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The Potential for Heat Recovery and Thermal Energy Storage in the UK Using Buried Infrastructure

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The Potential for Heat Recovery and Thermal Energy Storage in the UK Using Buried Infrastructure

Abstract

Dispersed space heating alone accounts for 40% of UK energy use and 20% of CO₂ 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 its infrastructure energy potential.

Keywords: District Heating, Renewable Energy, Thermal Effects, Geotechnical Engineering, Buried Structures

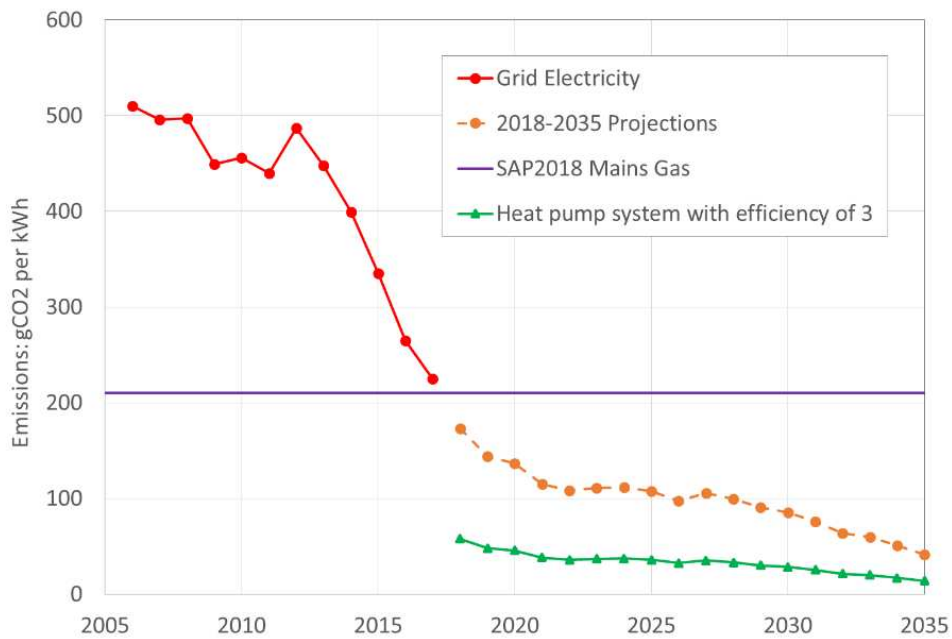
1 Introduction

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

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

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

26 downward trend in carbon intensity of the grid is projected to continue, emissions from heat pump
27 systems will follow this trend over their operating lifetime (Figure 1).



28

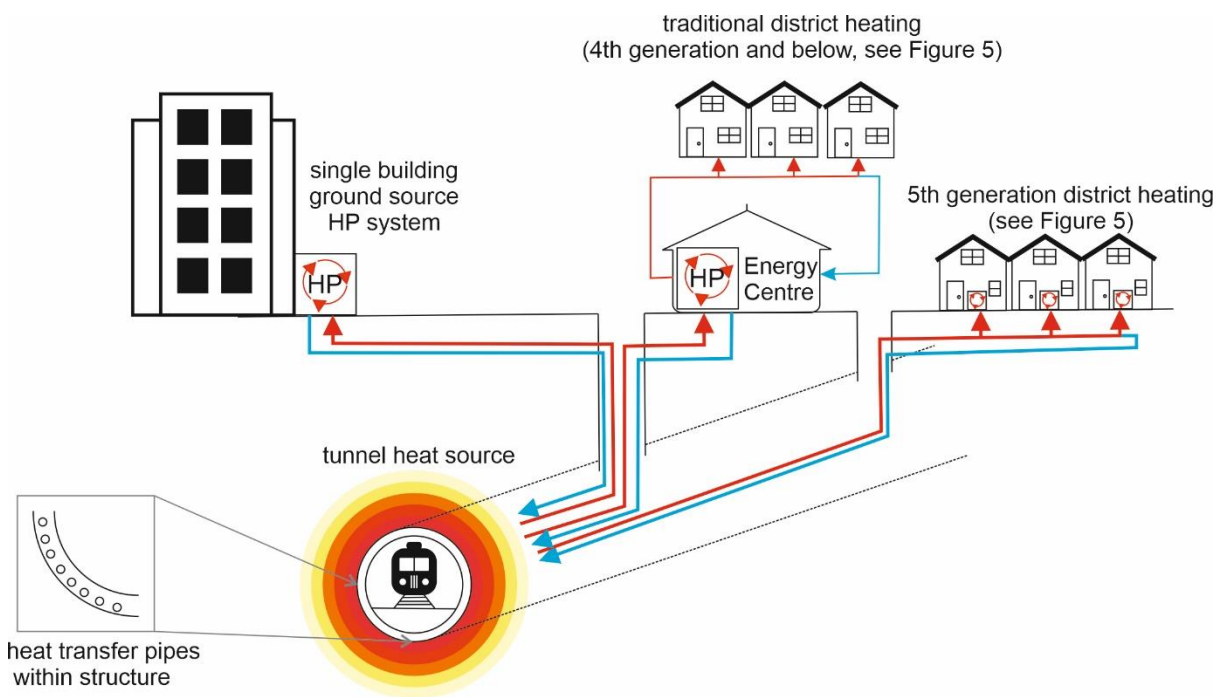
29 **Figure 1 Carbon intensity of UK grid electricity from 2006 to 2017 with projections to 2035.**
30 **Data: grid electricity data from the Digest of United Kingdom Energy Statistics (DUKES);**
31 **projections from BEIS (2018); mains gas from BRE (2018).**

