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Spatial and temporal considerations of implementing local renewable energy sources and decentralised heat recovery for domestic heat

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ABSTRACT

A UK case study area containing over 33,000 households has been used to investigate spatial and temporal conflicts in meeting domestic heat demand through renewable electrical energy supply and low-grade decentralised heat recovery from the urban drainage network. The case study area was selected as its water infrastructure and population density were representative of the conditions experienced by the majority of the UK's urban population. The findings suggest that adopting an optimised and integrated water-energy system would lead to a 60% reduction in current carbon emissions, compared to a natural gas based system. The integrated water-energy system proposed for domestic heating showed an annual surplus of renewable energy of 716 GWh. However, a non-renewable source of energy of 114 GWh is required to deal with the intermittency of the demand and renewable energy supply. Given the renewable surplus, it would be possible to eliminate carbon emissions from domestic heating with the addition of local low efficiency inter-seasonal energy storage. Taking a broader perspective, the calculated 60% carbon emission saving is significant as the domestic housing sector contributes 15% of the UK carbon emissions. A progressive adoption of such locally based schemes throughout the country would be able to make tangible reductions to national carbon emission targets.

1. Introduction

Climate change is already creating harmful impacts on humans and ecosystems, and this is expected to worsen. A substantial reduction in greenhouse gas emission is required. The UK, EU and China have all set targets for greenhouse gas emissions. Domestic energy consumption represents around 20% of the total energy consumption in both China (IEA, 2018) and the US (EIA, 2020). In the EU, households represented 26% of final energy consumption (Eurostat, 2018), whereas in the UK, the domestic sector consumed 29% of the total energy (BEIS, 2019a). Energy was primarily used by households for heating purposes (i.e. space heating and hot water). In the UK, 85% of the domestic gas consumption is used for space heating and hot water (DECC, 2014) and the domestic sector contributes to 15% of the national emissions (BEIS, 2018). The domestic sector has to decarbonise substantially to contribute to the overall carbon emission reduction target (Postnote, 2016). Changing the energy sources and reducing energy consumption for heating is therefore essential.

Transitioning to carbon neutrality brings significant opportunities as well as serious challenges. Forward-looking research and innovative policies will play a key role to achieve such a target, especially in the domestic sector. Decarbonisation of heating by generating electricity and heat from renewable sources on a large scale is inevitable. Electricity demand as a share of overall energy consumption is likely to increase over the long-term and this presents great challenges, as it can potentially create a significant increase of electricity demand which may require reinforcement on the electricity distribution networks and the need for new grid transmission infrastructure (Foxon et al., 2020). Therefore, there is also a growing interest in heat recovery and local heat networks (Spriet et al., 2020).

Lund (2018) compared different strategies to transform the heating sector, and concluded that the cost of grids and storage infrastructure may significantly exceed the costs of the renewable energy sources themselves, especially if a sole-electricity approach is taken. Lund (2018) also concluded that an integrated 'Smart Energy Systems' approach (based on a cross sectoral use of electricity, gas and heat grids), with a focus on how these sub-sectors may complement and assist each other seems to be essential to identify and design lower cost solutions for transformation to a 100% renewable domestic heat system. There is, however, limited research done on potential interactions between different energy sectors.

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Nomenclature

D_t	Hourly heat consumption
Y_t	Hourly solar generation
Y_r	Optimal size of solar panel area
Y_{min}, Y_{max}	Lower/upper bound of solar panel area
W_t	Hourly wind generation
W_r	Optimal wind turbine capacity
W_{min}, W_{max}	Lower/upper bound of wind turbine capacity
H_t	Hourly sewer heat recovery
S_t	Hourly input from water service reservoir
S_r	Size of water service reservoir
G_t	Hourly input from non-renewable source
t	Time step (1 h)
α,β,γ	Carbon emission factor

District heating is emerging as a key player in the challenge of reducing carbon emissions, it has large potential but only has an average market share of 10% in Europe (Millar et al., 2019). In the EU, the average percentage for the countries which have a district heating system is 24.5%, counties with a cold climate tend to have a higher percentage of district heating (40–60%) than the rest (Sayegh et al., 2018). The cost of implementing a district heating system is high which creates a significant barrier, many developers or local authorities would not be able to cope without significant investment from central government (Millar et al., 2019).

