Heat Recovery Opportunities from Wastewater Treatment Plants

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ABSTRACT

Wastewater offers the potential of a widespread resource for low-temperature waste heat, with wastewater in sewers normally at temperatures greater than ambient due to the use of hot water in buildings. Heat can be recovered from wastewater from different locations, such as the wastewater pipework within a building, the sewage network or at wastewater treatment plants (WWTPs). The latter represents an interesting alternative as wastewater flow rates are generally much higher in the effluent of treatment plants than in sewers. Additionally, the temperatures may be above ambient, as the biological sewage treatment process results in some heat generation. This paper investigates the potential availability of waste heat from WWTPs across the UK, with a total thermal energy output of 26.2 TWh [89.5 MMDth (US)] per annum being estimated. A possible configuration for recovering waste heat from the WWTP effluent is also presented and used to assess the benefits that could be obtained against conventional heating technologies based on a case study in London. Although the case study is based in the UK, the methodology hereby described can also be applied to evaluate the potential for heat recovery from wastewater treatment plants in other countries.

INTRODUCTION

Recovering waste heat from urban infrastructures is becoming increasingly important as governments around the world strive for decarbonisation and energy security. According to the United Nations (2022), more than 70 countries worldwide, which account for 76% of global greenhouse gas (GHG) emissions, have set a net-zero target. This includes major emitters such as the United States, China, and the European Union. In temperate climates, heating represents a significant proportion of energy use and associated carbon emissions. In Europe, almost 50% of annual energy consumption is related to the supply of space heating and domestic hot water, with just over 40% of that demand being met with gas boilers (European Commission, 2021). In the UK, where heating for buildings accounts for 23% of GHG emissions (BEIS, 2021a), gas dependency is even higher, with 85% of households being heated with natural gas (ESC, 2020). As a result of post-pandemic economic recovery and the Russo-Ukrainian War, the reliance of Europe on fossil fuel gas to meet its heating needs has been highlighted as an issue for energy security and fuel poverty. While 40% of the total gas consumed in Europe is imported from Russia (IEA, 2022), the UK has been severely affected by the rise in wholesale gas prices, which had already increased by nearly four times prior to the war, from January 2021 to January 2022 (ONS, 2022).

Meanwhile, electricity has been decarbonising rapidly; in the UK, for example, national emissions fell by 48.8% between 1990 and 2020 (BEIS, 2021b), a progress mainly attributable to the increasing shares of renewable energy generation in the UK's electricity production mix. In 2020, renewable energy accounted for a record of 43.1% of the electricity generated (BEIS, 2021c), a number expected to grow continuously in the coming years. The ongoing decarbonisation of the electricity grid, together with the current dependence of the heating industry on natural gas, makes the electrification of heat, e.g. through the use of heat pumps, an opportunity to help reduce the carbon footprint of UK buildings, as recognised by the UK Government's Heat and Buildings Strategy (BEIS, 2021a). Within that context, heat networks represent a key technology, particularly in densely populated urban areas, as they enable the coupling between heating and other energy vectors and can benefit from economies of scale. A recent report by the UK Government looked at opportunity areas for district heating networks in the UK (BEIS, 2021d) and estimated that

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they could provide up to 95 TWh [324 MMDth (US)] of thermal energy annually by 2050, which would represent approximately 20% of the UK's domestic heating demand. Another advantage of district heating is its ability to make use of waste heat from a variety of urban infrastructures, which could be widely exploited in cities across the globe. The Heat and Buildings Strategy has acknowledged waste heat as low-carbon energy that should be utilised by heat networks, with sewage being highlighted amongst potential sources (BEIS, 2021a). This paper aims to investigate the nationwide potential for heat recovery from wastewater and evaluate the cost and carbon benefits associated with this opportunity.

WASTEWATER HEAT RECOVERY

Wastewater offers the potential of a widespread resource for low-temperature waste heat, with wastewater in sewers normally at temperatures greater than ambient air. This is due to use of domestic hot water, which leads to wastewater temperatures as high as 30°C [86°F] exiting the drains of UK homes (Farman Ali and Gillich, 2021). A study from the U.S. Department of Energy estimated that 350 TWh [1,195 MMDth (US)] of waste heat is discarded through American drains annually (DOE, 2005). Waste heat can be recovered from wastewater at different locations along the sewage treatment cycle, as illustrated in Figure 1, and heat exchanger technologies that could be applied in each case can be found in the work of Schmid (2008).