32

33 Heat pumps offer their highest efficiencies when operating with the ground, or a similar stable
34 temperature medium, as a source (Self et al, 2013) and also when addressing both heating and
35 cooling demand using inter seasonal storage (Sarbu & Sebarchievici, 2014). However, a major barrier
36 to uptake in recent years has been the large capital costs (EGEC, 2014, Karytsas & Choropanitis,
37 2017), which are related to the construction of the ground heat exchanger (GHE). One solution to
38 this challenge is to make use of existing planned civil engineering works which involve the ground to
39 remove the need to make costly special purpose excavations. Heat pump technology could exploit a
40 wide range of heat sources related to the buried infrastructure themselves, including foundations,
41 urban drainage systems and drinking water systems.

42 While adoption of so called energy geostructures (Figure 2), where a civil engineering asset is used
43 for both its original purpose and for heat transfer and storage, has increased in recent years, the
44 total number of installations is still relatively low (Di Donna et al, 2017). However, with over £600

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



51

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

56

57 2 Background on Energy Geostructures

58 2.1 Substructures and Transport Infrastructure

59 The first energy geostructures, constructed in the 1980s, were piled foundations (Brandl, 2006), with
 60 deep foundations for a building used instead of traditional borehole heat exchangers to provide
 61 heating and/or cooling to the overlying building. Often piles alone were insufficient to meet all the
 62 energy demand of a building and either additional traditional open or closed loop GHE were used to

63 supplement the piles (e.g Turner et al, 2021), or auxiliary heating/cooling systems were used (e.g.
64 Pahud & Hubbach, 2007). The first pile heat exchangers in the UK were at Keble College in Oxford
65 (Suckling & Smith, 2002). Basement walls and slabs were a natural extension to the pile heat
66 exchanger concept, and while not as common, they have been adopted in a number of locations
67 (e.g. Kipry et al, 2008, Angelotti & Sterpi, 2018). The key difference between piles and embedded
68 retaining walls is that excavation space in front of walls reduces the energy available for exploitation.
69 In foundation slabs, which do not have the benefit of an embedded section, this capacity is reduced
70 again.

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

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

81 *2.2 Water and Wastewater Infrastructure*

82 Heat can be recovered from wastewater treatment works, from sewer networks, from wastewater
83 drainage pipework within homes, and potentially from drinking water networks. Hepbasli et al
84 (2014) estimates that worldwide over 500 systems of wastewater source heat pumps are
85 operational, mainly in Switzerland, Germany and Scandinavia. A considerable amount of research
86 has focused on heat recovery from wastewater treatment works (Hao et al., 2019) but less on heat
87 recovery at household levels or from sewer systems (e.g. Kretschmer et al., 2016; Hepbasli et al.,

88 2014). The first UK application of wastewater heat recovery technology was implemented at Nuffield
89 College, Oxford (Kell et al., 1963).