Other studies have looked at introducing decentralised technologies such as heat pumps on an existing district heating system to highlight the capability of decentralised approaches in reducing carbon emissions. Arnaudo et al. (2021) have assessed waste heat recovery potential and electricity grid loading status in a real catchment in Sweden and suggested that decentralised heat pumps are suitable, but the associated carbon footprint heavily depends on the carbon emission factor from the supporting electricity sources. Arnaudo et al. (2020) looked at the impact of distributed heat pumps on an electricity distribution grid and has shown that with current demand patterns the local electricity grid could fail, but this could be mitigated to some extend through use and better management of distributed thermal energy storage units and thermal mass control in buildings.

Various studies have looked at ground source heat pumps (GSHPs). Heat pumps offer their highest efficiencies when operating with the ground, or a similar stable temperature medium such as a surface water body as a pond as the source (Self et al., 2013). Unfortunately, ground source heat pumps require either a large undeveloped area (e.g. garden) or a deep borehole which results in high land and/or construction costs. As the cost of implementing the borehole heat exchanger can be up to half of the total installation cost of the ground source heat pump, it easily pushes any property owner to move towards another more economically viable solution (Ilisei et al., 2019).

Another stream of studies focused on the potential of wastewater heat recovery. Wastewater heat recovery can happen at the wastewater treatment works, the sewer network, or within the houses. A comprehensive review of the literature on wastewater heat recovery can be found in (Nagpal et al., 2021). A considerable amount of research has focused on heat recovery from wastewater treatment works (Hao et al., 2019). Spriet et al. (2020) investigated heat recovery at the wastewater treatment plant feeding into a district heating system, concluding that this provides a feasible and valuable contribution to sustainable urban energy supply, but that the spatial mix of land uses and their population density largely determine the lay-out and useable amount of this renewable energy source. An advantage of heat recovery further upstream in the sewer system is that this is closer to locations of heat demand (Cipolla and Maglionico, 2014). Kretschmer at al. (2016) has investigated wastewater temperature development in a sewer system when evaluating wastewater heat recovery potential. Their analysis gave useful insights in the spatial and temporal wastewater temperature variation within a sewer system. Abdel-Aal et al. (2018) simulated several sewer heat recovery location scenarios in a case study catchment, and estimated wastewater temperatures throughout the sewer network following heat recovery in different seasons. They reported a potential heat recovery of 116–207 MWh/day from a combined sewer network that served a population of 79,500, but did not consider where and whether this recovered heat may be utilised. Spriet and McNabola (2019) studied the heat recovery potential at a single residence scale and highlighted that there was a potential for reduction in heating-related carbon emissions but heating costs increased significantly. For a single residence, wastewater heat recovery system has a high capital investment, therefore, it is currently not financially competitive to traditional heating systems. Cecconet et al. (2020) have also analysed an application of energy recovery from wastewater in a sewer for heating and cooling a building in Czech Republic by means of heat exchangers and pumps. They evaluated two options: 1) heating and cooling using a conventional system (connected to the local grid) and 2) heat recovery from wastewater using heat exchangers and pumps. They found that option 2 was more feasible as it was able to provide a 59% decrease in energy consumption.

Table 1 summaries the advantages and disadvantages of the main options related to the use of derived heat reducing carbon emission within the domestic energy sector.

To summarise, there is growing interest in using derived heat as a low carbon energy source, but there is still limited research on optimising the combined use of electricity, gas and recovered heat networks. In order for heat recovery to be low carbon, both the heat source would need to be low-carbon, as well as any electricity used to derive the heat. Heat recovery from urban drainage systems, using renewable energy to operate the heat pumps, is promising as wastewater has been classified as a renewable energy source, and these systems are located near houses. Also, these systems may be more suitable for medium to low density housing, where district heating systems would not be feasible due to

Table 1
A comparison of different options for reducing carbon from domestic heating and their associated advantages and disadvantages.

