This is a repository copy of *The potential for heat recovery and thermal energy storage in the UK using buried infrastructure*.

White Rose Research Online URL for this paper:
https://eprints.whiterose.ac.uk/186253/

Version: Accepted Version

Article:

Loveridge, F, Schellart, A, Rees, S et al. (10 more authors) (2022) The potential for heat recovery and thermal energy storage in the UK using buried infrastructure. Proceedings of the Institution of Civil Engineers - Smart Infrastructure and Construction, 175 (1). pp. 10-26.

https://doi.org/10.1680/jsmic.21.00018

© 2022 The Author(s). This is the accepted manuscript of a paper subsequently published in Proceedings of the Institution of Civil Engineers - Smart Infrastructure and Construction. This version is distributed under the terms of the Creative Commons Attribution Licence (http://creativecommons.org/licenses/by/4.0), which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.

Reuse

This article is distributed under the terms of the Creative Commons Attribution (CC BY) licence. This licence allows you to distribute, remix, tweak, and build upon the work, even commercially, as long as you credit the authors for the original work. More information and the full terms of the licence here: https://creativecommons.org/licenses/

Takedown

If you consider content in White Rose Research Online to be in breach of UK law, please notify us by emailing eprints@whiterose.ac.uk including the URL of the record and the reason for the withdrawal request.

eprints@whiterose.ac.uk
https://eprints.whiterose.ac.uk/

Accepted manuscript
doi: 10.1680/jsmic.21.00018

Accepted manuscript

As a service to our authors and readers, we are putting peer-reviewed accepted manuscripts (AM) online, in the Ahead of Print section of each journal web page, shortly after acceptance.

Disclaimer

The AM is yet to be copyedited and formatted in journal house style but can still be read and referenced by quoting its unique reference number, the digital object identifier (DOI). Once the AM has been typeset, an ‘uncorrected proof’ PDF will replace the ‘accepted manuscript’ PDF. These formatted articles may still be corrected by the authors. During the Production process, errors may be discovered which could affect the content, and all legal disclaimers that apply to the journal relate to these versions also.

Version of record

The final edited article will be published in PDF and HTML and will contain all author corrections and is considered the version of record. Authors wishing to reference an article published Ahead of Print should quote its DOI. When an issue becomes available, queuing Ahead of Print articles will move to that issue’s Table of Contents. When the article is published in a journal issue, the full reference should be cited in addition to the DOI.

Downloaded by [UNIVERSITY OF SHEFFIELD] on [29/04/22]. Copyright © ICE Publishing, all rights reserved.

Submitted: 30 July 2021

Manuscript title: The potential for heat recovery and thermal energy storage in the UK using buried infrastructure

Authors: Fleur Loveridge[1], Alma Schellart[2], Simon Rees[1], Ross Stirling[3], David Taborda[4], Simon Tait[2], Luca Alibardi[5], Giovanna Biscontin[6], Paul Shepley[2], Ida Shafagh[1], Will Shepherd[2], Anil Yildiz[3,7], Bruce Jefferson[5]

Affiliations: [1]School of Civil Engineering, University of Leeds, Leeds, UK. [2]Department of Civil and Structural Engineering, University of Sheffield, Sheffield, UK. [3]School of Engineering, Newcastle University, Newcastle-upon-Tyne, UK. [4]Department of Civil and Environmental Engineering, Imperial College London, South Kensington Campus, London, UK. [5]Cranfield Water Science Institute, Cranfield University, Cranfield, UK. [6]Department of Engineering, University of Cambridge, Schofield Centre, Cambridge, UK. [7]Methods for Model-based Development in Computational Engineering, RWTH Aachen University, AachenGermany.

Corresponding author: Fleur Loveridge, School of Civil Engineering, University of Leeds, Leeds LS2 9JT, UK.

E-mail: f.a.loveridge@leeds.ac.uk

Abstract

Dispersed space heating alone accounts for 40% of UK energy use and 20% of CO_2 emissions. Tackling heating and building cooling demands is therefore critical to achieve net zero ambitions in the UK. The most energy efficient way to decarbonise heating and cooling is through the use of ground source heat pumps and district heating technology. However, capital costs are often high, sometimes prohibitively so. To reduce investment costs, it is proposed to use buried infrastructure as sources and stores of thermal energy. Barriers to this innovative approach include lack of knowledge about the actual net amount of recoverable energy, and impacts on the primary function of any buried infrastructure, as well as the need for new investment and governance strategies integrated across the energy and infrastructure sectors. Additional opportunities from thermal utilisation in buried infrastructure include the potential mitigation of damaging biological and/or chemical processes that may occur. This paper presents a first assessment of the scale of the opportunity for thermal energy recovery and storage linked to new and existing buried infrastructure, along with strategic measures to help reduce barriers and start the UK on the journey to achieving of its infrastructure energy potential.

1. Introduction

The UK has committed to bring all greenhouse gas emissions to net zero by 2050, compared with the previous target of 80% reduction from the 1990 level (BEIS, 2019). While the carbon intensity of the national electricity grid has more than halved in the last five years (Figure 1), there has been much slower progress in switching heating and cooling to renewable sources. In the UK, heating and hot water use account for 40% of energy consumption and approximately 20% of our greenhouse gas emissions (CCC, 2016). While the UK demand for space cooling is still relatively small, it is expected to increase substantially as the summer air temperatures increase (median prediction of a 3.1°C rise by 2061-2080; Murphy et al. 2019). Consequently, National Grid (2018) estimate that peak electricity demand due to cooling could more than double (to 36 GW) by 2050.

Burning of natural gas accounts for 70% of all heating in the UK and is the largest contributor to emissions (CCC, 2016). Now it is timely to switch to electrification (Figure 1). The UK Heat and Buildings strategy (HM Government, 2021) foresees a combination of district heating in urban centres and electric heat pumps in sub-urban developments as key elements of the national pathway to net-zero energy. Use of large-scale heat pumps in district heating is increasingly carbon efficient and can utilize a range of low temperture sources of thermal energy including infrastructure heat exchange systems.

Whether heat pumps are applied in large-scale district heating or are integrated locally to a building, to achieve emissions reductions is a function of both system thermal efficiency and the carbon intensity of the grid electricity supply. It has been demonstrated at a range of scales that heat pumps for buillding heating (and cooling) can operate with efficiencies greater than 300% (e.g Spitler & Gehlin, 2019). Given thermal power generation has efficiency greater than 35%, use of a heat pump is firstly beneficial in reducing primary energy consumption. More significantly, as the carbon intensity of delivered grid electricity reduces (Figure 1), heat pump systems are able to deliver ever incrasing carbon emission savings over conventional gas heating systems. Moreover, as the downward trend in carbon intensity of the grid is projected to continue, emissions from heat pump systems will follow this trend over their operating lifetime (Figure 1).

Heat pumps offer their highest efficiencies when operating with the ground, or a similar stable temperature medium, as a source (Self et al, 2013) and also when addressing both heating and cooling demand using inter seasonal storage (Sarbu & Sebarchievici, 2014). However, a major barrier to uptake in recent years has been the large capital costs (EGEC, 2014, Karytsas & Choropanitis, 2017), which are related to the construction of the ground heat exchanger (GHE). One solution to this challenge is to make use of existing planned civil engineering works which involve the ground to remove the need to make costly special purpose excavations. Heat pump technology could exploit a wide range of heat sources related to the buried infrastructure themselves, including foundations, urban drainage systems and drinking water systems.

While adoption of so called energy geostructures (Figure 2), where a civil engineering asset is used for both its original purpose and for heat transfer and storage, has increased in recent years, the total number of installations is still relatively low (Di Donna et al, 2017).

However, with over £600 billion due to be invested in approximately 700 infrastructure projects in the next ten years (Infrastructure and Projects Authority, 2018), many of them with significant ground works components, there are many opportunities to convert infrastructure assets to sources of heat and/or heat exchangers for seasonal thermal storage. This paper considers how UK infrastructure assets offers a wide range of future possibilities for accessing renewable and low carbon heating and cooling.

2. Background on energy geostructures

2.1 Substructures and transport infrastructure

The first energy geostructures, constructed in the 1980s, were piled foundations (Brandl, 2006), with deep foundations for a building used instead of traditional borehole heat exchangers to provide heating and/or cooling to the overlying building. Often piles alone were insufficient to meet all the energy demand of a building and either additional traditional open or closed loop GHE were used to supplement the piles (e.g Turner et al, 2021), or auxiliary heating/cooling systems were used (e.g. Pahud & Hubbach, 2007). The first pile heat exchangers in the UK were at Keble College in Oxford (Suckling & Smith, 2002). Basement walls and slabs were a natural extension to the pile heat exchanger concept, and while not as common, they have been adopted in a number of locations (e.g. Kipry et al, 2008, Angelotti & Sterpi, 2018). The key difference between piles and embedded retaining walls is that excavation space in front of walls reduces the energy available for exploitation. In foundation slabs, which do not have the benefit of an embedded section, this capacity is reduced again.

Transportation tunnels have also been used for energy exchange, with notable trials in

Austria and Germany (Schnieder & Moorman, 2010, Franzius & Pralle, 2011). While the inside of the tunnel is exposed to the air, there is the additional possibility of a heat source from air movement and train braking in metro systems. This makes the sections of tunnels close to metro stations of particular interest for energy exploitation. The excavations for metro stations themselves are also another opportunity for heat transfer and storage extraction (Bidarmaghz & Narsilio, 2018), with examples in London (Soga et al, 2015) and Paris (Delerablee et al, 2018).

Thermal design of piles, walls, slabs and tunnels to determine energy capacity can be carried out by analytical or numerical methods. The different approaches are reviewed in Loveridge et al (2019), with some rules of thumb provided in Table 1.

2.2 Water and wastewater infrastructure

Heat can be recovered from wastewater treatment works, from sewer networks, from wastewater drainage pipework within homes, and potentially from drinking water networks. Hepbasli et al (2014) estimates that worldwide over 500 systems of wastewater source heat pumps are operational, mainly in Switzerland, Germany and Scandinavia. A considerable amount of research has focused on heat recovery from wastewater treatment works (Hao et al., 2019) but less on heat recovery at household levels or from sewer systems (e.g. Kretschmer et al., 2016; Hepbasli et al., 2014). The first UK appliation of wastewater heat recovery technology was implemented at Nuffield College, Oxford (Kell et al., 1963).