90 Spriet et al. (2020) developed a methodology for assessing energetic, spatial and temporal patterns
91 in the performance of wastewater treatment plant (WWTP) effluent heat recovery. For a case study,
92 they concluded that heat recovery could be used to meet baseload heat demand, but with a need
93 for storage and/or auxiliary heating to cover peak demand. Abdel-Aal et al. (2018) simulated several
94 sewer heat recovery location scenarios in an urban area case study. They reported a potential heat
95 recovery of 116-207 MWh/day from a combined sewer network serving a population equivalent of
96 79000, concluding that heat recovery could potentially meet 7% to 18% of the area's heat demand.

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

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

110 *2.3 Sustainable Urban Drainage*

111 Green Infrastructure, including Sustainable Drainage Systems (SuDS) are becoming an increasingly
112 common new-build and retrofit feature in our cities to improve the quality and resilience of the

113 urban environment. While the exploitation of these systems for energy recovery is currently low,
114 there is increasing interest in their potential due to the advantageous ground conditions inherent in
115 their design and function.

116 Beneficial conditions have been established to exist for heat exchange in typical bioremediation
117 devices; infiltration of excess surface water improves soil thermal properties, while the primary
118 drainage function continues unaffected by the additional heat transfer (Yildiz & Stirling, 2022).

119 Similar concepts have been trialled for permeable paving (Charlesworth et al., 2017) and laboratory
120 scale experiments of heat exchange in wet swales have been successfully conducted (Rey-Mahía et
121 al., 2019). The nearest equivalent, commercial applications have been explored around the use of
122 urban green spaces and watercourses. These have most notably been documented by the
123 ParkPower programme (Greenspace Scotland, 2021) who determined the combined heat supply
124 potential from closed loop GHE in urban green spaces (and water source heat pumps in non-tidal
125 rivers) across Scotland is equivalent to 79% of all heat demand from Scotland's settlements.

126 However, this encompasses the broadest definition of green space and does not specifically target
127 SuDS.

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

132

133

134 **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 analogous 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/m ³	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)

135 Note: all figures given above focus only on the contribution available from the infrastructure source itself, and
 136 do not take account of heat pump contributions and efficiency.
 137

138 **2.4 Summary**

139 From experience to date, likely heat exchange rates for different structures and infrastructure types
 140 are included in Table 1. Different types of GHE are typically assessed for potential in terms of power
 141 (e.g. W/m or W/m²). However, this type of information is not available for all cases, and some

142 assessments in different areas have been based on total energy instead (e.g. kWhrs per unit time or
143 area/volume of GHE or wastewater). It should also be noted that power availability will always
144 depend on the magnitude, type and timescale of the thermal demand it is coupled with. For
145 example, better results will be obtained if heating and cooling demand can be balanced. Therefore
146 higher values in the ranges suggested in Table 1 may be closer to peak power availability and lower
147 values may be closer to baseload power. This may also explain the discrepancy in some sources, e.g.
148 for piles. In all cases, the power available will also depend upon the boundary conditions, ground
149 conditions, and especially whether there is groundwater present and flowing.

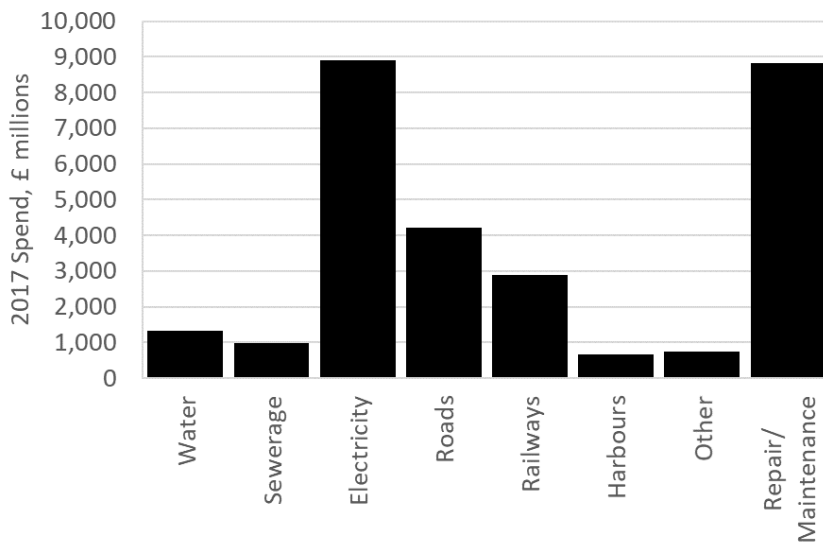
150 **3 Future Infrastructure Assessment for Great Britain**