Options	Advantages	Disadvantages
Existing district heating system (Millar et al., 2019)	High potential for carbon emission reduction	High investment cost; need relatively high urban density.
Existing district heating with new heat pumps with wastewater source (Arnaudo et al., 2021)	Potential for carbon footprint reduction (up to 24%) depending on electricity source used to run heat pumps	May not be suitable for a small community scale; heat generation cost is higher than for district heating; not suitable in high heat demand density areas
Distributed GSHP (Ilisei et al., 2019)	Heat available all year round; could be used for medium & low urban density. Potential for carbon footprint reduction depending on electricity source used to run heat pumps	Requires either a big garden space or a deep borehole which results in high cost of drilling
Distributed heat pumps with wastewater source (Cecconet et al., 2020)	Potential for heating consumption and heating related carbon emission reduction; energy efficient; could be used in medium to low urban density. Potential for carbon footprint reduction depending on electricity source used to run heat-pumps.	Mismatch between heat supply and demand

cost. However, spatial and temporal mismatches in demand and supply need to be overcome. There has been very limited research on quantifying where, at what times and how much surplus heat is available in sewer networks.

The objective of this paper is to investigate the amount of decarbonisation that could be achieved in a medium population density town by further developing a tool for optimising the use of local renewable electricity sources. These sources combine wind and solar with local heat recovery from urban drainage systems, and energy storage in drinking water reservoir, by minimising the operational and embedded carbon emissions of the system. The size and duration of demand-supply gaps as well as energy surpluses will be analysed at seasonal and daily time scales in order to assist planners in deciding on the possibility of different energy mixtures, and the size and type of energy storage that may be needed to achieve practical decarbonisation of domestic heating.

The novelty of this paper is to present a case study consisting of over 33,000 households with 486 km of predominantly combined sewers, to investigate the spatial and temporal variability and quantify the benefit of integrated water-energy system. This could be valuable as it can help urban planners to explore how different types of local energy sources could optimally be combined, and identify where additional energy storage would be needed, and at what space-time scales. The method also informs when and where there is surplus energy, and can be used to explore what efficiency and type (heat or electrical) energy storage would be needed. One can easily scale up these figures from a local scale to a national scale for implementation.

2. Methodology and case study description

A case study area in the North of England, UK, which consists of a medium sized town, surrounded by several smaller urban areas is the basis of this study. The model described in (Liu et al., 2020) has been developed to incorporate the spatial effects of heat demand and renewable supply from the case study area's water infrastructure. This model has been utilised to optimise the mix of mainly renewable energy sources that yield the lowest carbon emissions for the case study area, and then to investigate the distribution, size and duration of the heat demand-renewable supply mismatches at both hourly, monthly and annual timescales. The model was built to simulate the integration of existing water infrastructure with a range of renewable and non-renewable sources and the integration is designed to meet local hourly heat demand for households. The households were split into groups based on their spatial location within the case study area. This spatial distribution generally reflected their proximity with respect to existing water infrastructure. For group A, heat demand will be met by optimising a combination of electrical energy from wind turbines, solar panels, potential energy stored in the water service reservoir released as electrical energy, and a non-renewable back-up supply, in the UK this is essentially piped natural gas (methane) to individual properties. The heat demand from group B will be supplied by sewer heat recovery, supplemented with electrical energy from renewable sources (wind, solar) and a non-renewable source (i.e., piped natural gas). The time step of the simulations is hourly, energy storage is not considered and simulations are carried out over an annual time period. The nature of the formulated problem is constrained non-linear optimization and this is solved with MATLAB using the fmincon solver, a brief outline of the equations used is shown in appendix. A summary of model inputs and outputs are presented in Table 2.

The total population in the case study area is just over 80,000, served by the same combined sewerage network that comprises 486 km of pipes. The case study simulation is of one-year duration, 2018 was selected as it was the latest year where all data were available. The wind speed and solar radiation were typical, they were not the highest or the lowest compared to years in the previous decade. Hourly wind speed and solar radiation values of 2018 for the case study area were obtained from the Centre for Environmental Data Analysis (CEDA, 2018). The average wind speed is 5.83 m/s and the average solar radiation is 0.12 kWh/m2. The size of the water service reservoir is estimated to be 40,000 m3 based on the assumption of daily water consumption (including leakage) of 250 L/day/person and the service reservoir is able to store two days of drinking water (Liu et al., 2020). A typical pump efficiency of 0.8 and turbine efficiency of 0.6 are assumed and a 15 m drop in water level is assumed. Fixed pump and turbine efficiencies and flow rate are assumed. Predicted heat demand is based on an hourly profile for 2009 that was initially obtained from a UK national database (UK Data Service, 2009). This was randomised by drawing sets of 1000 households twenty times, and taking the average heat demand pattern, which resulted in a relatively stable pattern (as explained in detail by Liu et al., 2020). The UK's domestic gas consumption has reduced by 10.44% between 2009 and 2018 (BEIS, 2020), hence the demand is adjusted by lowering it by 10.44%, assuming the hourly pattern remains the same. Then the demand is scaled up to be a representative profile of the size of the studied groups. The carbon emission factor from wind and solar has assumed to be 0.0107 kgCO2/kWh (Bertasiene et al., 2015) and 0.0292 kgCO2/kWh (Koffi et al., 2017) and a carbon emission factor of 0.2 kgCO2/kWh has been used for natural gas (BEIS, 2019b).

