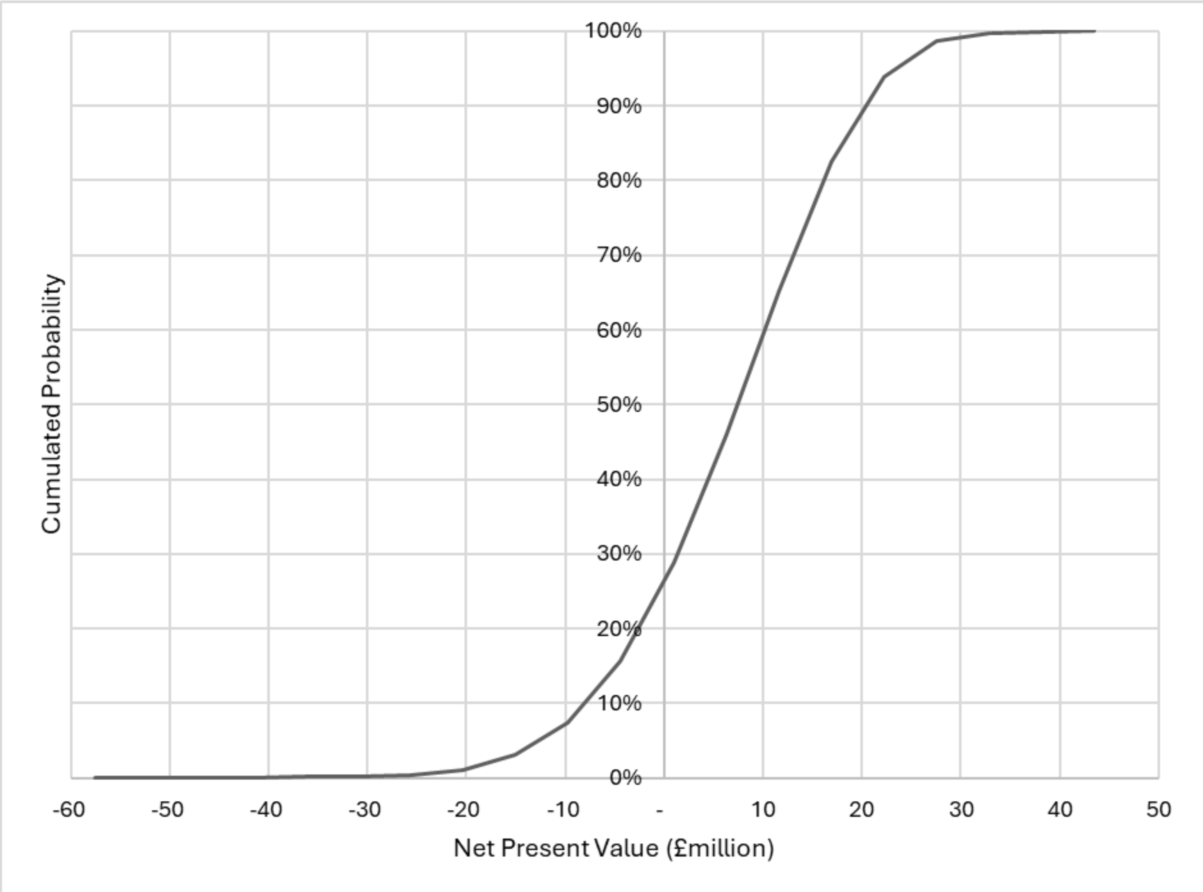


Figure 8 Results of Monte Carlo analysis for NPV showing the percentage of 20,000 simulations in which the geothermal solution results in a positive or negative NPV.

The findings of this analysis suggest that investing in the geothermal intervention is relatively secure. This is further supported by a uniform distribution between the pessimistic and optimistic values which likely overestimates the investment uncertainty.

A potential limitation of this analysis was the given input values for the cost of capital and the inflation rate which were provided by the HS2 financial appraisal using DfT approved values (DfT, 2022). Given the recent changes in inflation and interest rate levels, it is uncertain whether the values provided by the HS2 are still representative of the current and future economic context.

