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Heat from Underground Energy London (Heat FUEL)

Henrique R. P. LAGOEIRO[(a)], Daniel CURRY[(b)], Gareth FAULKS[(b)], John BIELICKI[(b)], Akos REVESZ[(a)], Gareth DAVIES[(a)] and Graeme MAIDMENT[(a)]

[(a)]London South Bank University, London, United Kingdom, roscoeph@lsbu.ac.uk
[(b)]London Underground Limited, London, United Kingdom

ABSTRACT

This paper provides an analysis of a heat recovery scheme that collects waste heat from the London Underground, a large potential source that produces significant amounts of heat throughout the year. The heat is captured by an air-to-water heat exchanger located within a ventilation shaft of the London Underground, then upgraded using a heat pump and used as a low carbon energy source for a local district heating network. This work introduces some of the key aspects of the technical design of this novel urban heat recovery and delivery system, as well as compares it to similar solutions that recover heat from urban underground railways. The theoretical performance of the system is evaluated and compared to the previous heating method used for the buildings supplied by the network. This paper also provides recommendations for the implementation of future installations for secondary heat recovery and reuse in cities.

Keywords Heat networks, heat pumps, low carbon heat, London Underground, waste heat recovery

1. INTRODUCTION

The United Kingdom has achieved significant reduction of Greenhouse Gas (GHG) emissions in recent years, cutting them by 43% since 1990 (CCC, 2018), as a result of the Climate Change Act (2008), which established a target to reduce carbon emissions by 80% of its 1990 baseline level by 2050. In order to keep track of the UK's progress in tackling climate change, the Act also set carbon budgets to be measured every five years. Despite having met its 1st (2010), 2nd (2015) and 3rd (2020) carbon budgets, the UK will require much greater efforts if it is to meet the 4th (2025) and 5th (2030) targets, especially from the heating and cooling and transport sectors, since the results to date can be mainly attributed to the transformation of the power sector, which has achieved a considerable reduction in the use of coal as an energy source and an increase in the use of renewable sources. Approximately one third of carbon emissions and around half of the energy consumption in the UK can be traced back to heating and cooling (BEIS, 2018a). Despite having a considerable impact in energy consumption in Britain, very little of heating and cooling is provided with renewable energy. In 2017, only 4.5% of heating in buildings came from low-carbon sources (CCC, 2018). Lack of sustainable heating is also a problem at city level, with gas-fired boilers representing 90% of the heating used in London, making a significant contribution to both the carbon footprint and the air pollution in the city. Recent developments based on Combined Heat and Power (CHP) systems have been introduced across the country as a cost-effective way of producing low-carbon heat. However, as the national electricity grid decarbonises, the carbon savings relating to CHP are declining and there is increasing evidence of their adverse impacts on air quality. The Greater London Authority (GLA) (2018), has set the ambitious goal of London becoming zero carbon by 2050. Decarbonising the heating sector will be crucial to achieve this target, as London's 3.5 million homes produce one third of the capital's total GHG emissions and nearly three quarters of the energy consumed by homes is used for space and hot water heating. Meanwhile, the energy used to power and heat London's workplaces accounts for approximately 40% of the city's emissions, with 51% of that energy being used for space and hot water heating (GLA, 2018).

2. HEAT NETWORKS

Heat networks, or district heating networks (DHNs), represent an interesting alternative to deliver cost-effective low carbon heat. They are very flexible, being able to incorporate new buildings and heat sources as the network grows, and are particularly attractive in densely populated urban areas. DHNs also enable the use of different generating technologies to feed heat into the network, avoiding a lock-in to technologies that may become obsolete in future decades. It also permits multiple heat sources to be used simultaneously in order to deliver heat to the network, providing a key mechanism to allow a smooth transition from current fossil fuel based heat to future low carbon heat sources.