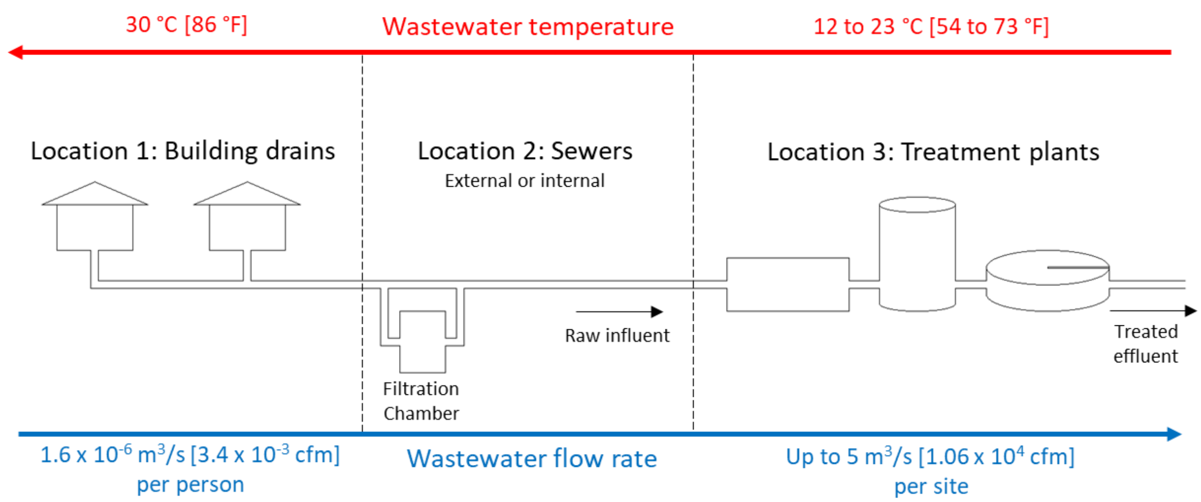

Figure 1. Locations for heat recovery from wastewater, with indicative flow rates and temperature for London.

The first potential location is at the discharge of dwellings or buildings, where higher temperatures are available, but at lower flow rates when compared to other locations. This waste heat could be used to preheat incoming cold water that is then heated for the provision of domestic hot water (DOE, 2022), which can be done through the use of heat pumps. One challenge associated with such a system is, however, the intermittency of hot water use in homes. Another opportunity involves recovering waste heat from the sewer mains, which are still close to potential end users and offer higher flow rates, though at lower temperatures. This may involve installing a heat exchanger inside the sewer (internal) or by diverting some of the flow into a filtration chamber (external), which is then connected to a heat recovery plant, as reported by Culha et al. (2015). Some challenges with this technology are the risk of fouling and possible limitations to the amount of heat that can be recovered, as it is undesirable to reduce the temperature of the wastewater entering a WWTP below 10°C [50°F] (Schmid, 2008). Finally, the third location for heat recovery from wastewater consists of treatment plants, which have the potential for district scale applications due to their much higher flow rates (Cipolla and Maglionico, 2014), as WWTPs are usually deployed to treat sewage from entire towns or large parts of cities. One example is the Beckton Sewage Treatment Works, the largest WWTP in Europe, serving a population equivalent (PE) of 3,040,238 as of 2018 (European Commission, 2018), which would equate to a flow rate of approximately 5 m^3/s [10,594 cfm], by considering that the average person in the UK consumes 142 litres [37.5 US gallons] of water daily

(EST, 2013a). One common challenge is that WWTPs are sometimes located away from densely populates areas, where heat networks are most cost effective.

The Wastewater Treatment Process

As discussed in the previous section, WWTPs represent an interesting location for heat recovery as wastewater flow rates are much higher at treatment plants than in sewers. Furthermore, wastewater effluent temperatures may also be above ambient, as the biological sewage treatment process results in some heat generation associated with oxidation (Alisawi, 2020). This means waste heat recovery from the effluent of treatment plants can also help to miminise thermal pollution in water bodies caused by the discharge of treated effluent (Wilson and Worrall, 2021).