Overall, results suggest that the proposed solution can work financially. Whilst there are scenarios considered where it does not, consistently conservative assumptions were applied to assess the investment's feasibility. To be able to make final decisions on financial viability would require better understanding of system design components, especially energy availability and SPF of the system. These could be determined through outline design, but would require more ground investigation information, and tunnel ventilation details. Additionally, the results are highly dependent on assumptions regarding interest rates, inflation, and future costs of electricity, which are all exogenous to HS2. However, these sources of uncertainty could be reduced significantly by government policy. For example, the SDE++ (Stimulering Duurzame Energieproductie en Klimaattransitie) in The Netherlands provides geothermal developers a guaranteed income through subsidies which cover the difference between the cost of geothermal heat production and the market price of energy for 12-15 years (RVO, 2023).

6.2 Carbon benefit

The carbon benefit of the geothermal solution compared to an ASHP counterfactual were modelled for the two scenarios, as set out in Table 9. Whilst both approaches can be considered net zero compatible when using input of grid electricity which is set on a path to very low carbon emissions. However, low levels of residual carbon emissions associated with grid electricity generation remain, meaning that the geothermal solution delivers some operational carbon reductions due to greater levels of efficiency over the project life.

Table 9 Carbon emissions of geothermal solution for Scenario 1 and 2, with savings compared to equivalent ASHP counterfactual

	Scenario 1	Counterfactual 1	Scenario 2	Counterfactual 2
Carbon emissions, per year (2035) (t/CO2)	881	1,152	1,596	2,086
Carbon savings, per year (t/CO2/yr)	-271	-	-490	-
Carbon emissions over 60 years (t/CO2)	11,234	14,681	20,349	26,593
Carbon savings over 60 years (t/CO2)	3,447	-	6,244	-

The results show a carbon saving of between 271 and 490 tonnes per year, primarily delivered early on in the operating life (in the late 2030s and early 2040s). The modelling was conducted prior to government Clean Power 2030 commitments to reach 95% of UK electricity generation from clean sources by 2030 (UK Government, 2024). This will reduce the direct carbon benefit of the higher efficiency geothermal solution. However, individual energy choices by large users such as HS2 potentially have significant system-wide impacts when scaled up to the level of a city or the GB energy system. Although not modelled here, the lower overall demand and greater flexibility of the geothermal solution can support carbon reduction in other parts of the energy system.

7. Delivery model

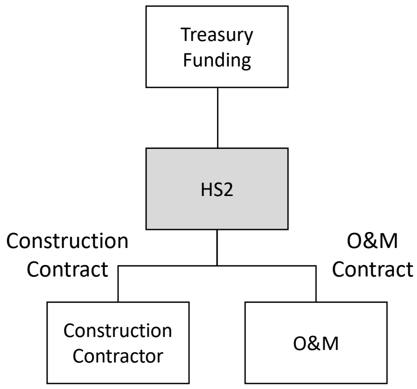
A range of delivery models were explored. Decisions about the appropriate model to pursue will depend on whether energy is self-consumed by the rail operator or sold to an external off-taker. In either case there are options of traditional financing (TF) (investment funded by HS2 Ltd / HM Treasury) or project financing (PF) (investment funded by lenders). Table 10 presents the four main combinations between the commercial assumptions (Scenario A, B, Table 10) and the financial ones (traditional financing, project financing).

Table 10 Primary business & financial models considered for the geothermal intervention

	Financial approach	
Commercial scenarios	**Traditional financing (TF)**	**Project financing (PF)**
Scenario A- HS2/rail operator self-consumption	Model 1 Scenario A - TF	Model 2 Scenario A - PF
Scenario B- Single large off-taker	Model 3 Scenario B - TF	Model 4 Scenario B - PF

The relationships involved in the two financial approaches are represented diagrammatically in Figure 9 for TF and with the additional complexity of PF in Figure 10. A special purpose vehicle (SPV) is required to ring-fence the assets and financial risk in the latter case (Sainati et al., 2017).

These general delivery modes supported discussions with large energy users and a potential lender to gauge their interest in becoming investors. They also informed various analyses to help HS2 Ltd decide whether to invest it directly or use project financing. Numerous issues regarding ownership and technical warranties make it impossible to view the geothermal source as a separate asset from the railway infrastructure, making project financing difficult to implement. Consequently, it is more practical to consider a TF approach in combination with long-term offtake contracts associated with the purchase of heat by large consumers. However, one critical challenge concerns the timing and governance complications related to negotiating such off-take agreements. To be negotiable, this investment requires a strong commitment and decision by the seller, in this case HS2 Ltd and the funding government departments.