Nowadays only around 2% of the overall heating demand in the UK is met using heat networks (BEIS, 2018a), whilst London has 6% of its energy requirements supplied via local networks (GLA, 2018). However, it is already possible to identify some governmental initiatives to promote the use of low-carbon district energy within the UK. London, for instance, has already set a target of meeting 15% of its energy demand using district schemes and renewable sources by 2030 (GLA, 2018). It is likely that DHNs will play a key role in this process, as they can accommodate any heat source of sufficient temperature, enabling the use of waste heat sources to provide heating. The recovery of waste heat involves capturing heat that would otherwise be rejected during a given process, such as the heat that is generated during the operation of many urban infrastructures, e.g. sewage systems, electricity substations and cables, data centres, and railway tunnels. This paper analyses one such application for heat networks that will soon be operational in London, known as the Bunhill Waste Heat Recovery System or Bunhill 2, an extension of the Bunhill Heat Network which involves the recovery of waste heat from the Underground. The analysis entails comparing state-of-the-art technologies that could be applied to recover heat from railway tunnels, as well as describing the Bunhill system as a whole, its key components and expected performance.

3. HEAT GENERATION IN THE LONDON UNDERGROUND

As London is home to the world's first metro system, with a network length of 402 km (45% in tunnels) and 1.35 billion passengers per year (TfL, 2019), underground railways represent a particularly good option for secondary heat recovery in the city. The Metropolitan Integrated Cooling and Heating (MICAH) project investigated how the London Underground (LU) network remains relatively warm in most locations throughout the year and that the system could also deliver cooling to the tunnels when required (Davies et al., 2017). The Underground represents a great opportunity for waste heat recovery, as the operation of the trains requires considerable energy, which ends up being degraded and released as waste heat. Over 80% of the heat introduced into the network can be traced back to mechanical losses, related to the running of the trains; mainly, braking friction and resistive losses in the traction-control system, whilst the remainder can be attributed to commuters and station and tunnel systems (Botelle et al., 2010). The London clay surrounding the tunnel walls, which is the main heat sink, has gradually become heated, leading to higher temperatures for both the surrounding soil and the air in the tunnels. By exploiting the opportunity to recover waste heat from the Underground, it is also possible to deliver cooling to the tunnels, which is also beneficial.

4. WASTE HEAT RECOVERY FROM RAILWAY TUNNELS

A number of recent studies have addressed the potential to recover waste heat from railway tunnels, focusing on different technologies that could be applied to effectively retrieve the energy that is dissipated in the form of heat during the operation of underground trains. Botelle et al. (2010) showed how groundwater based air handling units (AHU), using either seepage water or aquifer groundwater, have already been applied to cool stations of the LU network. Seepage groundwater is particularly interesting as over 30 million litres of water already need to be constantly pumped out of the Underground network. Therefore, using it for cooling/heating represents an efficient solution energy wise, as shown by Ampofo et al. (2011), who investigated the performance of a groundwater cooling trial based on 3 fan coil units at Victoria station. Although the warmed water represents a large potential source for waste heat recovery, this technology might be limited to use at station platforms only, as the deep tunnels of the London Underground are too narrow to fit fan coil units.

Geothermal energy technologies, which are based on the capacity of the soil to store and provide heat, have also been investigated as a means of recovering waste heat from underground rail networks, resulting in innovative solutions that are both environmentally friendly and cost-effective. Brandl (2006) and Adam and Markiewicz (2009) investigated how foundations and underground structures, including tunnels, can be designed as thermo-active structures, enabling them to capture heat from their surrounding environment. Brandl (2006) researched how absorber pipes could be applied to bearing structures, such as bored piles, diaphragm walls and foundation slabs, in order to capture waste heat from railway tunnels and stations in Vienna. Both Adam and Markiewicz (2009) and Brandl (2006) also highlighted the potential of heat extraction based on absorber pipes attached to an energy geocomposite placed between the outer and inner linings of a tunnel. The geotextile can also be connected to energy anchors, an important structural element that supports the tunnel excavation and could be applied as a new energy active element. In Stuttgart, Germany, a similar heat recovery trial was conducted on the city’s metro system, where absorber pipes were attached to a geotextile and placed between the tunnel linings (Buhmann et al., 2016).