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

161 **3.1 Transport Infrastructure**

162 Anticipated construction of future transport infrastructure as set out in Infrastructure and Projects
163 Authority (2018) has been used to make a first assessment of the potential for thermal energy
164 exploitation in this sector. 45 road construction projects were considered (refer to Appendix A and
165 Figure 4), excluding those already built since 2018, and also those without any major underground
166 works. The most common opportunity for energy geostructures comes with bridge foundations.
167 Based on publicly available scheme information, an estimate was made of the number of piers or

168 abutments to be expected, then a conservative assumption made regarding pile numbers and length
 169 (refer to Appendix A). A similar approach was applied to proposed underpasses or other retaining
 170 structures and tunnels, which were evaluated on the potential area available for heat transfer. The
 171 most significant contributions come from the proposed tunnel schemes at Silver Town, Lower
 172 Thames Crossing and Stonehenge.



173

174 **Figure 3 Cost of Infrastructure Investment in the UK in 2017 by Sector (ONS, 2018)**

175

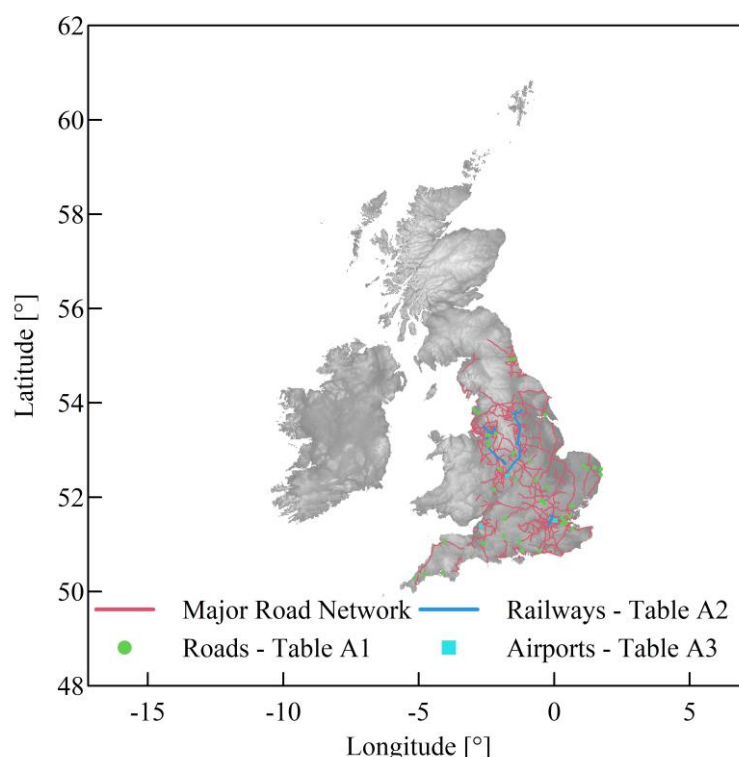
176 In all cases a conservative heat transfer rate per unit length or area was assumed (Table 2) based on
 177 estimates from Table 1. This was assumed to be equivalent to base load that could be utilised all
 178 year round for either heating or cooling, therefore permitting scaling up to kWh available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

181 A similar approach was adopted for future railway construction. Estimates of to be constructed
 182 infrastructure and its heat exchanger potential were made for Crossrail2, and High Speed 2 (Phase
 183 2A and Phase 2B West), as shown in Figure 4. Each of these comes with significant numbers of new
 184 structures, retaining walls associated with shafts, underground boxes or other cut and cover
 185 construction, and also tunnels. Based on the expected numbers of these structures and the

186 assumptions outlined in Appendix A, this suggests a heating potential of another 226 GWh/year as
187 shown in Table 2.