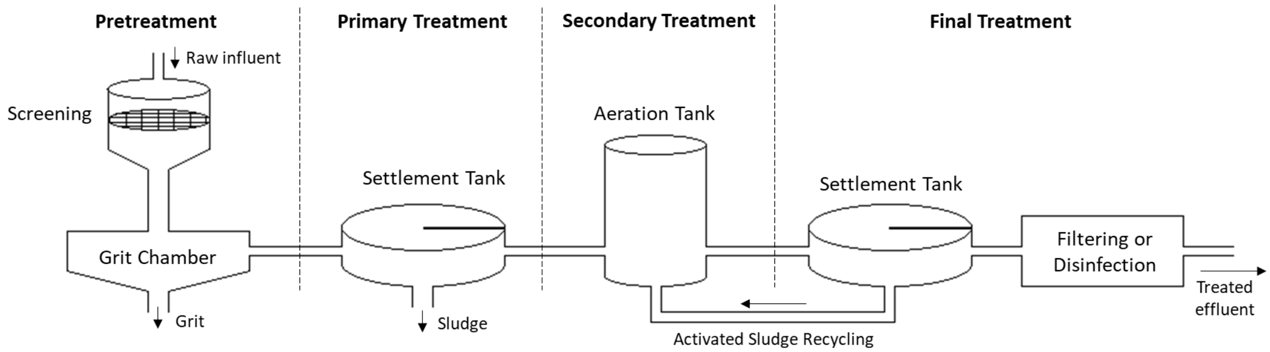

Figure 2. Representation of a typical wastewater treatment process.

Within a WWTP, the location for heat recovery must be selected according to any temperature thresholds associated with the different stages of the treatment process, which has been described by Thames Water (2022) and is illustrated in Figure 2. Upon arrival at the WWTP, raw influent from the sewers is screened for the removal of larger items that may damage the equipment within the plant. The sewage then passes through the grit chamber, which removes smaller solid materials that may have gone through the screens, such as sand, gravel, and food residue. The primary treatment then takes place, with a settlement tank or clarifier, which is used to separate organic biodegradable solids, i.e the sludge, from the water carrying them. The sludge is then dried and treated for use as a fertiliser or for the generation of electricity. The water leaving primary treatment is then taken to an aeration tank, where the biological treatment occurs, which involves using bacteria to remove smaller contaminants and organic particles from the water. This represents a critical process in terms of heat recovery, as bacteria is highly sensitive to temperature, with reduced activity being observed at temperatures below 10°C [50°F] (Metcalf & Eddy Inc., 2003), reducing the cleaning efficiency. The wastewater then goes to the final stage of the treatment process, where another settlement tank is used for recovering activated sludge. The water is then further filtered and/or disinfected prior to its discharge as treated effluent. As sewage temperatures must be kept at a minimum level due to the aerobic digestion process, which also leads to some heat generation, heat recovery must take place downstream of the aeration tank. Recovering heat from the treated effluent then becomes an interesting option, as it would involve lower fouling risks and potential maintenance costs. Additionally, heat recovery systems utilising treated effluent tend to have higher capacities and are typically linked to heat networks (Farman Ali and Gillich, 2021).

THE UK POTENTIAL FOR HEAT RECOVERY FROM TREATMENT PLANTS

The Urban Wastewater Treatment Directive (91/271/EEC) by the European Commission (2018) compiled data on the locations and plant entering volumes, based on PE, for WWTPs in the 27 EU member states and the UK. The dataset is based on reported values from each member state on wastewater collection, conduction, treatment, and discharge for agglomerations above 2,000 PE. This included 1,876 WWTPs in the UK; amongst those, 79% were in England, 11% in Scotland, 6% in Wales and 4% in Northern Ireland. Data on plant entering volumes have been used to estimate how much heat could be recovered from WWTPs in the UK. At first, the volumes entering each WWTP were converted from PE to volumetric flow rates ($\dot{V}$), in m³/s, as shown in Equation 1, assuming an average daily water consumption of 142 litres [37.5 US gallons] per person (EST, 2013). This approach was used as PE is a parameter that expresses wastewater volume in terms of the population that would generate that same load. The volumetric flow rates for wastewater were then utilised to estimate the theoretical potential for waste heat recovery (Q_{rec}) from WWTPs, as shown in Equation 2, assuming the density (ρ) and specific heat capacity (C_p) of wastewater to be 1000 kg/m³ [62.4 lb/ft³] and 4.2 kJ kg^{-1} K^{-1} [1.0 BTU lb^{-1} °R^{-1}], respectively. The calculations also considered different wastewater temperature reductions (ΔT) values across the heat recovery heat exchanger, between 4 and 6K [7.2 and 10.8°R], based on typical values reported in other studies (Cipolla and Maglionico, 2014; Neugebauer et al., 2015; Dénarié et al., 2021).