Nicholson et al. (2014) looked at the design of underground rail tunnels with absorber pipes embedded within segments of the tunnel lining, providing cooling to the Crossrail tunnels in London whilst harvesting waste thermal energy to heat nearby buildings. A similar system was proposed by Barla et al. (2016), which numerically analysed the feasibility of developing an energy tunnel in Turin. The proposed design also consisted of embedding pipes within the precast concrete lining and could operate in cooling and heating modes. Tunnels designed in this way can achieve high heat extraction rates, however, these technologies can only be applied to new underground railway developments and are not suitable to recover heat from the existing deep tunnels of the LU network. Revesz et al. (2019) proposed a different approach to recover the excess heat that is generated in railway tunnels in London, suggesting the use of ground source heat pumps (GHSPs) connected to geothermal heat exchangers (GHEs) to collect the heat that is conducted into the surrounding soil during the operation of trains due to the heat sink effect. As for the Bunhill Waste Heat Recovery System, an air-to-water heat exchanger will be applied so as to capture heat from a ventilation shaft within the LU network. The technology and its operation will be further described in the following sections of this paper. Davies et al. (2017) also investigated the potential to recover waste heat from ventilation shafts, identifying the benefits of applying this technology to a different shaft of the network.

Table 1 – Potential technologies for waste heat recovery from underground railway tunnels.

Technology	Location	Heat Source Medium	Heat Source Temperatures	Heat Extraction Rate	Service Disruption	Reference
Embedded absorber pipes in tunnel segments	London, UK	Air	17 to 36°C	7 to 30 W/m^2 of tunnel surface area	High	Nicholson et al. (2014)
	Turin, Italy	Air/ ground	14°C	53 W/m^2 of tunnel surface area	High	Barla et al. (2016)
Diaphragm and energy pile walls	Vienna, Austria	Air/ ground	>20°C	30 W/m^2 of earth-contact area	High	Brandl (2006)
Energy foundation slabs	Vienna, Austria	Ground	>20°C	10 to 30 W/m^2 of earth-contact area	High	Brandl (2006)
Pipes attached to geotextile between tunnel linings	Stuttgart, Germany	Air	6.5°C	20 W/m^2 of tunnel surface area	High	Buhmann et al. (2016)
Groundwater used in platform air handling units	London, UK	Air	22 to 32°C	50 kW/unit	Medium	Ampofo et al. (2011), Botelle et al. (2010)
Ground source heat pumps installed next to tunnels	London, UK	Ground	20 to 30°C	20 to 29 W/m of borehole length (depending on the GHE configuration)	Low	Revesz et al. (2016), Revesz et al. (2019)
Heat exchangers connected to ventilation shafts	London, UK	Air	20 to 28°C	900 kW/shaft	Low	Davies et al. (2017)

Table 1 summarises a range of previously investigated technologies that involve waste heat recovery from underground railway tunnels. The table also indicates the location where the technology was implemented/simulated; the temperatures and medium considered for the heat source; the calculated heat extraction rates; and the related risk of service disruption when installing each of the technologies. It also includes references to the authors reporting each study. Regarding the “risk of service disruption” category in the table, a low risk means that the implementation does not hinder or slightly affects the operation of the trains, while a medium risk represents the need for a partial disruption of the transport service, and a high risk implies the need to suspend operation during the installation of the related technology. As it can be seen in Table 1, extracting heat from ventilation shafts represents a great opportunity, as significant heat can be extracted while keeping service disruptions to a minimum.

5. THE BUNHILL HEAT NETWORK

The Bunhill Heat Network was an initiative from Islington Council, aimed at providing locally produced cost-effective, low carbon heat for nearby housing estates and service buildings. The project consists of two different stages: Bunhill 1, the original DHN launched in 2012, and Bunhill 2, an extension to the existing heat network that will involve utilising recovered waste heat. The concept for Bunhill 1 was to use a gas-fired CHP system, producing both electricity and heat, which is linked to a heat distribution network in order to supply heating for the local community. The Energy Centre for Bunhill 1 comprises a 1.9 MW_e/2.3 MW_{th} gas fired CHP and a 115 m^3 thermal store. The network currently operates with flow and return temperatures of 95°C and 75°C, respectively.