Spriet et al. (2020) developed a methodology for assessing energetic, spatial and temporal patterns in the performance of wastewater treatment plant (WWTP) effluent heat recovery. For a case study, they concluded that heat recovery could be used to meet baseload heat demand, but with a need for storage and/or auxillary heating to cover peak demand. Abdel-Aal et al. (2018) simulated several sewer heat recovery location scenarios in an urban area case study. They reported a potential heat recovery of 116-207 MWh/day from a combined sewer network serving a population equivalent of 79000, concluding that heat recovery could potentially meet 7% to 18% of the area’s heat demand.

De Graaf et al. (2008) explored use of the urban surface water system for energy recovery in a new residential district in the Netherlands. They showed the potential for meeting heating and cooling needs through aquifer thermal energy storage supplemented with surface water heat collection. By cooling the urban surface water by 1.5-1.6 °C during three summer months, enough heat can be collected to satisfy the entire residential thermal demand.

Very limited research on utilising heat recovered from drinking water systems exists and as far as the authors are aware no systems are operational. Modelling studies report mixed results (De Pasquale et al., 2017; van der Hoek et al, 2018, Hubeck-Graudal et al., 2020), probably due to local climate conditions. For example, De Pasquale et al. (2017) concluded that using the drinking water system in Milan (Italy) for heat recovery could reduce primary energy consumption. However, Hubeck-Graudal et al. (2020) concluded that taking heat from drinking water in Copenhagen (Denmark) would increase end-use heat demand in households, causing the overall “system” efficiency to drop to unfeasible values.

2.3 Sustainable urban drainage

Green Infrastructure, including Sustainable Drainage Systems (SuDS) are becoming an increasingly common new-build and retrofit feature in our cities to improve the quality and resilience of the urban environment. While the exploitation of these systems for energy recovery is currently low, there is increasing interest in their potential due to the advantageous ground conditions inherent in their design and function.

Beneficial conditions have been established to exist for heat exchange in typical bioremediation devices; infiltration of excess surface water improves soil thermal properties, while the primary drainage function continues unaffected by the additional heat transfer (Yildiz & Stirling, 2022). Similar concepts have been trialled for permeable paving (Charlesworth et al., 2017) and laboratory scale experiments of heat exchange in wet swales have been successfully conducted (Rey-Mahía et al., 2019). The nearest equivalent, commercial applications have been explored around the use of urban green spaces and watercourses. These have most notably been documented by the ParkPower programme (Greenspace Scotland, 2021) who determined the combined heat supply potential from closed loop GHE in urban green spaces (and water source heat pumps in non-tidal rivers) across Scotland is equivalent to 79% of all heat demand from Scotland's settlements. However, this encompasses the broadest definition of green space and does not specifically target SuDS.

It is not clear what assumptions are made about heat transfer rates in the Greenspace Scotland study. However, ranges of heat availability may be expected to be similar to those for other shallow GHE (Table 1) more typically used, as demonstrated by trials of GHE combined with infiltration trenches in the north of England (Ali et al, 2017).

2.4 Summary

From experience to date, likely heat exchange rates for different structures and infrastructure types are included in Table 1. Different types of GHE are typically assessed for potential in terms of power (e.g. W/m or W/m^2). However, this type of information is not available for all cases, and some assessments in different areas have been based on total energy instead (e.g. kWhrs per unit time or area/volume of GHE or wastewater). It should also be noted that power availability will always depend on the magnitude, type and timescale of the thermal demand it is coupled with. For example, better results will be obtained if heating and cooling demand can be balanced. Therefore higher values in the ranges suggested in Table 1 may be closer to peak power availabiltiy and lower values may be closer to baseload power. This may also explain the discrepancy in some sources, e.g. for piles. In all cases, the power avaialble will also depend upon the boundary conditions, ground conditions, and especially whether there is groundwater present and flowing.

3. Future infrastructure assessment for Great Britain

The combined public and private sector investment in infrastructure in the UK totals tens of billions of pounds each year (Figure 3). One third of this figure relates to upkeep of existing infrastructure. The latest Infrastructure and Projects Authority (2018) analysis of the forward construction programme in the UK contains almost 700 projects to be completed before 2028. Many of the infrastructure sectors will include significant underground assets, such as foundations, retaining walls, tunnels, and drainage networks. In the following sections we consider the major sectors of transport infrastructure, water and waste water infrastructure and drainage systems as potential source of future heat supply and storage in the UK. While this assessment is not comprehensive of all sectors of UK infrastructure sectors, it does provide an indication of the scale and types of future opportunities.

3.1 Transport infrastructure

Anticipated construction of future transport infrastructure as set out in Infrastucture and Projects Authority (2018) has been used to make a first assessment of the potential for thermal energy exploitation in this sector. 45 road construction projects were considered (refer to Appendix A and Figure 4), excluding those already built since 2018, and also those without any major underground works. The most common opportunity for energy geostructures comes with bridge foundations. Based on publicly available scheme information, an estimate was made of the number of piers or abutments to be expected, then a conservative assumption made regarding pile numbers and length (refer to Appendix A). A similar approach was applied to proposed underpasses or other retaining structures and tunnels, which were evaluated on the potential area available for heat transfer. The most significant contributions come from the proposed tunnel schemes at Silver Town, Lower Thames Crossing and Stonehenge.

In all cases a conservative heat transfer rate per unit length or area was assumed (Table 2) based on estimates from Table 1. This was assumed to be equivalent to base load that could be utilised all year round for either heating or cooling, therefore permitting scaling up to kWh available per year based on full time operation. The results of these calculations are given in Table 2, and come to a total of 97 GWh/year.

A similar approach was adopted for future railway construction. Estimates of to be constructed infrastructure and its heat exchanger potential were made for Crossrail2, and High Speed 2 (Phase 2A and Phase 2B West), as shown in Figure 4. Each of these comes with significant numbers of new structures, retaining walls associated with shafts, undeground boxes or other cut and cover construction, and also tunnels. Based on the expected numbers of these structures and the assumptions outlined in Appendix A, this suggests a heating potential of another 226 GWh/year as shown in Table 2.

Three airports are also marked for expansion in the Infrastructure and Projects Authority (2018) pipeline (Figure 4). Of these, the most information available is about the London City Airport Development Programme where 1,000 piles of 17.5m depth are expected to be installed. Extrapolating a similar level of development for the terminal extension and Birmingham and Bristol Airports suggests a heating potential of 13.8 GWh/year.

While the above discussion has focused on new build transport infrastructure, there remains a significant existing asset stock, including 15,904 km of railway routes operated by Network Rail (ORR, 2020) and 7,000 km of motorway and major trunk roads in England. Underground structures associated with these assets are harder to convert to energy geostructures. However, recently techniques have been developed recently to permit retrofitting of GHE to retaining walls (Baralis & Barla, 2021) and trials have been carried out to retrofit tunnel GHE (Lee et al, 2016). These approaches will not be suitable in all cases, but are avenues for further research and development.

3.2 Exploitation of water and wastewater infrastructure

The UK has over 624,200 kilometres of sewers, collecting over 11 billion litres of waste water every day from homes, municipal, commercial and industrial premises and rainwater run-off from roads, roofs, and other urban surfaces (DEFRA, 2012). Abdel-Aal (2018) estimated that if all UK wastewater could be lowered by 2°C, then potentially a maximum of 390 TWh of heat could be recovered per year.

Liu et al. (2020) made simulations at a scale of 1,000 households, optimising an idealised integrated system of sewer heat recovery, drinking water reservoir let down, solar panels, wind turbines and gas back-up. They showed that for 3 locations in the UK, the domestic heat demand could be satisfied for 63% of the time for one year with no CO_2 emissions. However, Liu et al. (2020) emphasised the daily and seasonal patterns of mistmatched energy demand and availability, and for the need for inter-seasonal storage of renewable energy.

Actual achieveable heat recovery will depend on the local wastewater temperature and mass flow rate. Data on wastewater and drinking water temperature are scarce. Frijns et al. (2013) described how in the Netherlands, 60% of drinking water is heated in the house, and the temperature of wastewater leaving the house varies throughout the day, averaging 27°C. However, in the sewer system network, the wastewater loses heat energy to the air, pipe materials, adjacent pipes, and the soil (Shafagh et al, in review), resulting in spatially and temporally varying temperatures. The potential amount of heat recovery from the sewer system also depends on network boundary constraints such as the need to maintain an acceptable Wastewater Treatment Works (WwTW) inlet temperature and not allowing in pipe freezing.

Therefore, the size of the opportunities of heat recovery is highly dependent on local conditions. Abdel Aal et al. (2018) is the only study to model a city wide system (79,000 PE - population equivalent) and estimated a recovery potential between 116-207 MWhr/day. This study was located in Belgium, in a similar climate to the UK and can be scaled up to the 55.3

million people living in homes in urban areas in the UK located close to a major sewer network. On this basis it could be conservatively estimated that between 80-140 GWhr/day (29 - 51 TWhr/year or 7-13% of the theoretical maximum value of recovery) could be harvested from the UK's sewer networks. This estimate gives a range of power per population equivalent (PE) values of 61-109 kW per 1,000PE, which is consistent with values reported in a literature review by Bulteau et al. (2019)..

There is also the potential to use new water and waste water infrastructure construction programmes for heat exchange. For example, the 25 km long, 7.2 m diameter Thames Tideway Tunnel and associated 18 shafts (Newman & Hadlow, 2021) could all have been equipped as GHE. The tunnel alone could have represented 49.5 GWh/year energy availability.

3.3 Sustainable urban drainage

New housing and associated local transport infrastructure now include a statutory requirement for Sustainable Drainage Systems (SuDS) to manage flood risk (Ministry of Housing, 2019). Focusing on housing, the UK government has a target for 300,000 new homes per year in England, although recent construction progress has peaked at 244,000 per annum in 2019-20 (Wilson & Barton, 2021). These developments will include SuDS in a variety of forms. For example, the Lamb Drove Sustainable Drainage Showcase includes permeable paving, swales, detention and wetland basins and a retention pond as part of a development of 35 new homes (Susdrain, n.d.). All of these green infrastructure solutions could also be converted to work in heat transfer and storage. Taking Lamb Drove, over 400 m^2 of permeable paving was installed, alongside a similar area of detention and wetland basins, and over 70 m of swales.