$$\dot{V} = \frac{142}{1000} \times \frac{PE}{24 \times 60 \times 60} \qquad [1]$$

$$Q_{\mathrm{rec}} = \dot{V} \times \rho \times C_p \times \Delta T \qquad [2]$$

The theorical potential of waste heat recovery from WWTPs is shown in Figure 3, together with estimates for the theoretical thermal energy output per annum, which was calculated assuming that WWTPs operate constantly throughout the year, i.e. for 8760 hours annually. The results in Figure 3 show potential waste heat availability ranging from 2 to 3 TW [6.8 to 10.2 Trillion BTU/h], approximately, which would lead to thermal energy outputs ranging from 17.5 to 26.2 TWh [59.7 to 89.5 MMDth (US)] per annum. This highlights how WWTPs could provide a very significant heat resource in the UK. However, the actual amount of waste heat that could be practically exploited depends on achievable flow rates and ΔTs across the heat recovery heat exchanger, as well as on the location of the WWTPs and their distance to potential end users. Many sites can be found in urban areas, where they could be used as an energy source for district heating. The following section will explore the geographical distribution of WWTPs across the UK.

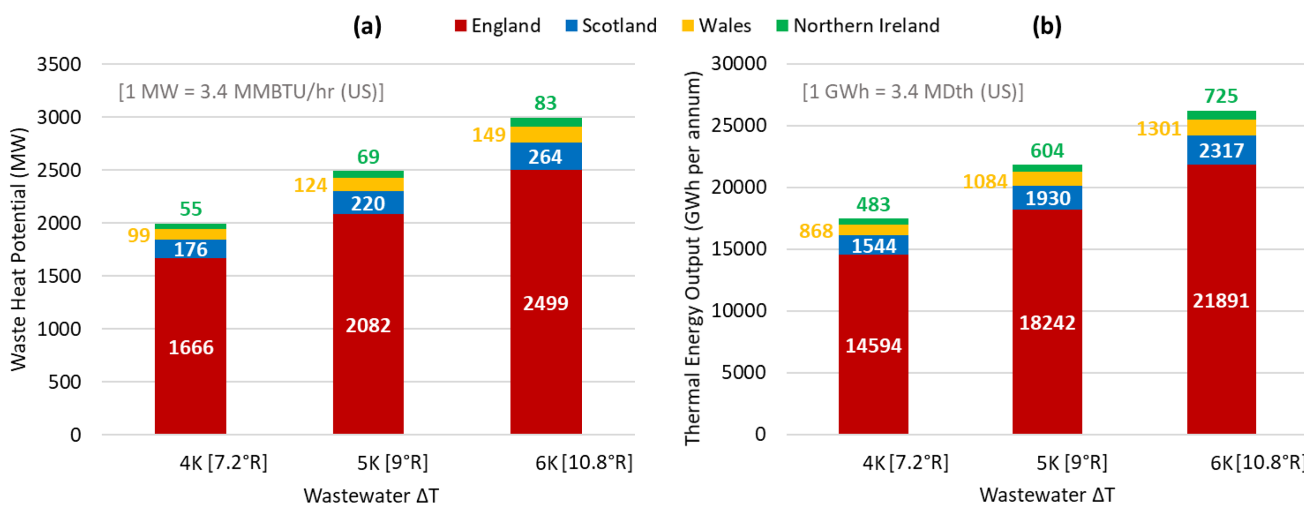

Figure 3. Theoretical values of waste heat potential (a) and annual thermal energy output (b) from WWTPs.

Mapping and Locations

The potential for heat recovery from a particular WWTP is primarily dependent upon the size and location of such plant. The distribution of the locations and sizes of WWTPs across the UK is illustrated by the maps in Figure 4, based on an assumed ΔT of 5K [9°R]. Figure 4(a) shows all UK WWTPs, whilst only the plants with a thermal energy output higher than 6 GWh [20.4 MDth (US)] per annum are highlighted in Figure 4(b). This threshold was chosen as it is equivalent to the annual heat demand of 500 average-sized UK households, considering the typical domestic consumption values for gas, as reported by Ofgem (2021). Results show that there are 550 WWTPs (29% of total) that would be able to provide more than 6 GWh [20.4 MDth (US)] of heat annually based on a 5K [9°R] cooling effect to the treated effluent stream. These 550 plants would account for 19 TWh [64.8 MMDth (US)] of heat, which represents 88% of the total thermal energy output estimated for WWTPs. This shows how the heat recovery potential is centred at the plants with the highest entering wastewater volumes; for example, the ten largest plants in the UK account for 20% of the national waste heat potential from WWTPs. As shown in Figure 4(b), the largest plants tend to be in urban centres, with five out of the ten largest UK plants located in London. This represents an opportunity for utilising waste heat from treatment plants to help decarbonise buildings at scale through the deployment of district heating networks. As the temperature of the final effluent from which heat would be recovered is quite low, i.e. 17.5°C [63.5°F] on average annually, and of the order of 12°C [54°F] in winter (for London), the recovered heat would need to be upgraded, e.g. by using a heat pump, prior to reuse. Different delivery temperatures can be used depending on the requirements of the heat network to which the heat recovery system is connected, having significant effects on achievable coefficient of performance (COPs). The next section will explore the carbon and cost benefits that can be achieved with different delivery temperatures against conventional technologies used for heating in the UK, based on a London case study.