In an effort to further expand the supply of low cost and low carbon heat to its residents, Islington Council started to research potential extensions to the Bunhill Scheme, which led to the opportunity of developing Bunhill 2, a waste heat recovery system based on heat capture from the London Underground, implemented in a partnership with Transport for London (TfL) and the GLA. This project is the first of its kind in Europe and is part of the EU CELSIUS Project, which aims to promote the use of sustainable heating and cooling in European cities. The decision to use waste heat sources is also related to the decreasing carbon efficiency of CHP systems due to the growing decarbonisation of electricity in the UK. Bunhill 2 will collect heat from one of the shafts that constitute the ventilation system of the Underground network. The heat will then be upgraded using a heat pump before being transferred into the DHN, which will be extended to connect new buildings to the new Energy Centre. The Energy Centre consists of the heat pump, a thermal store and two CHP engines, which will be added to the system so as to provide resilience and flexibility to the heat network. The development of Bunhill 2 will shed light on how London can become a truly smart city, showing how DHNs and heat pumps can be fundamental in future smart energy infrastructures, both at district and ultimately city levels, by allowing the capture of urban waste heat. As this paper aims to research the novelty related to the system, only the Bunhill 2 network will be presented, focusing on the first trial to recover waste heat from the London Underground.

6. THE OPERATION OF THE BUNHILL WASTE HEAT RECOVERY SYSTEM

The Energy Centre of Bunhill 2 is expected to meet an annual average heat output of 1,033 kW_{th}, with 780 kW of heat being recovered from the ventilation shaft and then upgraded by a two-stage heat pump, which will add the remaining 253 kW to the heat that is delivered to end users through the DHN. The two CHP units, each with an output of $237kW_e/372kW_{th}$, will power the heat pump and also add resilience and flexibility to the Energy Centre, although its output heat could be dumped if not needed. A thermal store of 77.5 m^3 will also be installed in order to add flexibility, helping to manage peak demand. The air that exhausts through the ventilation shaft has temperatures varying from around 18°C to 28°C. Thus, the first water loop, which transports the heat from the vent shaft to the heat pump, will also work with flow and return temperatures that vary according to the season of the year. The expected operating flow and return temperatures vary from 11 to 18°C and 6 to 13°C, respectively. The heat will be then upgraded and distributed with a flow temperature of 75°C, being returned to the heat pump at 55°C. Figure 1 shows a schematic of the Bunhill 2 heat network.

6.1. Heat Exchanger

The first stage of the system involves capturing the heat using an air-to-water heat exchanger in the City Road ventilation shaft. The heat exchanger used for this waste heat recovery system is a fan coil unit. A head house, where the coils were installed, was built on top of the ventilation shaft, which was upgraded to accommodate the variable speed reversible fan that enables the system to work in both Extract and Supply modes. The benefits of operation in these two different modes have been previously investigated by Davies et al. (2017) and consists of reversing the flow direction of the fan, allowing the system to operate by either extracting hot air from the Underground, which can then be used to warm the water in the coils, or using ambient air, which would be cooled by the coils and then supplied to the Underground, with the heat extracted being recovered by the heat exchanger.

Extract mode would be used during the colder months of the year, when the heat demand is at its peak and the underground air is warmer. Supply mode would be used to supply cooling to the Underground during the summer, when ambient temperatures are higher. Throughout the year, heat can be collected at average temperatures between 17 and 25°C, which explain the varying flow and return operating temperatures of the DHN. The coils have an annual average operating cooling duty of 780 kW and consist of 6 modules with 6 rows of copper tubes, resulting in a total of 36 rows of tubes - comprising the coil heat exchanger. The coils were built up in modules to make maintenance simpler and minimise downtime for cleaning. Figure 2 shows a schematic of the ventilation shaft and the head house, showing the coil heat exchanger and the reversible fan.