Taking figures of 35 W/m^2 (Table 1) for the paving and basins and 15 W/m for the swales suggests the SuDS installed at the site could release 29kW of heating/cooling power or around 254 MWh/year (i.e. >7 MWh/year for each dwelling).

In addition to new housing developments, SuDS are a retrofit solution for urban spaces to reduce surface water flooding and help with problems related to urban heat islands. Despite challenges with the compatibilty of this approach within the regulatory landscape, the consideration and construction of a SuDS retrofit is increasingly common (e.g. Stovin et al., 2013, Casares et al., 2021). As such schemes increase in future, they will provide further opportunities for thermal exploitation at similar rates to new construction.

3.4 Significance

Domestic heating demand in the UK is approximately 434 TWh/year (Ofgem, 2016). There are at least 28 million homes in the UK that need to be converted to low carbon heating (Net Zero Infrastructure Industry Coalition, 2020), which represents 15.5 MWh/year per home. While Abdel-Aal (2018) suggest that wastewater could theoretically release heat of 390 TWh/year, the more conservative assessment considering constraints at city scale (Section 3.2), imply up to 51 TWh/year or 2.5 MWh/year available per home in urban centres. Combined with the potential 7 MWh/year per home from SuDS GHE (Section 3.3.) this comes to 9.5 MWh/year per home, or almost two thirds of domestic urban heating demand for new build or where both technologies could be retrofitted. The advantage of using wastewater and drainage infrastructure is its proximity to domestic heating demand, with issues of distance and community assets discussed in Section 3.5 below.

Additionally, transport infrastructure substructures can play a role in the nation's heating and cooling delivery. At 0.33 TWh/year, the available energy may be orders of magnitude lower than that from wastewater, though it still offers significant heating potential to nearby heat users. These may not just be domestic users, but could include business and industrial buildings in urban areas, such as over station developments, and also buildings that support the operation of infrastructure such as station buildings, maintenance depots and plant rooms. Together with wastewater effluents, the contribution to the UK annual heat energy demand of new build infrastructure and SuDS for new housing could exceed 52 TWh/year. This is before any consideration of retrofitting GHE to transport and drainage infrastructure.

3.5 Delivery through heat networks

Harvesting of heat from infrastructure and delivery of heat at appropriate temperatures using heat pumps can be deployed at a wide range of scales – from individual properties to city scale (Figure 2). Property scale may not be feasible for many infrastructure schemes, whereby sufficient heat users are not necessarily immediately adjacent to the planned works. This will be especially true for transport infrastructure that by definition often connects urban centres (e.g. refer to Appendix A).

Therefore, beyond property scale, a heat network is required to deliver heating and cooling. A wide range of configurations, operating temperatures and integration with heat pumps are possible. At the largest scales, as well as when dealing with large demands, distribution at greater than km scale allows heat sources remote from the point of use to be accommodated. They also allow a variety of infrastructure and other heat sources to be connected, hence addressing the limitations of mismatched supply and demand highlighted in Section 3.2.

Heat networks are firmly established (along with financing/governance vehicles, supply chains and skills) in the UK. Development has progressed in the last decade in response to the national heat strategy and initiatives to provide finance for local government to undertake both feasibility studies and large-scale capital development in partnership with industry. UK Cities with new thermal network developments include Leeds and Gateshead; those seeing expansion of existing systems include Coventry and Birmingham. These systems are regarded as 'Third Generation' district heating in terms of the types of heat source and delivery temperature (75 – 90 ^{o}C) they use (Figure 5). Delivery of heat at these temperatures and systems efficiencies of 300% have been demonstrated at large scale using Ammonia heat pump technology (EHPA, 2015). Given the effectiveness of such MW scale heat pumps, waste heat from infrastructure could be collected and delivered at city scale using existing and new networks.

Infrastructure heat sources can be utilised in a number of different configurations of heat pumps and delivery networks. One example would be to use a central heat pump system located next to the infrastructure heat source or infrastructure GHE and deliver high temperature heated water to individual properties. An alternative (Figure 2) would be to deliver low temperature heat over a low temperature network coupled to small heat pumps integrated into each of the properties' heating system. Such local heat networks have the advantage of being able to be implemented in suburban areas where central district heating is not currently available. Recent examples include shared ground loops for apartment blocks (e.g. Kenny et al, 2018).

Heat network technology has progressed in Europe to fourth and fifth generations, each indicative of reducing operating temperatures and higher thermal efficiencies (Figure 5). Fourth generation systems typically use conventional network infrastructure but operate at lower flow and return temperatures. This allows lower thermal losses, greater generating efficiency and flexibility in terms of incorporating heat recovery sources. Such systems are best suited to modern building developments with lower operating temperatures (Lund et al, 2014, Millar et al, 2019).

Fifth generation heat networks (Buffa et al, 2019) are intended to operate at near-ambient temperatures with multiple providers of low temperature heat and sharing of thermal energy by combining cooling and heating customers on the same network (Figure 5). Such a system is under development for the city of Plymouth (HeatNet, 2019). Users requiring high temperature for existing heating systems would use a local heat pump integrated with the building and the networks as a source. Infrastructure thermal energy sources can be used at high efficiency with heat pumps to deliver heat or provide cooling at different times in the year, and to incorporate low temperature thermal storage. Such systems can be implemented at the scale of modest groups of buildings, to city scale. Their application with energy geostructures is considered in detail in Meibodi & Loveridge (2022).

4. Discussion: challenges and solutions

Section 3 of this paper has shown how infrastructure could make a substantive contribution to UK heating and cooling demand, either by direct implementation at individual building level or via application of heat networks. This raises the question of why greater progress is not being made to realise this approach to low carbon heating and cooling. Complex techno-economic barriers act to restrain the use of infrastructure for heat recovery. Long-term ownership and management remains a challenge and business models and policy interventions for practical implementation require further development. In some cases there are also technical challenges to be overcome, such as retrofitting techniques or development of design approaches for energy and structural analysis, as well as standardisation of solutions to mitigate risk.

4.1 Risks

Harvesting thermal energy from buried infrastructure can carry risks as well as opportunities. For example, sub-structures converted to energy geostructures will experience additional concrete stress and will induce additional ground and structural displacements due to the associated temperature changes induced. In general, the degrees of freedom of a structure, dependent on soil stiffnesss and structural characteristics of the foundation, will determine the magnitude of these streses and displacements. Larger freedom is associated with larger structural displacements and smaller additional forces, with the opposite being true for more restricted structures. While those changes in forces are expected to be relatively modest in comparison to design loads, there are situations where careful analyses are required, ideally including the modelling of the highly coupled thermo-hydro-mechanical behaviour of soil. One of such cases is linked to the use of low temperatures during heat extraction, which may result in tensile stresses and thus in cracking of concrete (Bourne-Webb et al., 2009). Measurements of settlement or heave of single energy piles show displacements of less than 3mm within typical operating temperature ranges (Di Donna et al, 2017). Additional cyclic effects could be expected and are yet to be fully characterised, but sensitivity analyses for London Clay suggest less than 10mm of additional movement would require accomodating depending on the conditions (GSHPA, 2018).

There has been less work on the effects of temperatrure on the operation of energy walls and tunnels, although for the former, the often larger temporary bending moments, shear forces and displacements that may happen during construction of major underground structures are expected to be more significant than those associated with operation as heat exchangers (Sterpi et al., 2017, Rui & Yin, 2018, Sailer et al., 2019). For tunnel linings some increase in hoop stress could be expected due to temperature effects, but again studies so far suggest the impacts should be relatively minor in terms of structural forces, meaning that additional ground movements are likely to take place (Nicholson et al., 2013, Barla & Di Donna, 2018, Gawecka et al., 2021).

Sewer heat recovery may negatively affect treatment processes in downstream WWTPs. Wanner et al. (2005) established that permanently lowering WWTP influent temperature negatively affects the nitrification process, but that lowering influent temperatures only for a few hours should not cause treatment performance problems. Retrofitting opportunities for heat recovery often involve additional infrastructure adjacent to the existing truck sewer. While some pilot schemes have shown this to be practically viable, financially the additional capital cost can be challenging given the lack of accepted methods for generating income from the use of recovered heat. Condidering the future, heat recovery systems could be combined with pipe rehabilitation schemes using in-pipe liners to strengthen degraded pipes, but this would need technical developments to combined cured in pipe lining systems with heat recovery elements.

4.2 Benefits

4.2.1 Carbon savings

The primary benefit of harvesting energy from buried infrastructure lies in the provision of abundant low carbon heat. As well as any financial benefit (see Section 4.3 below), this will come with more significant carbon emissions reductions. The extent of these carbon savings will depend on future electricity grid carbon intensity and the counterfactual condition. Taking the BEIS data shown in Figure 1, the carbon density of thermal energy from infrastructure sourced heat in 2025 would be 36 gCO_2 per kWh assuming an efficiency of 300%. This can be compared with either direct use of gas (210 gCO2 per kWh) or direct use electricity (108 gCO_2 per kWh). Scaled up for the potential of the UK, implementation of the 52 TWh/year calculated in Section 3.4 would result in between 3,888 and 9,393 million tonnes of CO_2 saved per year.

4.2.2 Infrastructure benefits

As well as temperature changes in structures causing additional stress and/or strain as described in Section 4.1 above, there is also the potential to use temperature changes to help control structural or thermal behaviour in a positive way. For example, many underground metro systems accumulate heat, which reduces comfort levels, and use of the tunnel linings and station sub-structures to control the temperature has clear operational benefits. Natural temperature changes can also have detrimental impacts on structures, e.g. thermal expansion and contraction of bridges leading to the use of bearings or accomodation of additional earth pressures behind abutments. These temperature changes could also be controlled by the use of the sub-structure for thermal exploitation.