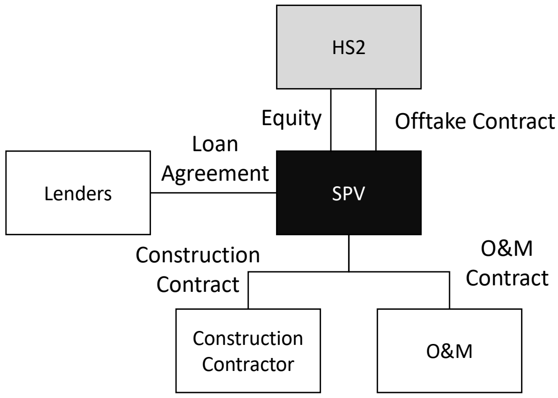


Figure 9 Model 1 scenario A (TF)

Figure 10 Model 2 Scenario A (PF)

8. Discussion

The study found a viable case for dual-use of rail tunnels to provide heating and cooling to users above in two UK locations. Whilst there are technical and construction challenges to be overcome, there was appetite from stakeholders to do so. There was a positive although marginal financial case for investment in the additional upfront construction costs based on long-term benefits of more efficient and lower running costs of low carbon heat, as well as support from potential future heat users.

Although viability was marginal at the individual scheme level, given the national need for sources of energy for heating and cooling and abundant low carbon heat which could be made available through dual-use buried infrastructure, the study findings make the case for further consideration and development. Currently the Phase 2B leg of HS2 is not expected to progress to construction, but huge opportunities remain. Loveridge et al (2022) found 226 GWh/year annual energy available from planned UK transport infrastructure construction. It is therefore important to explore why this remains a highly niche approach with few successful schemes worldwide and none in the UK.

From an economic perspective, the results of the sensitivity analysis shown in Figure 7 highlighted the most important determinant of a positive financial case to be the cost of electricity. This will become ever more important as electrified heat (primarily with heat pumps wither directly or via heat networks) is expected to do the heavy lifting of heat decarbonisation (BEIS, 2021c). However, a fundamental challenge and energy market failure is the GB energy system which ties the wholesale cost of electricity to the most expensive generation (currently gas-fired) and has the effect of inflating the cost of electricity for all consumers (Harrington, 2024; Zakeri et al., 2023). With the UK Government having made ambitious commitments to clean power by 2030 (Milliband, 2024), there is an important link to be made between greater heat electrification and delivering against this ambition. Whilst an unplanned deployment of inflexible, inefficient and destabilising electrified heating systems (such as electric resistance heating) could threaten the transition, the flexibility benefits of tunnel-sourced heating and cooling with the potential for storage could support the target in two ways. Firstly, as a technical mechanism to help balance the grid and intermittent renewables primarily through being able to reduce demand at times of reduced supply. Secondly, a scheme of this kind can also provide system-wide benefits through additional flexibility helping to decouple wholesale electricity prices from the most expensive generation and make electrified heat more cost-effective across the board (Harrington, 2024).

The findings illustrate where a more joined-up approach at a national government level may help unlock project development. In this case, investment in HS2 transport infrastructure originates from the Department for Transport (DfT), whilst the Department for Energy Security & Net Zero (DESNZ) is responsible for delivering against the UK's net zero pledges, including recent commitments to clean power by 2030 as well as scaling up deployment of heat networks including through Heat Network Zoning policies due to come into force in early 2025 (DESNZ, 2024). Both are tied to funding from HM Treasury and subject to political decisions around investment priorities. Engagement with stakeholders suggested the process for obtaining a budget uplift to fund additional capital expenditure for the tunnel heat solution would be through an application to DfT. In short, we see the costs falling to one part of government and benefits to another. However, access to low carbon heat is essential to support deployment of heat networks and in successful implementation of Heat Network Zoning. This applies to both new as well as established heat networks, which are expected to grow significantly to serve far greater heat demands within zonal areas. The study found interest for integrating the tunnel heat solution in both cases, including as part of zonal-scale heat networks seeking a mixed economy of heat sources to come on stream at various points over the project lifecycle.