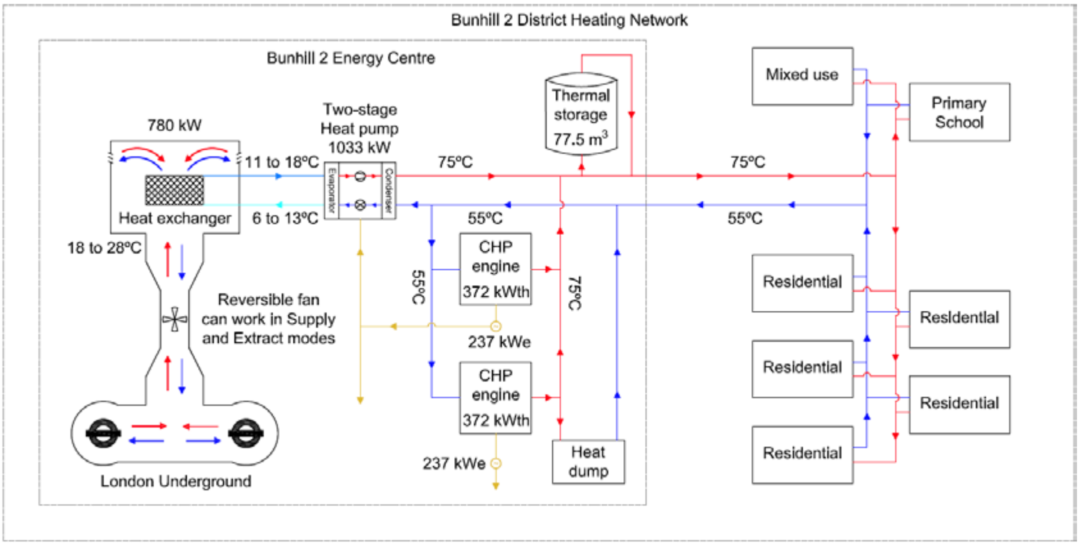

Figure 1 – Schematic of the Bunhill Waste Heat Recovery System.

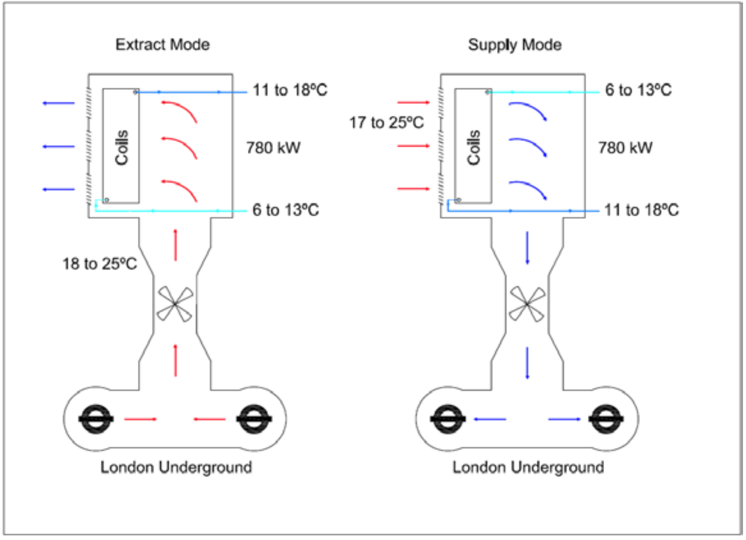

Figure 2 – Schematic of the heat exchanger and the ventilation shaft of the Bunhill Energy Centre 2.

6.2. Heat Pump

Before being delivered to the district heating network, the heat collected by the heat exchanger has to be upgraded by a two-stage water-to-water heat pump, which was designed based on the flow and return DHN temperatures of 75°C and 55°C, respectively. For district heating purposes, as the evaporator and the condenser operate with a large temperature difference, deploying single-stage heat pumps could lead to lower compression efficiency and decrease the overall system performance (Kwon et al., 2013). Two-stage compression represents a more flexible system, being able to operate at different capacities, and with greater efficiency. One advantage is that it allows intercooling, which decreases the necessary work input to the compressors, delivering high temperature lifts with a high Coefficient of Performance (COP) (Arpagaus et al., 2016). The flash intercooler also improves the efficiency of the system by allowing flash gas to be removed before the refrigerant enters the evaporator, increasing its heat transfer rate. The two-stage heat pump installed at Bunhill 2 operates differently according to the season of the year, due to the varying temperatures of its heat source. Table 2 shows the design parameters of the two-stage heat pump.