In sewer networks, implementation of heat exchange can additionally provide a simultaneous solution to some damaging biological and/or chemical process and hence potentially reduce management costs and increase environmental performance. For example, Abdel-Aal et al. (2019) utilised a case study to simulate anticipated temperature reductions in a sewer network due to heat recovery, and investigate its effects on unwanted in-sewer processes. Preliminary modelling showed considerable reductions in hydrogen sulphide formation, offering a promising method for managing hydrogen sulphide formation and hence reducing sewer corrosion and odours. Heat extraction could also reduce methane production in anaerobic sections of sewers. Methane is a greeenhouse gas, and measurements suggest that diffused emissions from sewer networks could contribute between 0.1 and 0.3 kgCO_2eq per meter cube of wasatewater (Liu et al., 2015). Finally, problematic deposition of fats, oil and grease (FOG) in sewers may be temperature dependent. A weak relationship between FOG formation and temperature has been shown in preliminary laboratory investigations (Abdel-Aal et al. 2019), confirming the need for further research into the phenomena.

Beyond the advantageous thermo-hydrological conditions present within SuDS for efficient heat transport around near-surface, closed loop GHE, there are several potential benefits to the function of SuDS. Increased soil temperature in the vicinity of the pipe due to use in cooling could enhance the drying rate (Salager et al. 2011). This leads to an accelerated recovery of water storage capacity in the soil in the combined GHE –SuDS ahead of subsequent rainfall events. Additionally, increasing the temperature of a surface water receiving SuDS will enhance the beneficial bioremediation of contaminated urban runoff, resulting in an accelerated and prolonged water quality improvement function (Le Fevre et al. 2015).

4.3 Business case

The financial attractivness of using buried infrastructure as a source or store of thermal energy lies in the potential for cost savings in ground heat exchanger construction compared with traditional techniques, and the potential in some case to access additional low cost sources of heat. However, the challenge in developing the business case, especially for large national infrastructure schemes, can be related to the early investment (during foundation construction) compared with the later financial payback (after infrastructure completion and opening). Costs during infrastructure construction are related to the pipe materials, labour for installation, header chambers and header pipes, and any change to construction programmes to include additional tasks. Costs are also incurred related to heat distribution, and these will depend on whether a small section of infrastructure is connected to a single user via an individual heat pump, or whether there is connection to a wider distribution system via district heating. Maintenance is expected to be minimal within the infrastructure itself, but pumps and other mechanical equipment for distribution and delivery systems will incur maintenance costs, hence giving rise to a mismatch between the working life of some of the overall system components.

Revenue will also depend on the nature of distribution. It could accrue directly to an infrastructure owner through reduced costs for thermal energy in their own buildings, or it could accrue through sale of low grade heat to third parties. The market for the latter is not yet well understood or developed, but is expected to change, for example as a result of the forthcoming government heat network zoning plans (BEIS, 2021, HM Government, 2021).

As a result of the above factors, new forms of business case will likely be needed for specific infrastructure scheme implementation. However, early indications are that infrastructure sourced heat will be financially viable. A study for the Grand Paris metro extensions looked at equipping tunnel segments for ground heat transfer and storage (Cousin et al, 2019). Profitability was assessed through net present value calculations, assuming sale of all thermal energy from the tunnel at 0.12 €/kWh. The time of obtaining profitability was between 10 and 20 years and dependent on the levelised cost of energy from the system, itself dependent on the density and size of the heat transfer pipes installed within the tunnel lining, and operating conditions. Some configurations were not proftiable, highlighting the need for future studies to include techo-economic assessments. Return on investment was predicted to be between 130% and 200% at 25 years depending on the conditions. However, it should be noted that since completion of this study, published in 2019, wholesale gas and electricity prices in the UK and the EU have peak at over twice the sale price assumed, which would significantly affect the net present value calculations, and likely improve the return on investment.

4.4 Implementation

The decarbonisation of heating through electrification already faces barriers due to anticipated costs, an industry skills gap for delivery, and the negative effect of incumbancy in the continued delivery of gas heating (Lowes et al, 2020). While innovation in provision of zero-carbon heat through dual-use of buried infrastructure systems brings the possibility of reduced costs in setting up low carbon heat sources, it also comes with challenges. Some of these challenges are technical, particularly related to the lag between fast moving innovation and the development of guidance and standardisation to help mitigate risks, such as those identified in Section 4.1. Currently a number of guidance documents exist for some aspects (e.g. GSHPA, 2018, NHBC, 2010, SIA, 2005), but full integration into codes of practice is lacking.

There are also non technical challenges related to policy, investment, ownership and operation of heat supplies and services. Buried infrastructure systems have longer life-spans than building heating systems, and similarly with utilities, heat from infrastructure may be exploited by new actors in the energy market place with the provision of heat viewed as a service. This environment has seen heat pump providers start to act as utility companies, operating shared GHE resources (e.g. Kenny, 2018), but will be especially important where a traditional infrastructure owner may be a different organisation from heat suppliers and users. A further possibility is for harvested heat to be contributed to a pool of diverse suppliers/prosumers in a heat network dynamic market (Meibodi & Loveridge, 2022). What business model is adopted will feed into the business case calculation as discussed in Section

4.3 above.

Nonetheless, to deliver on thermal exploitation from infrastructure some of the current policy gaps on decarbonisation of heating must also be filled. Technical innovation can go some way to reducing capitcal costs, but in the short term, certainty and stability in appropriate incentives and funding arrangments for decarbonising heat are likely to be required to encourage investment and skills training (Rosenow & Lowes, 2020). This is now especially pressing given recent energy price spikes (Hinson & Bolton, 2022) and energy security concerns. Given electrification of heat via energy geostructures connected with heat pumps and heat networks will contribute to a significant increase in grid demand compared with use of gas, policy to incentivise flexible use will also be important. As low temperature heat sources, with availability for use and storage all year round, energy geostructures connected to infrastructure have an excellent fit with this flexible approach.

5. Conclusions

This paper presents a comprehensive review of the use of infrastructure as a way to provide low carbon heating and cooling, highlighting opportunities, as well as risks and identifying paths for implementation. While this is inherently a complex topic which requires additional research, ultimatly leading to standardisation, the following conclusions can be drawn:

- Thermal energy exploitation from infrastructure, including by use of energy geostructures, has the potential to make significant contributions to decarbonising of UK heating and cooling. The waste water system is particularly attractive due to its higher temperatures, large water volumes and location within urban areas.

- Initial calculations suggest >50 TWh/year could be generated from a combination of a variety of new build infrastructure and exploitation of heat from existing wastewater systems. Development of a wider range of retrofit solutions will increase this capacity.
- There are additional benefits from adopting dual use infrastructure, including the opportunities to applying thermal control on certain biological or structural processes.
- Available heat can either be delivered directly by property level heat pumps where users are immediately adjacent, or by the adoption of heat networks at either city, district, or local scale. The latter is especially important where heat demand and sources are not immediately co-located, and where combinations of heat sources, and storage, are required to meet demand.
- To realise these ambitions certain policy and skills gaps remain to be filled, including appropriate use of incentives for heat decarbonisation. However, use of infrastructure heat sources could reduce decarbonisation costs, delivering value through dual use.
- The varying life span of infrastucture elements and the different arrangements for ownership and operation, mean that new business and investment models are also required to facilitate the adoption of heating and cooling functions in buried infrastructure.

Acknowledgements

This paper has been prepared as part of the work carried out in the PLEXUS Project: Priming

Laboratory EXperiments on infrastructure and Urban Systems [Engineering and Physical Sciences Research Council grant number EP/R013535/1]. The work of PLEXUS falls under the UK Collabatorium for Research on Infrastructure and Cities (UKCRIC) umbrella and the authors also acknowledge the collaborative environment of UKCRIC which made this work possible. Additionally, part of the sewer heat recovery analysis was carried out in the TWENTY65 project, also supported by the Engineering and Physical Sciences Research Council [grant number EP/N010124/1].

Appendix A. Transport infrastructure projects considered

Table A1. Roads

Scheme Name	Value	Construction Programme	Comments regarding potential for energy geostructures*	Source
The A4440 Worcester Southern Link Road Improvements	£55M	2019 - 2021	New two lane viaduct over River Severn in western most section	Worcestershire County Council
Great Yarmouth Third River Crossing	£120M	2020 - 2023	Lifting bridge with associated access route improvements	Norfolk County Council
Lowestoft Third Crossing	£92M	2019 - 2020	Lifting bridge with approach viaducts	Suffolk County Council
Melton Mowbray Eastern Bypass	£65M	2020 - 2022	Includes new bridges over rail and river crossings	The Construction Index
Middlewich Eastern Bypass	£58M	2021 - 2022	Includes new railway and canal overbridges	Cheshire East Council
North Devon Link Road	£93M	2020 - 2023	Includes one new grade separated junction	Devon County Council
St Austell to A30 link road	£87M	2020 - 2022	Includes two new underbridges	Cornwall Council
A13 Widening (Thurrock)	£79M	2019 - 2020	Four bridges to be replaced	Thurrock Council

Scheme Name	**Value**	**Construction Programme**	**Comments regarding potential for energy geostructures***	**Source**
Crewe High Growth City	>£5BN	2019 -	New station hub related to HS2, Middlewich Eastern Bypass, Crewe Green Link Road, The Congleton Link Road.	Cheshire East Council - General arrangement Cheshire East Council - Non-technical summary Cheshire East Council - Congleton Link Road
A509 Isham Bypass	£24M	2021 -	Includes 4 new bridges	Northamptonshire Highways
A127 Fairglen Interchange junction improvements & link road	£32M	2021 - 2023	Includes pedestrian-cycle bridge	South East Local Enterprise Partnership
Forder Valley Link Road	£80M	2020 - 2022	Includes a 3 pier viaduct	Plymouth City Council
Wichelstowe southern access scheme	£25M	2021	Underpass beneath M4, cut and cover using bored piles (assumed 2*40m, 1 pile per metre)	Swindon Borough Council
Luton Airport, Century Park Access Road	£124M		Link road and business park including at least three structures (footbridges, underpasses)	Luton Today
Luton Airport Direct Air Rail Transit (DART)	£200M	2018 - 2022	2.1 km guided mass transport, two stations, gateway bridge (4 pier), viaduct (est 10 pier), cut and cover tunnel (est 80 piles)	London Luton Airport Ltd
M1 A6 link	£33M	2021 -	Includes 6 bridges	Central Bedfordshire Council
M27 Junction 10	£60M	2020 -	New underpass, assumed piled wall	Hampshire County Council