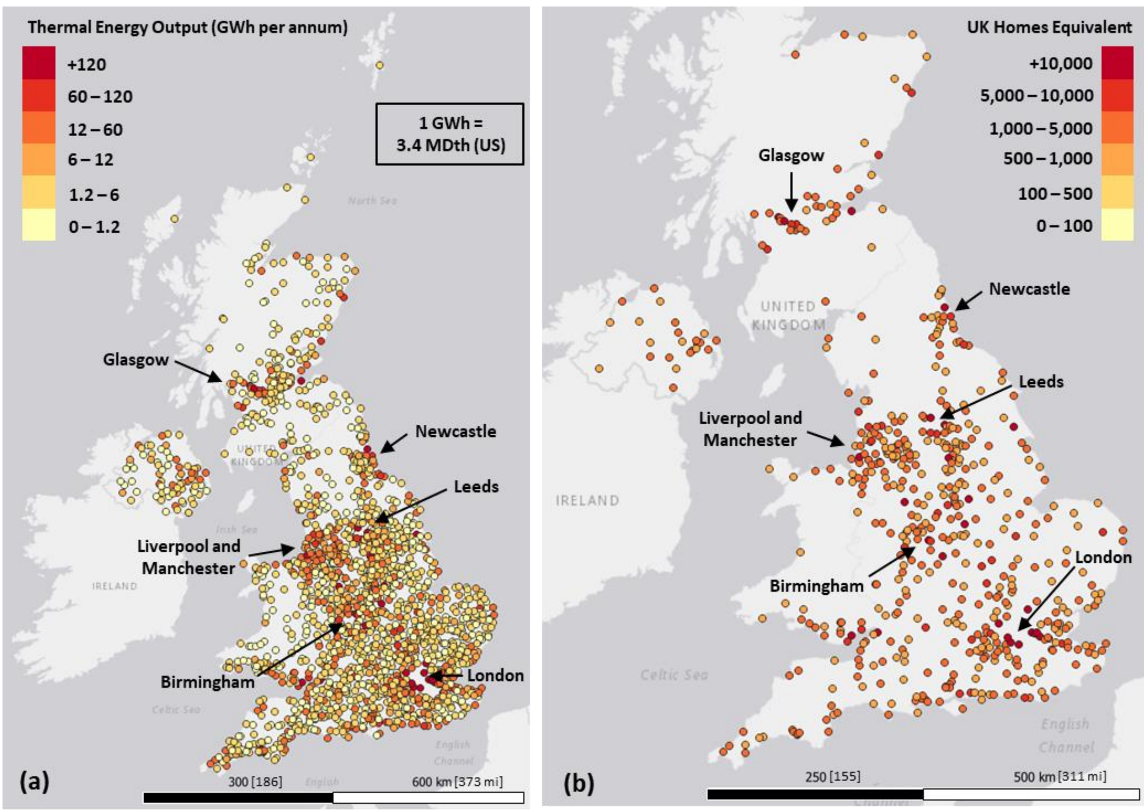

Figure 4. Maps of all the WWTPs across the UK (a) and for the sites that could provide more than 6 GWh of waste heat annually (b).

INVESTIGATING THE BENEFITS OF HEAT RECOVERY FROM WWTPS

The Case Study

The case study used in this paper to investigate the benefits of recovering heat from WWTPs is based upon the Hogsmill Sewage Treatment Works. The plant is located in the Royal Borough of Kingston-upon-Thames, in southwest London, and treats a load of 407,056 PE, which would equate to a volumetric flow rate of 669 litres [177 US gallons] per second, as per Equation 1. There are several potential end users in the vicinity of the plant, such as business parks with office spaces, university campi and schools, high-rise private accommodation buildings and large commercial stores. This analysis aims to assess the benefits of recovering waste heat from a WWTP against typical technologies used for heating. This is achieved by calculating the annual savings in energy costs and carbon emissions for the WWTP heat recovery system, and comparing those with savings achievable with air-source heat pumps (ASHPs) and a combined heat and power (CHP) system, all calculated against a reference case of communal gas boilers.