188 Three airports are also marked for expansion in the Infrastructure and Projects Authority (2018)
189 pipeline (Figure 4). Of these, the most information available is about the London City Airport
190 Development Programme where 1,000 piles of 17.5m depth are expected to be installed.

191 Extrapolating a similar level of development for the terminal extension and Birmingham and Bristol
192 Airports suggests a heating potential of 13.8 GWh/year.



193
194 **Figure 4 Map of the United Kingdom showing the existing road network, Major Road Network**
195 **(Department for Transport, 2020), as well as the major transport infrastructure assessed for**
196 **thermal energy potential (See Tables A1, A2 and A3). Background DEM data is modified from**
197 **EU-DEM v1.1 (Copernicus Land Monitoring Service, 2022). Shapefiles of railway projects are**
198 **obtained from High Speed 2 Limited (2020, 2022) and Nicholl (2018).**

199
200 While the above discussion has focused on new build transport infrastructure, there remains a
201 significant existing asset stock, including 15,904 km of railway routes operated by Network Rail (ORR,
202 2020) and 7,000 km of motorway and major trunk roads in England. Underground structures
203 associated with these assets are harder to convert to energy geostructures. However, recently
204 techniques have been developed recently to permit retrofitting of GHE to retaining walls (Baralis &

205 Barla, 2021) and trials have been carried out to retrofit tunnel GHE (Lee et al, 2016). These
 206 approaches will not be suitable in all cases, but are avenues for further research and development.

207 **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				

208

209 **3.2 Exploitation of Water and Wastewater Infrastructure**

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

215 Liu et al. (2020) made simulations at a scale of 1,000 households, optimising an idealised integrated
 216 system of sewer heat recovery, drinking water reservoir let down, solar panels, wind turbines and
 217 gas back-up. They showed that for 3 locations in the UK, the domestic heat demand could be
 218 satisfied for 63% of the time for one year with no CO₂ emissions. However, Liu et al. (2020)
 219 emphasised the daily and seasonal patterns of mismatched energy demand and availability, and for
 220 the need for inter-seasonal storage of renewable energy.

221 Actual achievable heat recovery will depend on the local wastewater temperature and mass flow
 222 rate. Data on wastewater and drinking water temperature are scarce. Frijns et al. (2013) described
 223 how in the Netherlands, 60% of drinking water is heated in the house, and the temperature of
 224 wastewater leaving the house varies throughout the day, averaging 27°C. However, in the sewer
 225 system network, the wastewater loses heat energy to the air, pipe materials, adjacent pipes, and the
 226 soil (Shafagh et al, in review), resulting in spatially and temporally varying temperatures. The

227 potential amount of heat recovery from the sewer system also depends on network boundary
228 constraints such as the need to maintain an acceptable Wastewater Treatment Works (WwTW) inlet
229 temperature and not allowing in pipe freezing.

230 Therefore, the size of the opportunities of heat recovery is highly dependent on local conditions.

231 Abdel Aal et al. (2018) is the only study to model a city wide system (79,000 PE - population
232 equivalent) and estimated a recovery potential between 116-207 MWhr/day. This study was located
233 in Belgium, in a similar climate to the UK and can be scaled up to the 55.3 million people living in
234 homes in urban areas in the UK located close to a major sewer network. On this basis it could be
235 conservatively estimated that between 80-140 GWhr/day (29 - 51 TWhr/year or 7-13% of the
236 theoretical maximum value of recovery) could be harvested from the UK's sewer networks. This
237 estimate gives a range of power per population equivalent (PE) values of 61-109 kW per 1,000PE,
238 which is consistent with values reported in a literature review by Bulteau et al. (2019)..

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

243 *3.3 Sustainable Urban Drainage*

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

252 Drove, over 400 m² of permeable paving was installed, alongside a similar area of detention and
253 wetland basins, and over 70 m of swales. Taking figures of 35 W/m² (Table 1) for the paving and
254 basins and 15 W/m for the swales suggests the SuDS installed at the site could release 29kW of
255 heating/cooling power or around 254 MWh/year (i.e. >7 MWh/year for each dwelling).