Scheme Name	**Value**	**Construction Programme**	**Comments regarding potential for energy geostructures***	**Source**
Upgrade				
M6 Junction 10 Improvements	£78M	2020 - 2023	Includes two new bridges	Highways England
Poynton Relief Road	£26.5 M	2019 - 2022	Includes three bridges	Cheshire East Council
Preston Western Distributor and East-West Link Road	£200M	2020 - 2023	Includes four bridges and three underpasses	Lancashire County Council
Silver Town Tunnel	£1BN	2020 - 2025	Two bridges, services and ventilation buildings, open cut, cut and cover (350m long, retaining walls >12m deep) and bored tunnelling (1km, 12.35m dia)	Transport for London
A38 Derby Junctions	£250M	2021 - 2025	Three new bridges and underpass (assumed pile wall) included	Highways England
A47 Blofield to North Burlingham Dualling	£100M	2022 - 2025	Includes two structures	Highways England
A47/A11 Thickthorn Junction	TBD	2023 - 2024	Three bridges and two under passes (assume piled) included	Highways England
A428 Black Cat to Caxton Gibbet	£507M	2022 - 2026	Ten river, road and rail crossings for new dual carriageway, plus two overhead gantries	Highways England
A12 Chelmsford to A120 Widening	£1250 M	2023 - 2028	Widening on many structures on the route, or of line new structures. Includes at least 8 water courses and many minor roads	Highways England

Scheme Name	**Value**	**Construction Programme**	**Comments regarding potential for energy geostructures***	**Source**
A47 North Tuddenham to Easton	£250M	2022 - 2025	Includes 7 new structures	Highways England
A19 Testos & Downhill Lane	£52M	2020 - 2023	New motorway bridge	Highways England
A1 Birtley to Coal House Widening	TBD	2021 - 2025	Widening, includes new footbridge and railway bridge	Highways England
A585 Windy Harbour - Skippool	£150M	2021 - 2023	Includes three new bridges	Highways England
M25 Junction 28 improvement	£150M	2021-2022	Includes two new bridges	Highways England
Arundel Bypass	£320M	2023 - 2034	Viaduct, railway bridge, Binstead Rife Bridge	Highways England
M2 Jct 5 Improvements	£100M	2021 - 2025	Viaduct over roundabout, of minimum four piers	Highways England
M3 Junction 9 improvements	£175M	2023 - 2030	One footbridge, three foot subways, two major road underpass, two new M3 overbridges	Highways England
Lower Thames crossing			2.6 mile road tunnel 16.4m diameter, 50 new bridges and viaducts	Highways England
A2 Bean & Ebbsfleet	£112M	2020 - 2023	1 new bridge	Highways England
A30 Chiverton to Carland Cross	£330	2020 - 2024	4 new structures and 2 new grade separated junctions (assume 2 bridges each)	Highways England

Scheme Name	Value	Construction Programme	Comments regarding potential for energy geostructures*	Source
A303 Amesbury to Berwick Down (Stonehenge)		2022 - ?	4 green bridges, river Till viaduct, long barrow junction overbridge, 2 mile twin bored tunnel, cut and cover and retained cut at portals, flyover at countess junction	Highways England
A303 Sparkfold to Ilchester	£250M	2021 - 2024	Potential for three new structures	Highways England
A46 Coventry junctions		2020 - ?	6 pier viaduct for grade separation at Binley junction, assume similar at Walsgrave junction	Highways England
M42 Jct 6 improvements	£282M	2020 - 2025	5 new structures required	Highways England
A63 Castle Street Improvements	£355M	2020 - 2025	3 new footbridges and new two span highway bridge	Highways Agency
M6 Jct 19 improvements	£66M	2020 - 2021	New structures spanning existing roundabout	Highways England
M6 Junction 10 Improvements	£78M	2020 - 2023	2 new cross motorway overbridges	Highways England
Smart motorways (various, 400km long)			Refuge every 1.2 km (100m long and 4.6m wide)§, gantry every 1 km¥	Highways England

* All bridges are assumed to have 10 piles of 20 m depth each per pier or abutment

§ As per GD 301 (2020), Smart motorways (formerly IAN 161/15 and MPI 66), Revision 0, Design Manual for Roads and Bridges, Highways England.

¥ As per IAN 87/07 The Provision of Signal Gantries, Design Manual for Roads and Bridges, Highways England.

Table A2. Railways

Scheme Name	Value	Construction Programme	Comments	Source
Crossrail2			35km of tunnels at 7.8m dia 8 shafts - assume 25m dia and 32m depth based on Crossrail dimensions 11 underground stations or works to existing stations. Up to four shafts per station for access etc. Assume 80m perimeter each to 35m depth 7 level crossings to become grade separated	Crossrail 2
HS2 Phase 2A			17 viaducts, assume 8 piers each, 20 pile per pier, 25m deep 65 bridges, assume 2 piers each, 10 piles per pier, 20m deep 2 tunnels, assume 8m diameter and 10km each (no specific information) Ignoring stations, depots, and retaining walls as little information available.	HS2
HS2 Phase 2B West			16 viaducts 16 retaining walls, assume 200m long each and 5m depth bored tunnels, one 5km, one 15km, assume 8m dia 6 underground boxes, assume 200m2 area available each	HS2

Table A3. Airports

Scheme Name	Value	Construction Programme	Comments	Source
Birmingham International Airport	£15M	2018 - 2033	40% extended terminal building over three stories (~6000m2 footprint), new aircraft stands	Birmingham Airport
Bristol Airport improvements			Two terminal extensions, new airport stands	Bristol Airport
City Airport Development Programme	£480M	2017 - 2022	Terminal expansion with three fold increase in floor space; reclaiming docklands. Includes 1000no. 17.5m deep steel piles with concrete infill for dock reclaim.	London City Airport

References

Abdel-Aal, M., Schellart, A., Kroll, S., Mohamed, M. and Tait, S. (2018). Modelling the potential for multi-location in-sewer heat recovery at a city scale under different seasonal scenarios. Water Research, 145, pp 618–630.

Abdel-Aal, M., Villa, R., Jawiarczyk, N., Alibardi, L., Jensen, H., Schellart, A., Jefferson, B., Shepley, P. and Tait, S. (2019). Potential influence of sewer heat recovery on in-sewer processes. Wat. Sc. Tech., 80, 12, 2344-2351. doi: 10.2166/wst.2020.061

Ali A., Mohamed M., Abdel-Aal M., Schellart A., Tait S. (2017) Analysis of grpound sourec heat pumps in north of Englend homes. Proc Inst Civil Engrs Energy 170, 103-115, 10.1680/jener.15.00022

Angelotti, A. & Sterpi, D. (2018). On the performance of energy walls by monitoring assessment and numerical modelling. ICE Environmental Geotechnics. https://doi.org/10.1680/jenge.18.00037.

Baralis, M & Barla, M. (2021) Development and testing of a novel geothermal wall system, International Journal of Energy and Environmental Engineering, https://doi.org/10.1007/s40095-021-00407-y.

Barla, M. & Di Donna, A. (2018). Energy tunnels: concept and design aspects. Underground Space 3(4): 268–276, https://doi.org/10.1016/j.undsp.2018.03.003

BEIS (2018) Updated Energy and Emissions Projections April 2018. Available at: https://www.gov.uk/government/publications/updated-energy-and-emissions-projections-2018 [Accessed 3rd June 2019]

BEIS (2019). Department for Business, Energy & Industrial Strategy – Climate change and energy. https://www.gov.uk/government/news/uk-becomes-first-major-economy-to-pass-net-zero-emissions-law [Accessed: 27.07.2020].

BEIS (2021) Heat Network Zoning, October 2021. Available at: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1024216/heat-network-zoning-consultation.pdf [Accessed 23 March 2022].

Bidarmaghz, A. & Narsilio, G. A. (2018) Heat exchange mechanisms in energy tunnel systems, Geomechanics for Energy and the Environment, 16, 83 – 95.

Birchall, S., Wallis, I., Churcher, D., Pezzutto, S., Fedrizzi, R., Causse, E. (2014) INSPIRE - Deliverable D2.1a - Survey on the energy needs and architectural features of the EU building stock, 2014.

Brandl, H. (2006) Energy foundations and other thermo active ground structures, Geotechnique, 56 (2), 81 – 122.

BRE (2018) SAP10.0 The government’s standard assessment procedure for energy ratings of dwellings. Version 10.0 July 2018.

Bourne-Webb, P.J., Amatya, B., Soga, K., Amis, T., Davidson, C. & Payne, P (2009) Energy pile test at Lambeth College, London: geotechnical and thermodynamic aspects of pile response to heat cycles, Géotechnique 59 (3), 237-248.

Buffa, S., Cozzini, M., D’Antoni, M., Baratieri, M., & Fedrizzi R. (2019)5th generation district heating and cooling systems: A review of existing cases in Europe, Renewable and Sustainable Energy Reviews, Issue 104, 2019, 504-522.

Bulteau G., Hoffman J., Fairhurst R., Orman N. (2019) Energy from Sewers Report No. 19/SW/03/1 UK Water Industry Research Ltd ISBN 978-1-84057-884-3.

Casares, P S, Benton L & Bull, J (2021) Sustainable drainage retrofit case study: Counters Creek Flood Allevation Scheme UK, Journal of Environmental Engineering and Science, https://doi.org/10.1680/jenes.21.00021

CCC (2016) Next Steps for UK Heat Policy, Committee on Climate Change, October 2016. Available at https://www.theccc.org.uk/wp-content/uploads/2016/10/Next-steps-for-UK-heat-policy-Committee-on-Climate-Change-October-2016.pdf [Accessed 3rd June 2019]

Charlesworth et al (2017) Renewable energy combined with sustainable drainage: Ground source heat and pervious paving. Renew Sustain Energy Rev, 68, 912-919.

CIBSE (2013) TM51: Ground Source Heat Pumps. Chartered Institute of Building Services Engineers, London. 70pp. August 2013.

Cousin, B., Rotta Loira, A. F., Bourget, A., Rognon, F. & Laloui, L. (2019) Energy performance and economic feasibility of energy segmental linings for subway tunnels. Tunneling and Underground Space Technology, 91, 102997.