Thames Water provided temperature measurements for the treated effluent at Hogsmill over a one-year period, from August 2014 to July 2015. The annual temperature profile has been used for the modelling of system performance and is highlighted in Figure 5(a). As it can be observed, temperatures for the treated effluent at Hogsmill vary seasonally between approximately 13 and 22°C [55 and 72°F], meaning that a heat pump would be required to upgrade the heat to appropriate temperature for domestic use. As previously mentioned, different delivery temperatures can be utilised depending on the topology of the heat network the heat recovery system connects to. According to Revesz et al. (2020), the general trend for heat networks has been towards lower operating temperatures, as featured in the contemporaneous 4th (4G) and 5th generations (5G) of district heating. 5th generation networks operate at ultra-low temperatures and are ideal for situations where there is a balance between heating and cooling demands that could be met via a district network (Jones et al., 2019; Lund et al., 2021). As this case study is focused solely on heat demands, the analysis will consider 3G and 4G applications, looking at delivery temperature varying from 65 to 80°C [149 and 176°F] based on a centralised wastewater-based heat pump (WWHP), as illustrated in Figure 5(b).

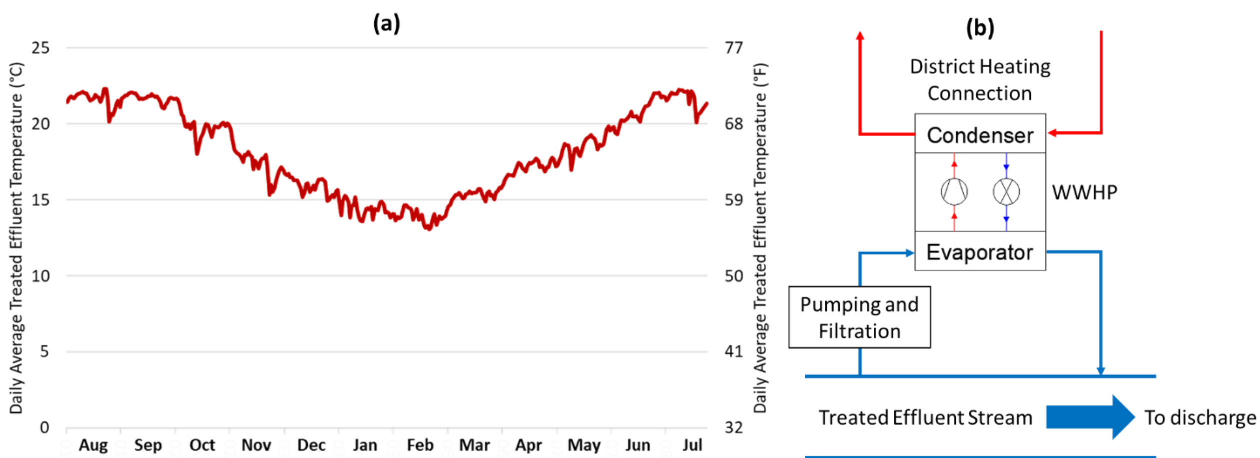

Figure 5. Temperature profile (a) and schematic of a heat recovery system (b) for the treated effluent from the Hogsmill WWTP.

Modelling the Heat Recovery System and Other Heating Technologies

The first step in the modelling work involves estimating how much heat would be recoverable from the Hogsmill site. This was achieved by applying the same approach utilised to estimate the waste heat recovery potential from WWTPs in the UK. By applying Equation 2 for a volumetric flow rate of 669 litres [177 US gallons] per second and a ΔT of 5K [9°R], 14 MW [48 MMBTU/h] of waste heat would be recoverable (Q_{rec}) from Hogsmill. This represents a feasible estimate as many of the case studies reported by Farman Ali and Gillich (2021) have capacities above 20 MW [68 MMBTU/h]. For instance, the Katri Vala heat recovery scheme in Helsinki, Finland, is capable of processing approximately 3,000 litres [793 US gallons] of treated effluent per second. The capacity of the WWHP plant (Q_{cap}) was then estimated as a function of the recoverable heat (Q_{rec}) and the maximum achievable COP, as shown in Equation 3. The maximum COP was considered as it would be achieved at the timestep when the heat recovered also reaches its maximum point, which should be equal to the total amount of heat recoverable (14 MW [48 MMBTU/h]).

$$Q_{cap} = Q_{rec}/(1 - \frac{1}{COP_{max}}) \qquad [3]$$

The performance of the WWHP, represented by its COP, was modelled utilising the commercial software tool Engineering Equation Solver (EES). The WWHP model was developed considering ammonia (R717) as the refrigerant, and hourly COP figures were derived using the treated effluent temperature profile shown in Figure 5(a) and the aforementioned delivery temperatures, ranging from 65 to 80°C [149 and 176°F]. Modelling assumptions include approach temperatures of 2 and 5K [3.6 and 9°R] for the evaporator and condenser, respectively, 5K [9°R] of superheat at the evaporator and an isentropic efficiency of 80%. The maximum COP (4.73) was obtained for the lowest temperature difference between the treated effluent and the heat network, which was achieved for a delivery temperature of 65°C [149°F] when the treated effluent reaches approximately 22°C [72°F].