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

262 *3.4 Significance*

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

273 Additionally, transport infrastructure substructures can play a role in the nation's heating and
274 cooling delivery. At 0.33 TWh/year, the available energy may be orders of magnitude lower than
275 that from wastewater, though it still offers significant heating potential to nearby heat users. These
276 may not just be domestic users, but could include business and industrial buildings in urban areas,

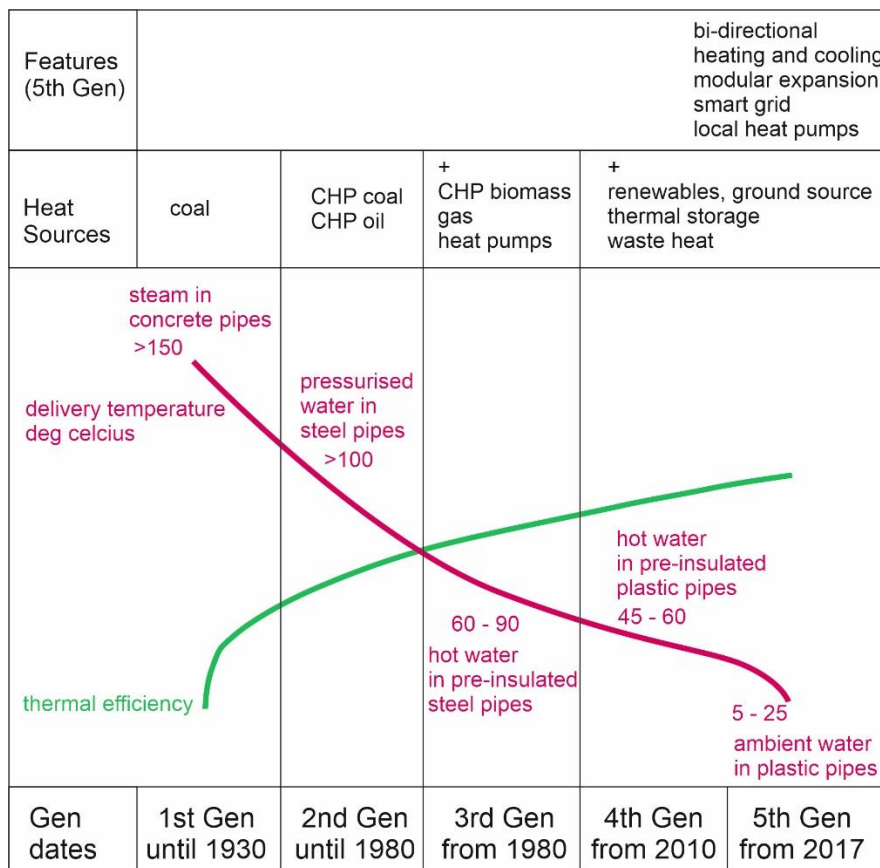
277 such as over station developments, and also buildings that support the operation of infrastructure
278 such as station buildings, maintenance depots and plant rooms. Together with wastewater effluents,
279 the contribution to the UK annual heat energy demand of new build infrastructure and SuDS for new
280 housing could exceed 52 TWh/year. This is before any consideration of retrofitting GHE to transport
281 and drainage infrastructure.

282 *3.5 Delivery through heat networks*

283 Harvesting of heat from infrastructure and delivery of heat at appropriate temperatures using heat
284 pumps can be deployed at a wide range of scales – from individual properties to city scale (Figure 2).
285 Property scale may not be feasible for many infrastructure schemes, whereby sufficient heat users
286 are not necessarily immediately adjacent to the planned works. This will be especially true for
287 transport infrastructure that by definition often connects urban centres (e.g. refer to Appendix A).
288 Therefore, beyond property scale, a heat network is required to deliver heating and cooling. A wide
289 range of configurations, operating temperatures and integration with heat pumps are possible. At
290 the largest scales, as well as when dealing with large demands, distribution at greater than km scale
291 allows heat sources remote from the point of use to be accommodated. They also allow a variety of
292 infrastructure and other heat sources to be connected, hence addressing the limitations of
293 mismatched supply and demand highlighted in Section 3.2.