Copernicus Land Monitoring Service. 2022. EU-DEM v1.1. url: https://land.copernicus.eu /imagery-in-situ/eu-dem/eu-dem-v1.1. [Accessed on 02.03.2022]

De Pasquale, A.M., Giostri, A., Romano, M.C., Chiesa, P., Demeco, T., Tani, S., 2017. District heating by drinking water heat pump: Modelling and energy analysis of a case study in the city of Milan. Energy 118, 246–263. https://doi.org/10.1016/j.energy.2016.12.014

DEFRA (2012). Waste water treatment in the United Kingdom – 2012 Implementation of the

European Union Urban Waste Water Treatment Directive – 91/271/EEC. https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/69592/pb13811-waste-water-2012.pdf [Accessed 04.09.2020]

Delerablee, Y. & Rammal, D., Mroueh, H., Burlon, S., Habert, J. & Froitier, C. (2018). Integration of Thermoactive Metro Stations in a Smart Energy System: Feedbacks from the Grand Paris Project. Infrastructures. 3 (4), 56. https://doi.org/10.3390/infrastructures3040056.

Department for Transport. 2020. Major Road Network. url: https://data.gov.uk/dataset/95f58bfa-13d6-4657-9d6f-020589498cfd/major-road-network. [Accessed on 02.03.2022]

Di Donna, A., Barla, M. & Amis, T. (2017) Energy Geostructures: Analysis from research and systems installed around the World, Proceedings of the 42nd Annual Conference on Deep Foundations, New Orleans (USA), 24-27 October 2017.

EGEC (2014) Market Report, 2013-14 Update, European Geothermal Energy Council, Fourth Edition, December 2014. Available at: https://www.egec.org/wp-content/uploads/2011/03/EGEC-Market-Report-Update-ONLINE.pdf [Accessed 3rd June 2019}.

EHPA (2015). The Worlds Largest Natural District Heat Pump. European Heat Pump Association Newsletter: Available at https://www.ehpa.org/about/news/article/the-worlds-largest-natural-district-heat-pump/ [Accessed 15 July 2021].

Franzius, J.N. & Pralle, N. (2011) Turning segmental tunnels into sources of renewable energy, Proceedings of the ICE Civil Engineering, 164, 35-40.

Frijns, J., Hofman, J., Nederlof, M. (2013). The potential of (waste)water as energy carrier.

Energy Conversion and Management, 65, 357–363.

Gawecka K, Cui W, Taborda D, Potts D, Zdravkovic L, Loukas A (2021) Predictive modelling of thermo-active tunnels in London Clay. Geotechnique 71(8): 735-748. https://doi.org/10.1680/jgeot.19.P.376

Graaf de R, van de Ven F, Miltenburg I, van Ee B, van de Winkel L, van Wijk G.Exploring the technical and economic feasibility of using the urban water system as a sustainable energy source. Thermal Sci 2008;12(4):35–50.

GSHPA (2018) Thermal Pile Design, Installation and Materials Standards, September 2018, Version 2, 92pp. Ground Source Heat Pump Assocation.

Greenspace Scotland (2021). Green Heat in Greenspaces: National Results Report, May 2021. Available at: https://www.greenspacescotland.org.uk/Handlers/Download.ashx?IDMF=4d6e8ece-ff64-4dd9-8253-1a357bb6bfaf [Accessed 9th July 2021].

Gussem de, K.R.L., Smits, R., Donckels, B.M.R. and Weemaes, M. (2013). Impact of sewage heat extraction on waste water treatment plant performance and greenhouse gas emission. Proceedings of the 7th Int. Conf. On Sewer Processes and Networks, Sheffield, United Kingdom.

Hao, X., Li, J., van Loosdrecht, M., Han, J. and Liu, R. (2019) Energy recovery from wastewater: heat over organics. Water Research, vol.161, pp.74-77

HeatNet (2019). Plymouth 4 & 5DHC Roadmap. HeatNet NWE. Available at: https://www.plymouth.gov.uk/sites/default/files/HeatNetNWEPlymouthTransitionRoadmap.pdf [accessed 15 July 2021].

Hepbasli, A. , Biyik, E., Ekren, O., Gunerhan, H., Araz, M. (2014). A key review of wastewater source heat pump (WWSHP) systems, Energy Convers. Man., 88, 700–722.

High Speed 2 Limited. 2020. Phase 2a West Midlands to Crewe. url: https://data.gov.uk/dataset/bb1f45a1-1864-4754-92dc-a2baf6f71a99/phase-2a-west-midlands-to-crewe. [Accessed on 02.03.2022]

High Speed 2 Limited. 2022. HS2 Phase Two: from the West Midlands to Leeds and Manchester. url: https://data.gov.uk/dataset/c0b9f4e6-82eb-43d1-93a7-d2b8252717f6/hs2-phase-two-from-the-west-midlands-to-leeds-and-manchester. [Accessed on 02.03.2022]

Hinson, S. & Bolton, P. (2022). The energy price crunch, The House of Commons Library, Research Briefing, 14 January 2022. Available at: https://researchbriefings.files.parliament.uk/documents/CBP-9340/CBP-9340.pdf. [Accessed 14 March 2022.]

HM Government (2021) Heat and Buildings Strategy, Presented to Parliament by the Secretary of State for Business, Energy and Industrial Strategy by Command of Her Majesty, October 2021. ISBN 978-1-5286-2459-6. Available at https://www.gov.uk/government/publications/heat-and-buildings-strategy [Accessed 14 March 2022].

Hubeck-Graudal, H., Kirstein, J.K., Ommen, T., Rygaard, M., Elmegaard, B., 2020. Drinking water supply as low-temperature source in the district heating system: A case study for the city of Copenhagen. Energy 194, 116773. https://doi.org/10.1016/j.energy.2019.116773

Infrastructure and Projects Authority (2018) Analysis of the national infrastructure and projects pipeline, 26 November, 2018. Available at: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/759222/CCS207_CCS111898724

8-001_National_Infrastructure_and_Construction_Pipeline_2018_Accessible.pdf [Accessed 3 June 2019].

Karytsas,S., & Choropanitis, I. (2017) Barriers against and actions towards renewable energy technologies diffusion: A Principal Component Analysis for residential ground source heat pump (GSHP) systems, Renewable and Sustainable Energy Reviews, 78, 252-271.

Kell, J.R. & Martin, P.L. (1963). The Nuffield College heat pump. J Inst Heat Vent Eng. 30(1), 333-356.

Kenny, J. et al (2018), The UK's largest ground source heat pump system, Construction Manager, 11 January 2018, Available at: https://constructionmanagermagazine.com/work-starts-uks-largest-ground-source-heat-pump-sy/ [Accessed 23 July 2021].

Kipry, H., Bockletmann, F., Plesser, S. & Fisch, M. N. (2008) Evaluation and optimization of UTES systems of energy efficient office buildings (WKSP) – a project within the new German R&D framework EnBop. In Proceedings of ICEBO'08 – 8th International Conference for Enhanced Building Operations, Berlin, Germany. 8pp..

Kretschmer, F., Simperler, L. and Ertl, T. (2016) Analysing wastewater temperature development in a sewer system as a basis for the evaluation of wastewater heat recovery potentials. Energy and Buildings, vol.128, pp. 639-648.

Le Fevre GH, Paus KH, Natarajan P, Gulliver JS, Novak PJ, Hozalski RM. Review of dissolved pollutants in urban storm water and their removal and fate in bioretention cells. J Environ Eng (United States). 2015;141(1). doi:10.1061/(ASCE)EE.1943-7870.0000876.

Lee, C., Park, S., Choi, H.-J. Lee, I.-M., Choi, H. (2016) Development of energy textile to use geothermal energy in tunnels, Tunnelling and Underground Space Technology 59 (2016) 105–113.

Liu, F., Tait, S., Schellart, A., Mayfield, M., and Boxall, J. (2020) Reducing carbon emissions by integrating urban water systems and renewable energy sources at a community scale. Renewable and Sustainable Energy Reviews, vol.123, 109767.

Liu, Y., Ni, B.J., Sharma, N.R., Yuan, Z., 2015. Methane emissions from sewers. Sci. Total Environ. 524-525, 40-51. https://dx.doi.org/10.1016/j.scitotenv.2015.04. 029.

Loveridge, F., McCartney, J. S., Narsilio, G. & Sanchez, M. (2019), Energy geostructures: a review of analysis approaches, in situ testing and model scale experiments, Geomechanics for Energy and the Environment. 22, Article 100173.

Lowes, R. Woodman, B & Speirs, J (2020) Heating in great britain: An incumbent discourse coalition resists an electrifying future, Environmental Innovation and Societal Transitions 37 (2020) 1–17.

Lund, H., Werner, S., Wiltshire, R., Svendsen, S., Thorsen, J.E., Hvelplund, F., & Vad Mathiesen, B. (2014) 4th Generation District Heating (4GDH): Integrating smart thermal grids into future sustainable energy systems, Energy, 68, 2014, 1-11.

MCS (2011) MCS022: Ground heat exchanger look up tables. Supplementary material to MIS 3005. Issue 1.0. Department of Energy and Climate Change, London. 22pp. Avaialble at: https://www.gshp.org.uk/pdf/MIS_3005_Ground_loop_sizing_tables.pdf [Accessed 13 July 2021]

Meibodi, S & Loveridge, F (2022) The future role of energy geostructures in fifth generation district heating and cooling networks, Energy, 240 (1) 122481.

Murphy J. et al. (2019) UKCIP18 Land Projections: Science Report v2, Available at: https://www.metoffice.gov.uk/pub/data/weather/uk/ukcp18/science-reports/UKCP18-Land-report.pdf [Accessed 29 July 2021].

Millar M-A, Burnside N, Yu Z. An Investigation into the Limitations of Low Temperature District Heating on Traditional Tenement Buildings in Scotland. Energies. 2019; 12(13):2603.