Table 2
Summary of model inputs and outputs.

Category	Inputs	Outputs
Optimization routine	Hourly wind speed, solar radiation, domestic heat demand Hourly available sewer heat energy, electrical energy from water service reservoir Carbon emission factors	Optimal solar panel area, optimal wind turbine capacity, hourly and annual total carbon emissions Hourly optimised energy availability and usage from each source
Sewer model	Pipe network information (diameters, lengths, gradients, spatial coordinates of pipes), wastewater daily dry weather flow profiles, spatial distribution of population, daily wastewater generation temporal profile, daily wastewater generation per person, wastewater temperature profile	Hourly sewer heat recovery potential
Water service reservoir	Daily water consumption per person, total population within the case study area, volume of the water service reservoir	Electricity generation by releasing water from the water service reservoir

The heat recoverable from sewers is based on dry weather flow. The sewers in the catchment are predominantly combined and would therefore have intermittent rainfall inputs, which would affect the flow and temperature. Rainfall has not been considered due to its variability year to year; relatively infrequent impact on the sewer and, most importantly, a knowledge gap on the impact of rainfall runoff on sewage temperatures. Thermal energy cannot be transported over long distances without having major heat losses, hence, the thermal energy recovered from the wastewater network should be consumed within an appropriate distance. A radius of 100 m has been identified as the appropriate area for heat recovery from the sewer network to be distributed. This distance has been considered reasonable in the study by Spriet at al. (2020). Abdel-Aal (2015) presented annual sewage temperature variability at four locations in a Belgian sewer network. As Belgium has a similar climate to UK, this data has been used to derive appropriate wastewater temperatures, the temperatures reported were 8–10 °C in winter (Dec–Feb), 11–14 °C in spring (Mar–May), 16–19 °C in summer (Jun–Aug) and 12–16 °C in autumn (Sep–Nov). A polynomial equation of power four was fitted to estimate the daily wastewater temperature. Dry weather flows are estimated using a hydrodynamic sewer network model (Infoworks ICM, www.innovyze.com), which has been verified using UK water industry guidelines valid at the time the model was created (WaPUG, 2002). At locations where heat has been recovered from the network, the wastewater temperature drops, and it rises again when additional fresh wastewater enters downstream. With fresh wastewater being added, the mixed wastewater temperature is calculated by a function of incoming flows and wastewater temperature (Abdel-Aal, 2015). Heat loss or heat gain through soil and air is neglected in this study, but should be considered in a more detailed study of sewer heat recovery (Abdel-Aal et al., 2021). No heat will be recovered if the sewer temperature is below 10 °C. The coefficient of performance of the heat pump is assumed to be 4 (The Green Age, 2014).

Data from the Office for National Statistics (ONS, 2019a) shows that the case study area has a spread of population densities slightly lower than the UK national values, but within a range which would be reasonably expected in many towns and cities in the UK. For example, in the case study area, 68% of the population lives in a Lower Layer Super Output Area (LLSOA) with a density >1000 people per square km, compared to 77% in England and Wales. The difference is greater for high population densities, with only 2% within a LLSOA >10,000 per square km, compared to 10% nationally. It should be noted that these LLSOAs are areas with an average of 1700 people.

Households in the case study area are split into groups A and B. Group B households are within a 100 m radius of sewers with sufficient sewer flow and with sufficient heat demand for heat recovered from the sewer network to be distributed. Group A comprises all households not meeting these criteria. A cut-off flow of 25 L/s in the sewer was stipulated as sufficient for heat recovery, based on the research by Abdel-Aal et al. (2018). The number of houses within a 100 m radius of identified potential sewer heat recovery locations was assessed manually using Ordnance Survey MasterMap, this was converted to a population based on the assumption of each household containing 2.4 people (ONS, 2019b).