294 Heat networks are firmly established (along with financing/governance vehicles, supply chains and
295 skills) in the UK. Development has progressed in the last decade in response to the national heat
296 strategy and initiatives to provide finance for local government to undertake both feasibility studies
297 and large-scale capital development in partnership with industry. UK Cities with new thermal
298 network developments include Leeds and Gateshead; those seeing expansion of existing systems
299 include Coventry and Birmingham. These systems are regarded as ‘Third Generation’ district heating
300 in terms of the types of heat source and delivery temperature (75 – 90 °C) they use (Figure 5).
301 Delivery of heat at these temperatures and systems efficiencies of 300% have been demonstrated at

302 large scale using Ammonia heat pump technology (EHPA, 2015). Given the effectiveness of such MW
 303 scale heat pumps, waste heat from infrastructure could be collected and delivered at city scale using
 304 existing and new networks.



305

306 **Figure 5 Evolution of District Heating Technology to 5th Generation, adapted and extended**
 307 **from Lund (2014).**

308

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

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

323 Fifth generation heat networks (Buffa et al, 2019) are intended to operate at near-ambient
324 temperatures with multiple providers of low temperature heat and sharing of thermal energy by
325 combining cooling and heating customers on the same network (Figure 5). Such a system is under
326 development for the city of Plymouth (HeatNet, 2019). Users requiring high temperature for existing
327 heating systems would use a local heat pump integrated with the building and the networks as a
328 source. Infrastructure thermal energy sources can be used at high efficiency with heat pumps to
329 deliver heat or provide cooling at different times in the year, and to incorporate low temperature
330 thermal storage. Such systems can be implemented at the scale of modest groups of buildings, to
331 city scale. Their application with energy geostructures is considered in detail in Meibodi & Loveridge
332 (2022).

333 **4 Discussion: Challenges and Solutions**

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

343 **4.1 Risks**

344 Harvesting thermal energy from buried infrastructure can carry risks as well as opportunities. For
345 example, sub-structures converted to energy geostructures will experience additional concrete
346 stress and will induce additional ground and structural displacements due to the associated
347 temperature changes induced. In general, the degrees of freedom of a structure, dependent on soil
348 stiffness and structural characteristics of the foundation, will determine the magnitude of these
349 stresses and displacements. Larger freedom is associated with larger structural displacements and
350 smaller additional forces, with the opposite being true for more restricted structures. While those
351 changes in forces are expected to be relatively modest in comparison to design loads, there are
352 situations where careful analyses are required, ideally including the modelling of the highly coupled
353 thermo-hydro-mechanical behaviour of soil. One of such cases is linked to the use of low
354 temperatures during heat extraction, which may result in tensile stresses and thus in cracking of
355 concrete (Bourne-Webb et al., 2009). Measurements of settlement or heave of single energy piles
356 show displacements of less than 3mm within typical operating temperature ranges (Di Donna et al,
357 2017). Additional cyclic effects could be expected and are yet to be fully characterised, but
358 sensitivity analyses for London Clay suggest less than 10mm of additional movement would require
359 accomodating depending on the conditions (GSHPA, 2018).

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

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

378 **4.2 Benefits**

379 **4.2.1 Carbon Savings**

380 The primary benefit of harvesting energy from buried infrastructure lies in the provision of abundant
381 low carbon heat. As well as any financial benefit (see Section 4.3 below), this will come with more
382 significant carbon emissions reductions. The extent of these carbon savings will depend on future
383 electricity grid carbon intensity and the counterfactual condition. Taking the BEIS data shown in
384 Figure 1, the carbon density of thermal energy from infrastructure sourced heat in 2025 would be 36
385 gCO₂ per kWh assuming an efficiency of 300%. This can be compared with either direct use of gas
386 (210 gCO₂ per kWh) or direct use electricity (108 gCO₂ per kWh). Scaled up for the potential of the
387 UK, implementation of the 52 TWh/year calculated in Section 3.4 would result in between 3,888 and
388 9,393 million tonnes of CO₂ saved per year.

389 **4.2.2 Infrastructure Benefits**

390 As well as temperature changes in structures causing additional stress and/or strain as described in
391 Section 4.1 above, there is also the potential to use temperature changes to help control structural
392 or thermal behaviour in a positive way. For example, many underground metro systems accumulate

393 heat, which reduces comfort levels, and use of the tunnel linings and station sub-structures to
394 control the temperature has clear operational benefits. Natural temperature changes can also have
395 detrimental impacts on structures, e.g. thermal expansion and contraction of bridges leading to the
396 use of bearings or accomodation of additional earth pressures behind abutments. These
397 temperature changes could also be controlled by the use of the sub-structure for thermal
398 exploitation.