Ministry of Housing, Communities and Local Government (2018) English Housing Survey, Floor Space in English Homes – main report, Available at: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/725085/Floor_Space_in_English_Homes_main_report.pdf [Accessed 14 July 2021]

National Grid (2018) Future Energy Scenarios http://fes.nationalgrid.com/media/1243/ac-2050-v21.pdf

Newman T G & Hadlow N W (2021) Geological structures beneath the River Thames in London: findings from the Thames Tideway Tunnel investigations, Quarterly Journal of Engineering Geology and Hydrogeoloy, https://doi.org/10.1144/qjegh2020-157

Net Zero Infrastracture Industry Coaltion (2020), The path to zero carbon heat, What we need to do, and when: three roadmaps for decarbonising UK heat by 2050. Available at: https://www.mottmac.com/download/file?id=39141&isPreview=True [Accessed 28 July 2021]

NHBC (2010) Efficient design of piled foundations for low rise housing, design guide, National House Building Concil Foundation, February 2010.

Nicholl, I.R. 2018. Crossrail 2 Core Alignment 2015. url: https://hub.arcgis.com/datasets/CR2::crossrail-2-core-alignment-2015. [Accessed on 02.03.2022]

Nicholson, D. P., Chen, Q., Pillai, A. & Chendorain, M. (2013). Developments in thermal pile and thermal tunnel linings for city scale GSHP systems. In Proceedings of the 38th workshop on geothermal reservoir engineering (ed. J. P. Castro), 1437–1444. Red Hook, NY, USA: Curran Associates, Inc.

Ofgem (2016) Ofgem’s Future Insights Series, The Decarbonisation of Heat. 17pp. Available at https://www.ofgem.gov.uk/sites/default/files/docs/2016/11/ofgem_future_insights_programme_-_the_decarbonisation_of_heat.pdf [Accessed 19 July 2018].

ONS (2018) Developing new statistics of infrastructure: August 2018, Available at: https://www.ons.gov.uk/economy/economicoutputandproductivity/productivitymeasures/articles/developingnewmeasuresofinfrastructureinvestment/august2018 [Accessed 14 July 2021].

ORR (2020) Rail Infrastructure and Assets 2019 -2020, Office of Rail and Road, 5 November 2020. Avaialble at: https://dataportal.orr.gov.uk/media/1842/rail-infrastructure-assets-2019-20.pdf [Accesssed 14 July 2021]

Pahud, D. & Hubbach, M. (2007) Measured Thermal Performances of the Energy Pile System of the Dock Midfield at Zürich Airport, Proceedings European Geothermal Congress 2007, Unterhaching, Germany, 30 May-1 June 2007.

Rey-Mahía et al (2019) Evaluating the thermal performance of wet swales housing ground source heat pump elements through laboratory modelling Sustain, 11 (11), 3118.

Rosenow, J & Lowes, R (2020) Heating without the hot air: Principles for smart heat electrification, Regulatory Assistance Project, Brussels, Belgium, 36pp. Available at https://www.raponline.org/wp-content/uploads/2020/03/rap-rosenow-lowes-principles-heat-decarbonisation-march-2020.pdf [Accesssed 19 July 2021].

Rui, Y, Yin, M (2018) Thermo-hydro-mechanical coupling analysis of a thermo-active diaphragm wall. Canadian Geotechnical Journal, 55(5): 720-35.

Sailer, E, Taborda, DMG, Zdravkovic L, Potts, DM (2019) Fundamentals of the coupled thermo-hydro-mehcanical behaviour of thermo-active retaining walls. Computers and Geotechnics, 109:189-203

Salager S, Rizzi M, Laloui L. An innovative device for determining the soil water retention curve under high suction at different temperatures. Acta Geotech. 2011;6(3):135-142. doi:10.1007/s11440-011-0141-817.

Sarbu, I. & Sebarchievici, C. (2014) General review of ground-source heat pump systems for heating and cooling of buildings, Energy and Buildings, 70, 441-454.

Schneider, M. & Moormann, C. (2010) GeoTU6 – a geothermal tesearch project for tunnels. Tunnel. 2/2010, 14-21.

Self, S.J., Reddy, B.V., & Rosen, M.A. (2013) Geothermal heat pump systems: Status review and comparison with other heating options, Applied Energy, 101, 341-348.

Shafagh, I., Shepley, P., Shepherd, W., Loveridge, F., Schellart, A., Tait, S. & Rees, S.J. (in review) Thermal energy transfer around buried pipe infrastructure, Geomechnics for Energy and the Environment.

SIA (2005) *Utilisation de la chaleur du sol par des ouvrages de fondation et de soutènement en béton*, D 0190, Swiss Society of Engineers and Architects, Zurich, Switzerland.

Soga, K, Yi, R., & Nicholson, D. (2015), Behaviour of a thermal wall installed in the Tottenham Court Road station box. Proc. Crossrail Conf., Crossrail Ltd & Federation of Piling Specialists, City Hall, London, 112–119.

Spiter, J. & Gehlin, S. (2019) Measured Performance of a Mixed-Use Commercial-Building Ground Source Heat Pump System in Sweden, Energies, 12 (10), https://doi.org/10.3390/en12102020.

Spriet, J., McNabola, A., Neugebauer, G., Stoeglehner, G., Ertl, T., and Kretschmer, F. Spatial and temporal considerations in the performance of wastewater heat recovery systems. (2020) Journal of Cleaner Production, 247.

Sterpi, D, Colleto, A, Mauri, L (2017) Investigation on the behaviour of a thermo-active diaphragm wall by thermo-mechanical analyses. Geomechanics for Energy and the Environment, 9: 1-20

Stovin, V, Moor, S, Wall M & Ashley R (2013) The potential to retrofit sustainable drainage systems to address combined sewer overflow discharges in the Thames Tideway catchment, Water and Environment Journal, 27, 216-228.

Suckling, T.P., Smith, P. (2002) Environmentally friendly geothermal piles at Keble College, Oxford, UK. In: Proceedings of 9th International Conference on Piling and Deep

Foundations, Nice, France, Deep Foundations Institute, Article 1016, pp. 8.

Susdrain (n.d) Lamb Drove, Residential SuDS scheme, Cambourne, Cambridge. Available at https://www.susdrain.org/case-studies/pdfs/lamb_drove_residential_suds_scheme_cambourne.pdf [Accessed 19 July 2021].

Turner, JL , Loveridge, F , Rees, S et al (2021) Energy Performance of CFA Piles used as Heat Exchangers in a GSHP System. In: Piling 2020: Proceedings of the Piling 2020 Conference. Piling 2020, 23-26 Mar 2021

van der Hoek, J.P., Mol, S., Giorgi, S., Ahmad, J.I., Liu, G., Medema, G., 2018. Energy recovery from the water cycle: Thermal energy from drinking water. Energy 162, 977–987. https://doi.org/10.1016/j.energy.2018.08.097

Wanner, O., Panagiotidis, V., Clavadetscher, P., Siegrist, H. (2005). Effect of heat recovery from raw wastewater on nitrification and nitrogen removal in activated sludge plants. Wat. Res., 39, 4725–4734

Wilson, W & Barton, C (2021) Tackling the under supply of housing in England. House of Commons Library Briefing Paper, Number 07671, 14 January 2021. Available at https://researchbriefings.files.parliament.uk/documents/CBP-7671/CBP-7671.pdf [Accessed 19 Jult 2021].

Yildiz A, Stirling RA (2022). Ground heat exchange potential of Green Infrastructure. *Geothermics* 2022, 101, 102351 https://doi.org/10.1016/j.geothermics.2022.102351.

Table 1. Typical energy extraction rates for energy geostructures

Type of system	Typical Extraction Rates	Comments	Source
Shallow horizontal ground heat exchanger	1 – 35 W/m 5 – 40 W/m^2	Per length of pipe Per area of heat exchanger	MCS (2011) CIBSE (2013)
Borehole heat exchanger	20 – 55 W/m		CIBSE (2013)
Pile heat exchangers	20 – 75 W/m 15 – 40 W/m	The higher range recommended by CIBSE is out of step with longer term testing reported from other sources, but does illustrate that piles should have greater energy per drilled metre than boreholes.	CIBSE (2013) SIA (2005), Di Donna et al., (2017), Loveridge et al. (2019)
Embedded Walls	10 – 20 W/m^2	Depends on amount of embedment, whether heat source inside the retained space (e.g. train braking).	Di Donna et al., (2017), Loveridge et al. (2019)
Slabs	5 – 10 W/m^2	Depends on use of space above the slab.	Kipry et al. (2008), Angelotti & Sterpi (2018)
Tunnels	10 – 25 W/m^2	Depends on whether the tunnel space can act as a heat source (e.g. train braking, sewerage).	Di Donna et al., (2017), Loveridge et al. (2019)
SuDS or other green infrastructure	~ 35 W/m^2	Figure based on shallow GHE in infiltration trenches. More broadly, may be analagous to pond or shallow ground heat exchangers, depending on type.	Ali et al (2017
Pond heat exchanger	~ 100 W/m^2	Per unit of surface area. Actual amount will depend on depth and temperature conditions	CIBSE (2013)
Wastewater effluent	0 – 3.5 kWh/m3	Depends on where in the wastewater system the heat is recovered, seasonal temperature variations of the wastewater and the amount the wastewater temperature could be lowered.	Based sources summarised in Hao et al. (2019)

Note: all figures given above focus only on the contribution available from the infrastructure source itself, and do not take account of heat pump contributions and efficiency

Table 2. Annual energy available from planned UK transport infrastructure construction

	Piles at 30W/m base load		Walls at 15W/m^2 base load		Tunnels at 10 W/m^2 base load	
	Length (m)	Energy (GWh/yr)	Area (m^2)	Energy (GWh/yr)	Area (m^2)	Energy (GWh/yr)
Roads	182,300	42.9	140,100	18.4	414,000	35.9
Railway	160,800	42.0	160,500	21.0	1,863,000	18.6
Airports	52,500	13.8				

Figure 1. Carbon intensity of UK grid electricity from 2006 to 2017 with projections to 2035. Data: grid electricity data from the Digest of United Kingdom Energy Statistics (DUKES); projections from BEIS (2018); mains gas from BRE (2018)