Based on these values, the capacity of the WWHP plant (Q_{cap}) would be of 17.8 MW [60.6 MMBTU/h]. An annual heat demand of 133 GWh [418 Dth (US)] was calculated for the heat network, which would be equivalent to 11,083 average-sized UK homes. This number is based on the heat pump's annual output, assuming a continuous operation with 5% downtime and distribution heat losses of 10%, which is the recommended target for district heating loss rates by CIBSE (2020). The benefit analysis was carried out assuming that all technologies would meet the same heat demand of 133 GWh [418 Dth (US)] per annum. A seasonal COP (SCOP) of 2.68 was assigned for ASHPs, based on site survey data (EST, 2013b). As for the CHP counterfactual, respective thermal (η_{th}) and electrical (η_{el}) efficiencies of 56% and 35% were considered, based on an existing heat network in central London (Lagoeiro et al., 2022). The gas boilers were modelled assuming a typical thermal efficiency of 85%. All modelled scenarios are shown in Table 1.

Table 1. A list of the modelled scenarios based upon their heat source, seasonal efficiency, and description.

Scenario	Heat Source	System Seasonal Efficiency	Description
0	Gas Boilers	η_{th} = 85%	Reference case of communal gas boilers being used to supply the same heat demand.
1	WWHP @ 65°C [149°F]	SCOP = 4.35	Heat network with a flow temperature of 65°C [149°F], supplied by a wastewater heat pump.
2	WWHP @ 70°C [158°F]	SCOP = 3.98	Heat network with a flow temperature of 70°C [158°F], supplied by a wastewater heat pump.
3	WWHP @ 75°C [167°F]	SCOP = 3.67	Heat network with a flow temperature of 75°C [167°F], supplied by a wastewater heat pump.
4	WWHP @ 80°C [176°F]	SCOP = 3.40	Heat network with a flow temperature of 80°C [176°F], supplied by a wastewater heat pump.
5	ASHPs	SCOP = 2.68	Individual ASHPs being used to supply the same heat demand.
6	CHP Engine	η_{th} = 56%, η_{el} = 35%	Heat network with a flow temperature of 95°C [203°F], supplied by a centralised gas-fired CHP engine.

Energy Tariffs and Carbon Factors

The calculation of operational carbon and cost savings for all scenarios contemplated in this appraisal were carried out with energy tariffs and carbon factors obtained from the latest central projections from BEIS (2021e). These projections consider commercial/public sector energy pricing, averaged over a 20-year period (2023-2042). This approach led to average energy tariffs of £141.00/MWh [$169.20/MWh] and £38.20/MWh [$13.43/Dth (US)] for electricity and natural gas, respectively. The average carbon factors for the same period were calculated as 0.184 tCO_2e/MWh [0.59 tCO_2e/th (US)] for gas and 0.102 tCO_2e/MWh [0.112 tCO_2e/MWh (US)] for electricity, reflecting the expected decarbonisation of the electricity grid in the coming years. The revenue from electricity generated with the gas-fired CHP counterfactual was calculated considering electricity export payments of £55.90/MWh [$67.08/MWh], as reported in the UK's Standard Assessment Procedure (SAP) (BRE Group, 2022).

RESULTS AND DISCUSSION

The results from the benefit analysis are summarised in Figure 6 for annual carbon emission (a) and energy cost