The town has a total population of approximately 80,000, which is equivalent to a community of 33,334 households. Five locations were identified with both sufficient flow and sufficient households within 100 m for a heat pump to be viable. These five locations form group B (see Table 3) that consists of 614 homes (just under 1500 people), so there are 32,720 remaining households (approximately 79,000 people) in the town that will be supplied by a mix of energy sources (Group A). These areas are shown schematically in Fig. 1, heat is recovered from all sewers upstream of the heat pumps. Downstream of the heat pumps and in separate parts of the sewer network which do not meet the criteria for heat recovery, no heat is recovered. For Group A, the hourly heat demand ranges between 2.6 and 279 MW, and for group B between 50 and 5240 kW.

Main equations:

Objective function

$$f(Y_r, W_r, S_r) = \sum_{t=1}^{n} \alpha \times Y_t + \beta \times W_t + \gamma \times G_t$$

Subject to

$$Y_{min} \le Y_r \le Y_{max}$$

$$W_{min} \le W_r \le W_{max}$$

$$D_t \le Y_t + W_t + H_t + S_t + G_t$$

Hourly energy balance $= Y_t + W_t + H_t + S_t - D_t$ (either positive or negative).

Monthly surplus $= \sum(\textit{positive values})$

Monthly deficit $= \sum(\textit{negative values}) = \sum G_t$

The full detailed model is described in (Liu et al., 2020) - Reducing carbon emissions by integrating urban water systems and renewable energy sources at a community scale, included in the reference list.

3. Results

3.1. Group A: households not suitable for sewer heat recovery in the case study area

The simulation is run for the year 2018, when total annual heat consumption from group A is 440 GWh. With the optimised energy mix for group A, the total carbon emission generated is 34,562 tCO_2. The optimised solar panel area is 0.239 km^2 and the peak wind power supply is 230 MW. Considering there are 32,720 houses in this group, each house would then be required to have just over 7 m^2 of available roof area for solar PV panels. The actual number of wind turbines required depends on the selected turbine type and capacity. With this mixture of energy sources, 61% of the heat demand can be satisfied through renewable sources, and for 71% of time in the year all heat demand is met through renewable sources. The hourly peak supply is 230 MWh from wind and 30 MWh from solar. Given the estimated capacity of the water service reservoir, theoretically releasing all of the available water generates an electricity output of almost 1 MWh, which can supply a number of households. Importantly pump storage is a highly responsive source, so it can be used to meet short duration peaks in demands, not captured at the resolution of these simulations, but important for network reliability and resilience. As for the non-renewable source, some of this is required throughout the year, with a peak supply of 245 MWh in the year.

The optimal energy generation mix for group A is demonstrated for four consecutive randomly selected example days in both the winter and summer, shown in Fig. 2&3 respectively. In winter, hourly heat demand is high and the optimised energy mix showed regular shortages of renewable energy sources, and regular use of the back-up energy supply. Energy generation from solar and water service reservoir is reliable but small compared to wind and non-renewable supply, hence it is difficult to visualise on the plot. There is considerable surplus wind energy during the first 36 h, solar on the other hand has very limited surplus. The surplus from wind (denoted by Wind^{+}) and solar (denoted by Solar^{+}) is displayed on the secondary vertical axis. During the summer days, heat demand is almost ten times lower than in the winter, and can be satisfied using renewable sources for most of the period, with surplus from both wind and solar. However, some non-renewable source is still regularly required to cover brief shortages. Fig. 4 shows the monthly

Table 3
Population and heat recovery statistics for group B areas.

Area		Heat supply area (within 100 m radius of heat pump)				Upstream of heat pump[a]	
	No. of houses	Population	Population Density (per km^2)	Hourly heat demand (kW)	Average hourly heat recovery per person (kW)	Population equivalent	Population Density (per km^2)
1	110	264	8403	9–939	1.4	4957	6850
2	133	320	10154	11–1135	4.7	23076	4795
3	69	166	5284	6–589	4.3	5699	7465
4	161	387	12287	13–1374	0.4	828	9203
5	141	339	10759	11–1203	0.6	1234	3249
Total	614	1476	9377	50–5240	11.4	35794	5287

[a] Population equivalent is taken from the hydrodynamic model, it is the total population, plus an equivalent population representing industrial and commercial flows. The population density is calculated using the sub-catchments areas in the hydrodynamic model with the population equivalent.