399 In sewer networks, implementation of heat exchange can additionally provide a simultaneous
400 solution to some damaging biological and/or chemical process and hence potentially reduce
401 management costs and increase environmental performance. For example, Abdel-Aal et al. (2019)
402 utilised a case study to simulate anticipated temperature reductions in a sewer network due to heat
403 recovery, and investigate its effects on unwanted in-sewer processes. Preliminary modelling showed
404 considerable reductions in hydrogen sulphide formation, offering a promising method for managing
405 hydrogen sulphide formation and hence reducing sewer corrosion and odours. Heat extraction could
406 also reduce methane production in anaerobic sections of sewers. Methane is a greenhouse gas,
407 and measurements suggest that diffused emissions from sewer networks could contribute between
408 0.1 and 0.3 kgCO₂eq per meter cube of wasatewater (Liu et al., 2015). Finally, problematic
409 deposition of fats, oil and grease (FOG) in sewers may be temperature dependent. A weak
410 relationship between FOG formation and temperature has been shown in preliminary laboratory
411 investigations (Abdel-Aal et al. 2019), confirming the need for further research into the phenomena.

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

418 contaminated urban runoff, resulting in an accelerated and prolonged water quality improvement
419 function (Le Fevre et al. 2015).

420 *4.3 Business Case*

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

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

440 As a result of the above factors, new forms of business case will likely be needed for specific
441 infrastructure scheme implementation. However, early indications are that infrastructure sourced
442 heat will be financially viable. A study for the Grand Paris metro extensions looked at equipping

443 tunnel segments for ground heat transfer and storage (Cousin et al, 2019). Profitability was assessed
444 through net present value calculations, assuming sale of all thermal energy from the tunnel at 0.12
445 €/kWh. The time of obtaining profitability was between 10 and 20 years and dependent on the
446 levelised cost of energy from the system, itself dependent on the density and size of the heat
447 transfer pipes installed within the tunnel lining, and operating conditions. Some configurations were
448 not profitable, highlighting the need for future studies to include techno-economic assessments.
449 Return on investment was predicted to be between 130% and 200% at 25 years depending on the
450 conditions. However, it should be noted that since completion of this study, published in 2019,
451 wholesale gas and electricity prices in the UK and the EU have peak at over twice the sale price
452 assumed, which would significantly affect the net present value calculations, and likely improve the
453 return on investment.

454 *4.4 Implementation*

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

464 There are also non technical challenges related to policy, investment, ownership and operation of
465 heat supplies and services. Buried infrastructure systems have longer life-spans than building
466 heating systems, and similarly with utilities, heat from infrastructure may be exploited by new actors
467 in the energy market place with the provision of heat viewed as a service. This environment has

468 seen heat pump providers start to act as utility companies, operating shared GHE resources (e.g.
469 Kenny, 2018), but will be especially important where a traditional infrastructure owner may be a
470 different organisation from heat suppliers and users. A further possibility is for harvested heat to be
471 contributed to a pool of diverse suppliers/prosumers in a heat network dynamic market (Meibodi &
472 Loveridge, 2022). What business model is adopted will feed into the business case calculation as
473 discussed in Section 4.3 above.

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

484 5 Conclusions

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

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

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

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517 7 Data Statement

518 All data generated or analysed during this study are included in this published article

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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
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

Scheme Name	Value	Construction Programme	Comments regarding potential for energy geostructures*	Source
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 Upgrade	£60M	2020 -	New underpass, assumed piled wall	Hampshire County Council
M6 Junction 10 Improvements	£78M	2020 - 2023	Includes two new bridges	Highways England
Poynton Relief Road	£26.5M	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

Scheme Name	Value	Construction Programme	Comments regarding potential for energy geostructures*	Source
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	£1250M	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
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

Scheme Name	Value	Construction Programme	Comments regarding potential for energy geostructures*	Source
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
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 countless 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 Gantry, 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