The refrigerant used in the heat pump is R717 (ammonia). The low stage includes a compressor that can run at a wide range of capacities in order to accommodate the variation in ventilation temperatures exhausted from the LU shaft. The high stage includes two compressors, which can also accommodate varying capacity, while maintaining the desired outlet water temperature at 75°C. The heated water from the first water loop will deliver heat to the heat pump's evaporator, with an approach temperature (ΔT) of 5°C, however, the cooling duty increases slightly, as higher temperature water enters the evaporator, to between 778 kW and 784 kW, with an annual average of 780 kW. By varying the cooling duty, the power input to the compressors can be minimised without compromising the design outlet temperatures. This results in higher COPs as cooling duty is increased, with an annual average COP of 3.76. The heat pump includes a heating circuit with 5 shell and plate heat exchangers, which are the flooded evaporator, a condenser, a subcooler and two desuperheaters. Figure 3 shows a schematic of the two-stage water-to-water heat pump installed at the Energy Centre of the Bunhill 2 heat network.

Table 2 – Design parameters for the two-stage ammonia heat pump installed at Bunhill 2.

Design Parameters	Operating Mode 1	Operating Mode 2	Operating Mode 3
Cooling Duty - Qe (kW)	778	780	784
First Loop Water Flow Temp. (°C)	11	13	18
First Loop Water Return Temp. (°C)	6	8	13
Heating Duty - Qc (kW)	1042	1033	1012
Estimated Shaft Power (kW)	264	253	228
Estimated Electrical Consumption (kW)	286	275	248
Cooling COP	2.72	2.84	3.16
Heating COP	3.64	3.76	4.08

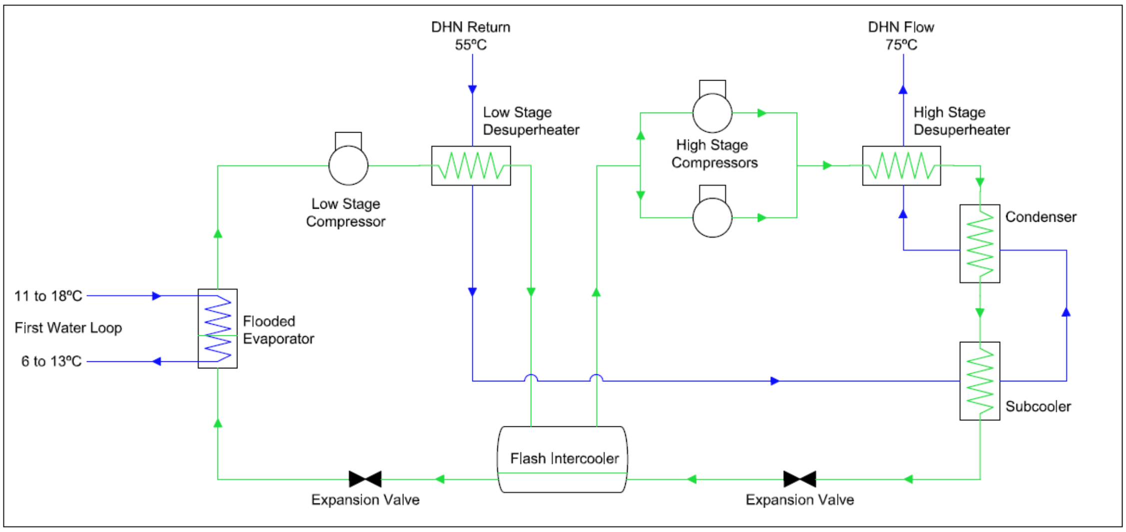

Figure 3 – Schematic of the two-stage heat pump of the Bunhill Energy Centre 2.

6.3. Thermal Storage

In order to provide flexibility, a thermal storage tank filled with 77.5 m^3 of water will be installed at the Energy Centre. Storing thermal energy is crucial to manage peak demand, securing the reliability of the system when it is most requested. The thermal store also avoids short cycling of the heat pump, enhancing its efficiency, since frequent start/stop operation can harm the system and increase its need for maintenance.