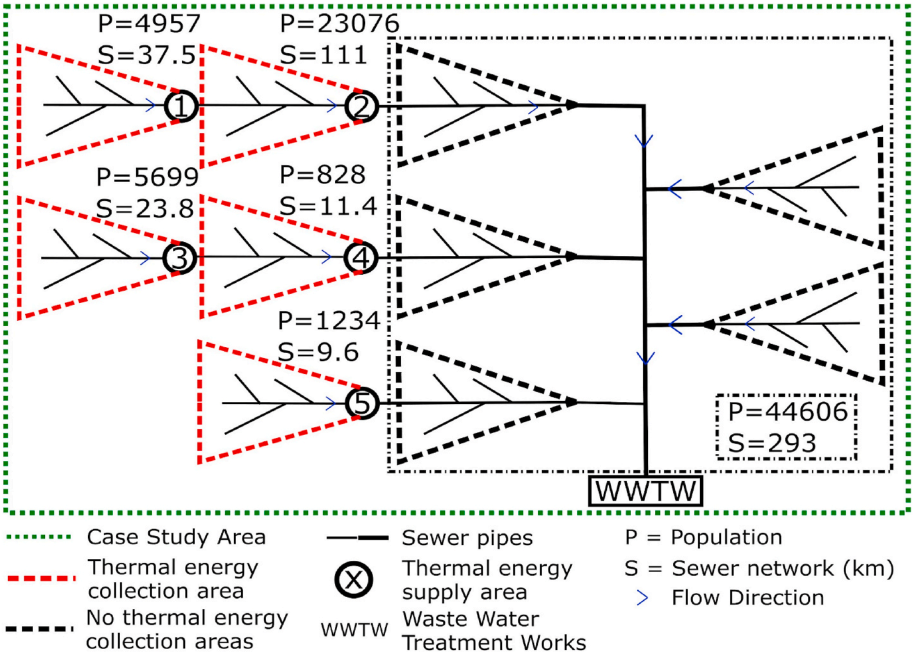

Fig. 1. Schematic of case study area showing the subdivision of the sewer network into sub areas in which thermal heat recovery occurs and does not occur.

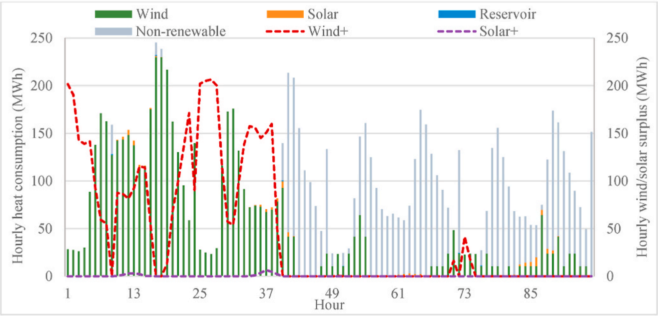

Fig. 2. The supply mix and wind/solar surplus 1–4 Feb 2018 – Group A.

accumulated surplus from renewable energy and the monthly accumulated amount of non-renewable supply required. Monthly surplus is the sum of hourly surplus from wind and solar. Monthly shortage is the sum of the hourly supply from the non-renewable source. Please refer to the appendix for the detailed calculation. For the months Dec to Feb, the accumulated surplus exceeds the supply from the non-renewable source approximately by a factor of 3, in Mar–May by a factor of 6, Jun–Aug by a factor of 34 and Sep–Nov by a factor of 12. Over 95% of the surplus is generated from wind energy. In the example, four winter days in Fig. 2 shows the accumulated surplus is 4430 MWh and the accumulated deficit is 4440 MWh respectively. Four summer days in Fig. 3 shows the accumulated surplus exceeds accumulated deficit by a factor 47, and the accumulated surplus is 5437 MWh and the accumulated deficit is 116 MWh respectively.

3.2. Group B: households within a 100 m radius of a sewer location suitable for heat recovery in the case study area

There are 614 households in this group (2% of the households in the case study area), and they are primarily supplied by sewer heat recovery. In the one-year period simulated, sewer heat alone could cover demand for 43–67% of the time among the five selected areas. Total annual heat demand for the five areas is 1481, 1790, 929, 2167, 1898 MW, and total demand fully satisfied using sewer heat solely is 357, 643, 327, 258, 276 MW. On average, about 23% of the heat demand over the five areas can be fully satisfied using sewer heat. During winter, the wastewater temperature rarely exceeds 10 °C, hence there is almost no heat recovery possible, and this is when the high heat demand occurs. In spring and autumn, the wastewater temperature gradually rises, but there are still other energy supplies needed to cover any shortage.