(b) savings. Both the carbon and cost analyses were carried out for scenarios 1 to 6, as shown in Table 1, and all technologies were compared against the reference case of communal gas boilers (scenario 0) to yield the percentage of annual savings. As it can be seen in Figure 6(a), all scenarios involving electrification led to carbon savings higher than 80% against the reference case, with a maximum value of 88% being achieved for scenario 1, which achieved the highest SCOP. It is interesting to note how a heat network utilising heat produced by a gas-fired CHP unit would lead to a 95% increase in carbon emissions against communal gas boilers, as CHP systems burn more natural gas to produce the same amount of heat, whilst also displacing greener electricity from the grid. As for the energy cost analysis, Figure 6(b) illustrates how the WWHP could reach up to 20% in annual savings against the reference case, which highlights the potential for low temperature networks to make waste heat recovery more cost effective, which is particularly challenging in the UK due to the disparity in prices between natural gas and electricity. This disparity represents the main reason behind the poor economic performance of ASHPs (scenario 5). A 3G network operating with flow temperatures of 80°C [176°F] (scenario 4) constituted the only WWHP scenario where the running costs would be higher than that of communal gas boilers. As for the CHP counterfactual, the revenues from electricity exports can compensate its higher fuel costs, with combined cost savings of 18% being achieved against the reference case.

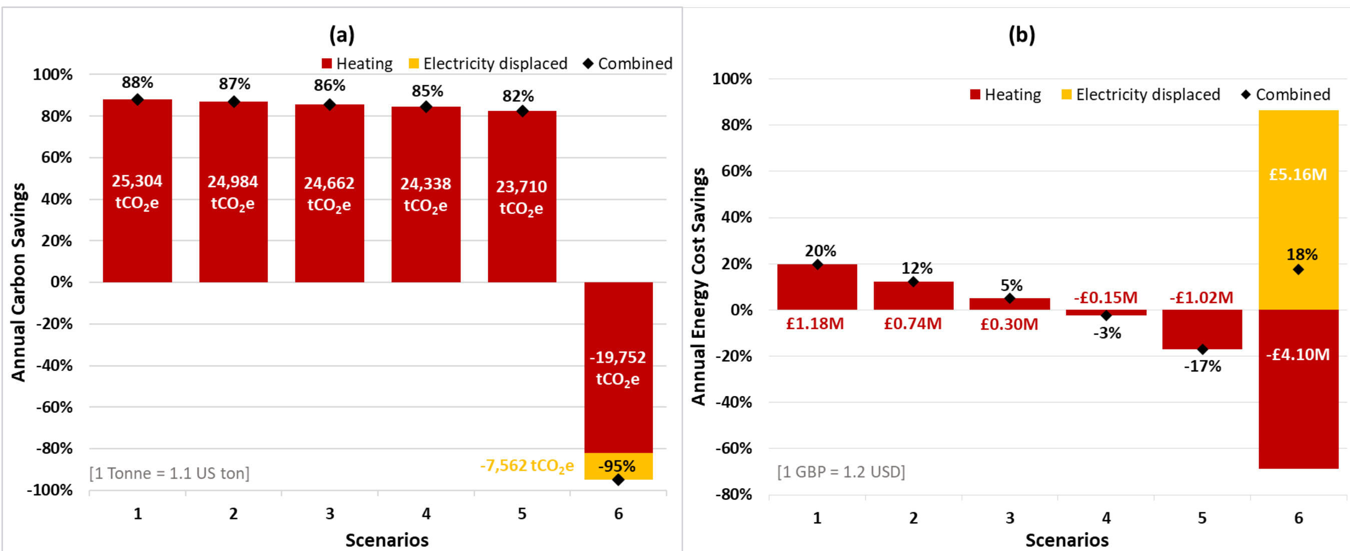

Figure 6. Modelled annual carbon (a) and energy cost (b) savings for scenarios 1 to 6.

CONCLUSION

This paper has investigated the potential benefits of recovering heat from treated wastewater based on the concept of a centralised wastewater heat pump (WWHP) connected to a district heating system. At first, the paper compared different locations for heat recovery throughout the wastewater collection and treatment processes, showing how WWTPs are particularly interesting based on their operating volumetric flow rates and temperatures. The paper then estimated the waste heat recovery potential for all WWTPs across the UK to be between 2 and 3 TW [6.8 to 10.2 Trillion BTU/h], depending on the heat extraction rate considered. By exploiting all WWTPs in the country, the total thermal energy recovered would be between 17.5 and 26.2 TWh [59.7 to 89.5 MMDth (US)] per annum. Based on a case study of the Hogsmill Sewage Treatment Works, in London, this investigation then analysed the operational savings that a district-scale WWHP would achieve, in terms of carbon emissions and energy costs, against a business-as-usual reference case of gas boilers and other heating technologies. Overall, the analysis has demonstrated how a heat network utilising heat recovered from a WWTP could lead to cost and carbon savings of up to 20% and 88%, respectively, when compared to communal gas boilers. This indicates how WWTPs have the potential to become a key resource for future low-carbon district heating, helping the UK to achieve its decarbonisation goals whilst improving energy security.

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