6.4. Heat Distribution Pipework

The heat distribution network will have an approximate length of 2.4 km and will utilise two parallel insulated pipes, for the flow, i.e. heat delivery, and return water streams. Water will leave the heat pump outlet at a design flow rate of 37.2 kg/s. The network has different pipe diameters, varying from DN 80 for local building connections to DN 250 for the main flow/return pipes, which distribute the heated water from the heat sources to local circuits, which feed one or more buildings connected to the network. The scheme is expected to provide heating to 455 dwellings in 5 building blocks of a local housing estate and to a primary school. A new mixed use building complex that is currently being developed will also be connected to Bunhill 2, adding to the network 720 residential units, a 160-bed student accommodation and a 125-bed hotel, as well as areas for offices, retail and restaurants as new end users. The expected annual heat demand of the network is 11,358 MWh.

7. BENEFIT ANALYSIS

In order to assess the benefits of this new waste heat recovery system in terms of carbon and cost savings, a spreadsheet based model was developed and used. The method aims to provide a high-level appraisal of the system's benefits based solely on energy input costs and carbon emissions related to heat delivered from the heat pump, and does not include any other operational costs, such as for staff support and maintenance. The analysis compares a scenario where all the heat demand is met by the heat pump to the previous heating method based entirely on communal gas boilers. The calculations were based upon a 25-year design life (2019-2043) and the following assumptions: gas boiler efficiency of 80% for the previously used boilers (BRE Group, 2018), carbon factors of 0.184 $kgCO_{2e}$/kWh for gas and 0.145 $kgCO_{2e}$/kWh for electricity, based on the averages of annual projections for the design life of the system (BEIS, 2018b), fuel tariffs of 3.89 p/kWh for natural gas and 14.22 p/kWh for electricity, considering the average values of central annual projections for public sector tariffs during the design life of the project (BEIS, 2018b), and distribution losses of 10% related to the primary heat network fed by the heat pump. The results of the analysis can be seen in Table 3, which shows that a heat pump based system results in yearly carbon savings of 2,133 tCO_{2e}, a decrease of 82% in emissions, demonstrating how waste heat recovery could reduce the carbon footprint associated with heating. This is due to the high energy efficiency of heat pumps and similar carbon factors for natural gas and electricity, which has considerably decarbonised in the UK in recent years. The cost analysis demonstrated how heat pumps can lead to annual savings of £79,778 or 14%, indicating how waste heat recovery systems can be financially attractive.

Table 3 – Calculated annual carbon and cost savings for a heat pump based heat recovery system.

Energy Consumption				
Technology	Efficiency/COP	Heat Demand (MWh)	Annual Energy Spent (MWh)	
Gas Boilers	80%	11,358	14,198	
Heat Pump	3.76		3,323	
Carbon Savings				
Technology	Carbon Factor ($kgCO_{2e}$/kWh)	Emissions (tCO_{2e})	Annual Savings	
			(tCO_{2e})	%
Gas Boilers	0.184	2,615	2,133	82%
Heat Pump	0.145	482		
Cost Savings				
Technology	Energy Tariff (p/kWh)	Costs (£)	Annual Savings	
			£	%
Gas Boilers	3.89	552,283	79,778	14%
Heat Pump	14.22	472,505		

8. CONCLUSIONS

The results obtained show the importance of investing in waste heat recovery systems, as they can lead to significant carbon savings compared to conventional heating methods and could become a key technology in minimising climate change, especially as electricity is expected to keep on decarbonising in the coming years. Despite leading to operational cost savings, the conducted economic assessment did not consider the capital costs related to heat pumps or the utilisation of the other heat sources within the Energy Centre, which can impact the overall financial performance of the scheme considerably. Even though the costs of implementing district scale heat pumps are known to be high, it is anticipated that they may become more attractive in the near future. As their deployment becomes more popular, the capital costs related to waste heat recovery tend to become lower. In addition, as natural gas reserves diminish over the next decades and possible new carbon taxes are introduced, gas prices are likely to rise, making heat pumps a viable alternative for heating.

Further studies on the Bunhill Heating Scheme will be undertaken as part of a PhD project, which will study the overall system particularly with regard to its technical and financial performance. Bunhill 2 is expected to become operational in 2019. The study will involve investigating the network components and their performances in detail, comparing the design performance with the actual operation of the system. The benefits of the system will also be looked into in more detail, considering seasonal variations, capital costs and other operational costs and issues, as well as any other challenges that might be encountered after Bunhill 2 starts running.

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