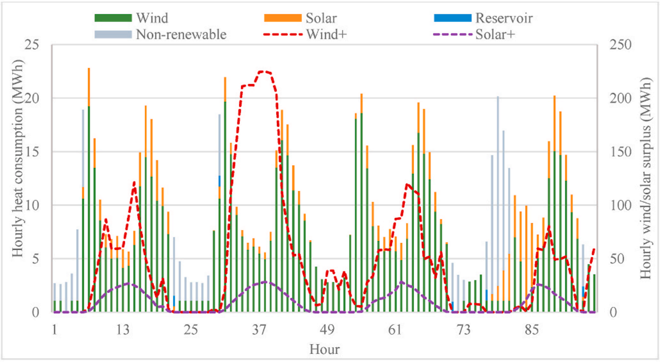

Fig. 3. The supply mix and wind/solar surplus 1–4 Jul 2018 – Group A.

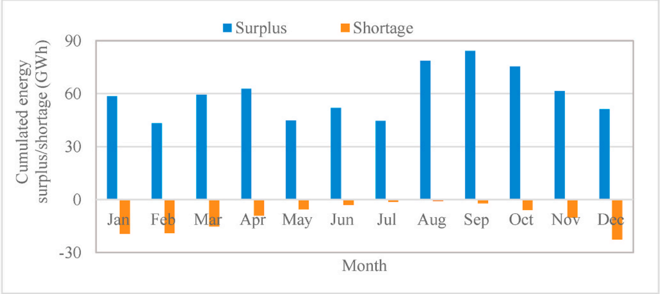

Fig. 4. Monthly accumulated hourly surplus (from wind/solar) and shortage – Group A.

The detailed breakdown of the heat available from the wastewater system is shown in Fig. 5, the positive values represent the surplus while the negative values represent shortage. The accumulated annual deficit in Areas 1–5 is 991, 1038, 543, 1708, 1443 MWh and the cumulated annual surplus is 1521, 7649, 3602, 462, 625 MWh.

Sewer heat recovery alone is not sufficient to meet the heat demand at all times. When there is insufficient sewer heat recovery, a mix of other sources are to be used to cover the difference and the electricity input of the heat pump is also provided by a mix of energy sources. Running simulation for this group over one year, the total associated carbon emission is 517 tCO_2. The optimised solar panel area is 1004 m^2 and optimal wind power capacity is 3.9 MW. This suggests that each household is required to have just over 1.6 m^2 of roof area for solar PV panels. If a wind turbine with power capacity of 2 MW is selected, then two wind turbines are sufficient for this group. Heat demand can be fully satisfied for 85% of the time in the year using sewer heat, wind and solar. A non-renewable source (with a maximum hourly value of 4.6 MWh) is used to cover any shortage and this mainly occurs in Nov–May.

The optimal energy generation mix for four randomly selected days in the winter and the summer respectively, is shown in Fig. 6&7. Hourly heat demand is higher in the winter and there is no sewer heat recovery, therefore, the demand has to be supplied by a mix of wind, solar and a non-renewable resource. The surplus from wind (denoted by Wind^+), solar (denoted by Solar^+) and heat (denoted by Heat^+) is displayed on the secondary vertical axis. Solar surplus is very small compared to wind, it is difficult to visualise from the graph. Fig. 7 shows the supply mix and surplus for the four randomly selected summer days, and it reveals that all of the heat demand can be met by sewer heat (denoted by Heat) alone. There is surplus from wind and solar, as well as sewer heat.

Fig. 8 shows the accumulated energy surplus and shortage. For the months Nov to Apr, the accumulated surplus exceeds the supply from the non-renewable source approximately by a factor of 4 and in May–Oct there are no deficits of renewable energy. Roughly 50% of the surplus is generated from wind energy, and 50% by sewer heat. Over four winter days in Fig. 6, the accumulated surplus is 67 MWh and the accumulated deficit is 87 MWh. For the four summer days in Fig. 7, the accumulated surplus is 435 MWh and there is no deficit.