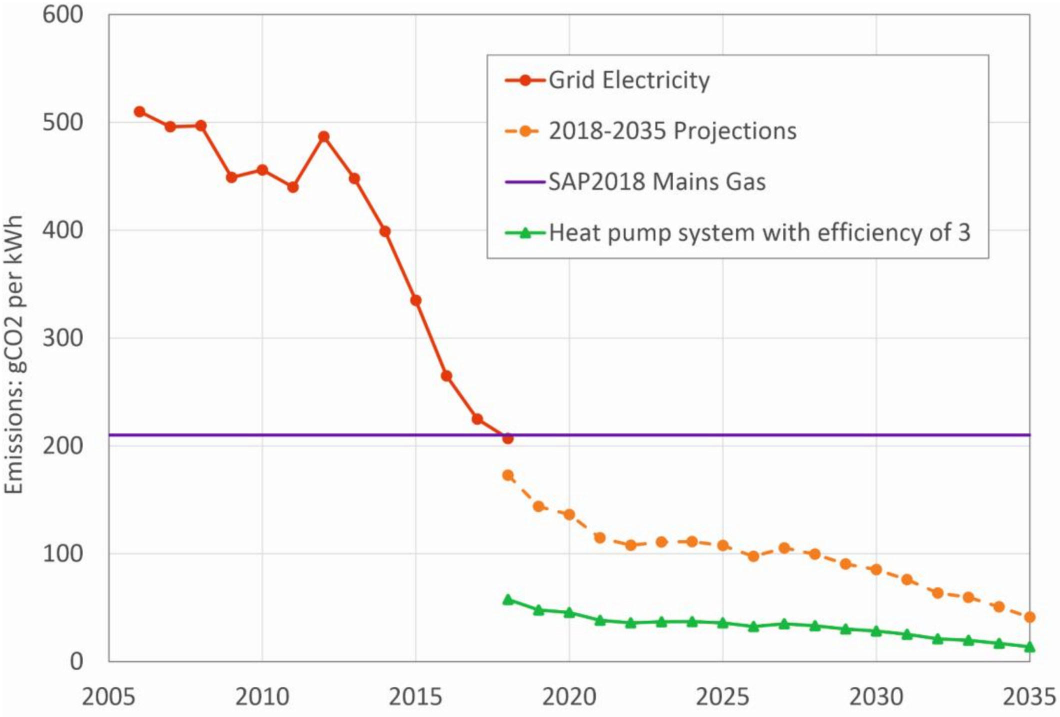

Figure 2. An example of an energy geostructure system based around a transport tunnel equipped with heat transfer and storage, with different options for connections to heat and cool nearby buildings via heat pumps (HP). Main figure: overall concept. Detail: typical heat transfer pipe details

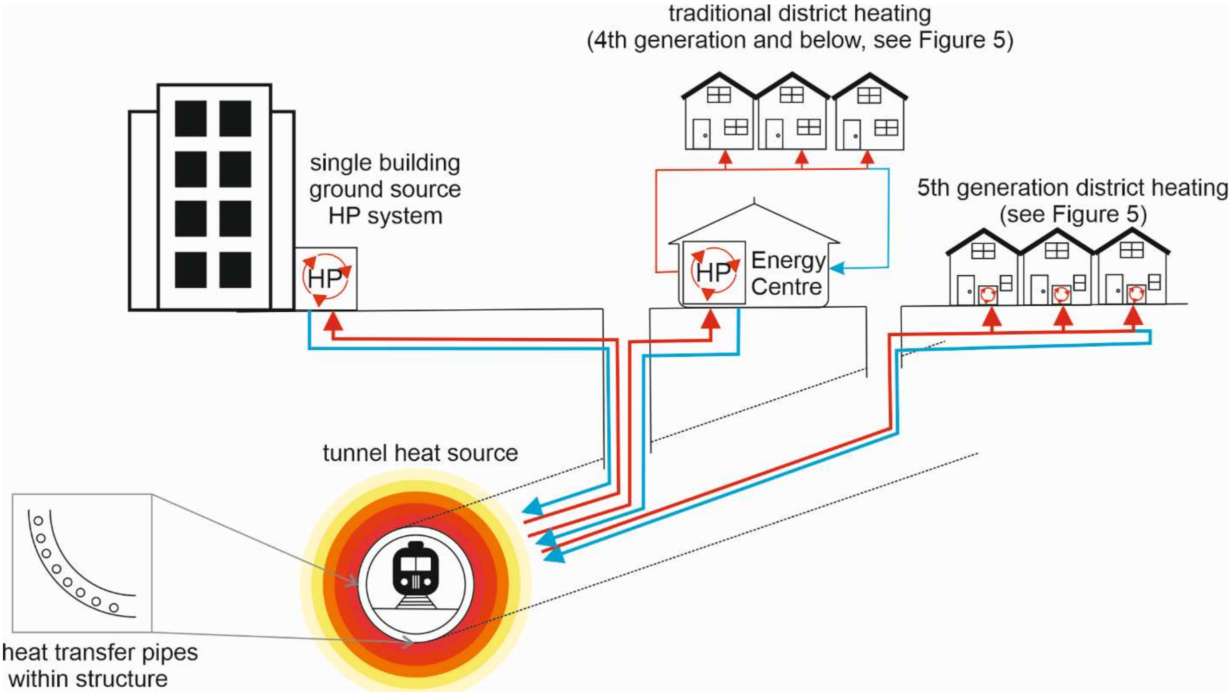

Figure 3. Cost of infrastructure investment in the UK in 2017 by Sector (ONS, 2018)

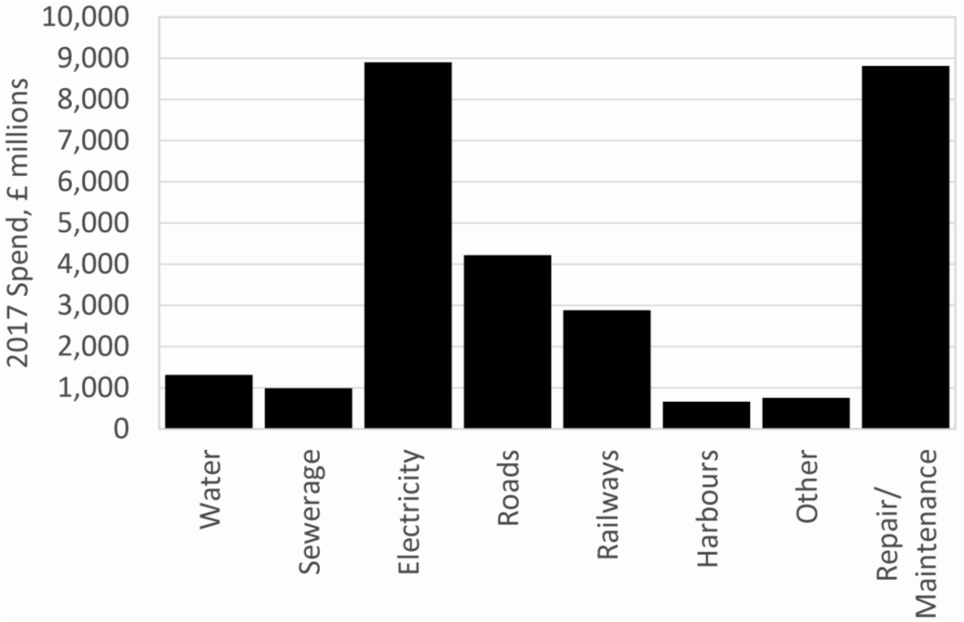

Figure 4. Map of the United Kingdom showing the existing road network, Major Road Network (Department for Transport, 2020), as well as the major transport infrastructure assessed for thermal energy potential (See Tables A1, A2 and A3). Background DEM data is modified from EU-DEM v1.1 (Copernicus Land Monitoring Service, 2022). Shapefiles of railway projects are obtained from High Speed 2 Limited (2020, 2022) and Nicholl (2018)

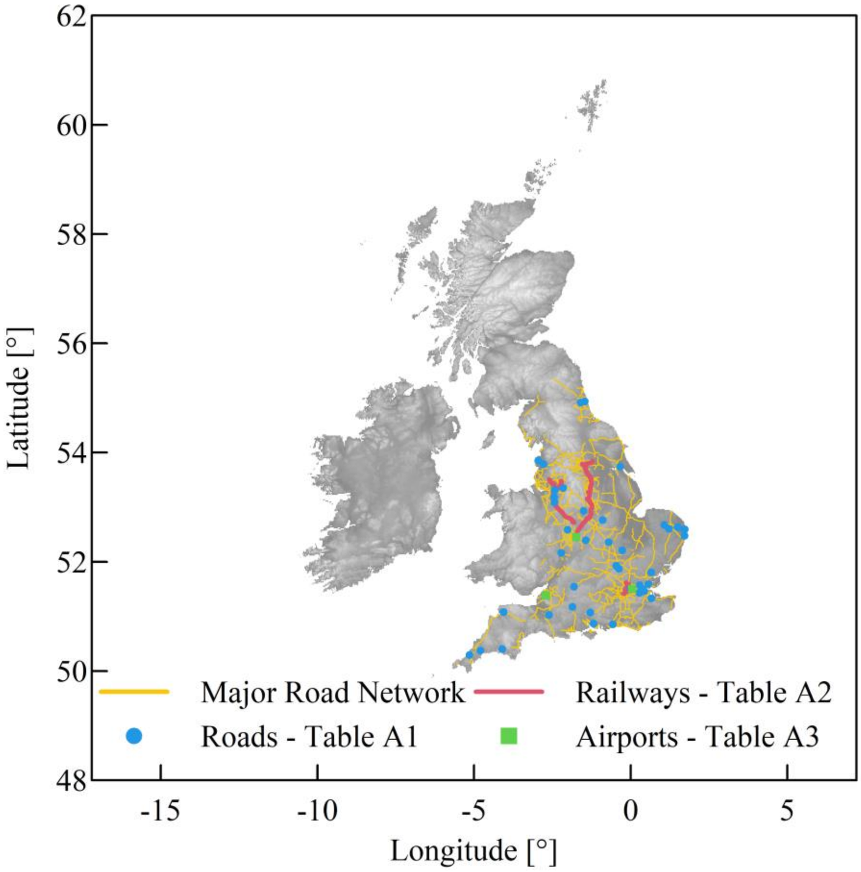

Figure 5. Evolution of district heating technology to 5th generation, adapted and extended from Lund (2014)