Taking these considerations together with the resolvable technical hurdles supports the case for government to recognise currently non-quantified benefits across departments and incentivise deployment of these types of schemes. One approach could be through HM Treasury establishment of a dedicated fund for flexible heat sources to be administered by DESNZ but which can be support schemes across the public estate. Importantly with the GB energy system operator identifying £60bn investment will be required by 2030 (ESO, 2024) prior to the even more ambitious 2030 clean power targets, recognising that investment in schemes like this now reduces system costs elsewhere means this does not have to be new money. Government rightly recognises required investment in the UK's energy system as an opportunity to create economic value, as well as the important role of the private investment in delivering a clean, secure and affordable energy system (Prime Minster's Office, 2024). An alternative may be to support government departments and their agencies to work with private sector partners to include innovative schemes like the tunnel heat solution in project development.

9. Conclusion

This study demonstrated that it is technically feasible and a worthwhile endeavour to use of HS2 Phase 2b tunnels beneath Manchester and Crewe for the extraction of geothermal heat alongside their primary structural function. The financial case for was found to depend especially on the following key input parameters to the techno-economic assessment:

- Future cost of borrowing and inflation
- Future cost of electricity
- Seasonal performance factor (or system efficiency) of the ground energy system
- Future cost of thermal energy from alternative sources
- Amount of thermal energy available

A future phase of the research would ideally include a more dynamic scenario analysis to model changes in heat demand due to climate or policy shifts.

Despite the opportunities, the geothermal solution carries additional costs and comes with technical and contractual challenges that would need to be addressed. The success of the financial model depends on reducing uncertainty in two aspects. First, a better understanding of the future system that would come as the design progresses. Second, external financial factors such as interest rates and electricity prices.

Overall, the geothermal solutions like this have the potential to deliver a valuable resource of low-carbon energy to provide heating and cooling to the population above. This would not only support the wider decarbonisation but also help infrastructure developers to meet their requirements as good corporate citizens. With only one opportunity to include the solution and many opportunities for future removal if it should prove to be a non-viable investment, early adoption and development should be pursued. Since the benefits of such solutions align to different government departments to likely funding sources, cross department support may be required. Combined with an overdue review of energy price policy, this could unlock many otherwise inaccessible but valuable heat sources in the national interest.

Acknowledgements

The authors would like to acknowledge HS2 Ltd which funded the project, and in particular thank the Phase 2b Geotechnical and Innovation Teams for their guidance and support as well as access to relevant materials and opening doors to engagement with wider stakeholders. Partners from the UK Collaboratorium for Research in Infrastructure and Cities (UKCRIC) supported and provided the framework for delivery of this work. FL acknowledges funding from the Engineering and Physical Sciences Research Council under grant EP/S001417/1.

Abbreviations

ASHP, air source heat pump; COP, coefficient of performance; DfT, Department for Transport; GSHP, ground source heat pump; GWh, gigawatt-hour; HS1, High Speed 1; HS2, High Speed 2; km, kilometre; NPV, net present value; IRR, internal rate of return; PF, project financing; SCL, Sprayed Concrete Lining; SPF, seasonal performance factor; SPV, special purpose vehicle; TBM, Tunnel Boring Machine; TF, traditional financing; TRT, Thermal Response Testing;

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Figure 1. Schematic representation of a tunnel segmental lining equipped as ground heat exchanger.

Figure 2. Schematic of tunnel energy system showing embedded pipework and flow/return pipes in the tunnel (Nicholson et al., 2014a).

Figure 3. Maps showing route and shaft locations for the proposed Manchester and Crewe tunnels (Arrowsmith, 2022)

Figure 4. Tunnel energy per unit area for different conditions

Figure 5. Tunnel energy system with different supply options

Figure 6. Real Price of Heat (£/kWh) expressed in £2024, against the real interest rate. Calculated equating NPV to zero

Figure 7. Sensitivity analysis of the impact of various inputs on payback time

Figure 8. Results of Monte Carlo analysis for NPV showing the percentage of 20,000 simulations in which the geothermal solution results in a positive or negative NPV

Figure 9. Model 1 scenario A (TF)

Figure 10. Model 2 Scenario A (PF)