4. Discussion

If all the residential heat demand in the case study area was satisfied by the use of natural gas, the total annual carbon emission would be 89,731 tCO_2. The total annual carbon emission following the simulations for group A and B is 35,079 tCO_2, an emission reduction of 61%. The benefit of this type of local renewable energy sources integration is that it makes use of existing water assets and the installation of sewer heat recovery uses existing technology. Wind turbine and PV technology are relatively mature. The peak PV power production in this study is 30 MW, and this level of local PV capacity should not cause any problems on the local electricity distribution network (Mondol and Jacob, 2018). Whereas for the wind output, to distribute a peak power production of 230 MW would require reinforcements on the local distribution network or a new infrastructure. A wind turbine that is connected to the substation directly, a maximum production of 10 MW would be manageable in the majority of cases (Northern Powergrid, 2019). Otherwise, a constraint would need to be imposed to limit the amount of wind energy to be distributed without causing issues on the network.

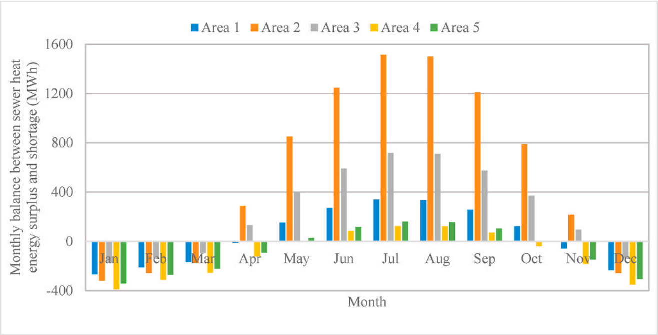

Fig. 5. Monthly balance between sewer heat surplus and shortage for the five selected areas.

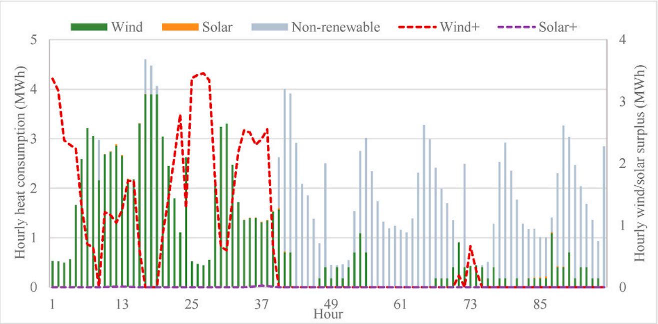

Fig. 6. The supply mix and wind/solar hourly surplus 1–4 Feb 2018

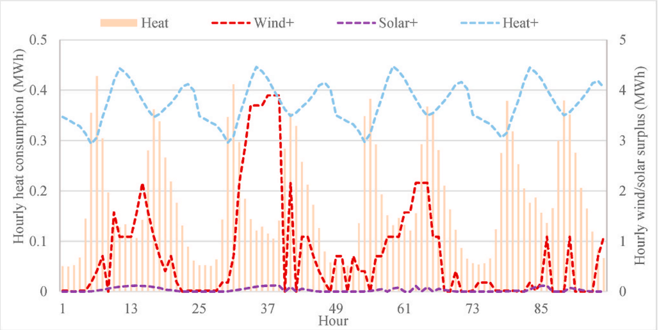

Fig. 7. The supply mix and wind/solar hourly surplus 1–4 Jul 2018

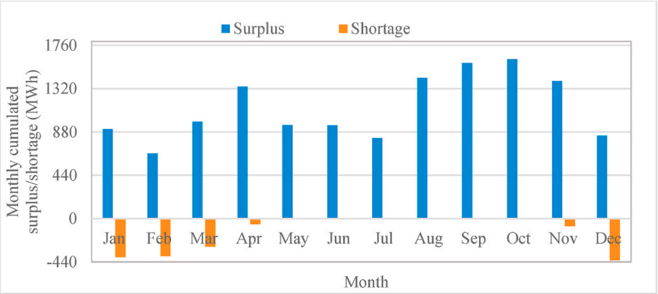

Fig. 8. Monthly accumulated hourly surplus (from wind/solar/sewer heat) and monthly accumulated hourly shortage.

In this paper it has been demonstrated that for this case study with a realistic population and spatial constraints that reflect common characteristics of water infrastructure systems that substantial carbon emissions can be achieved. However, the economics of such local integrated distributed systems are complex. Studies of heat recovery from sewers have reported a range of costs, indicating that local spatial factors are important. A major potential economic benefit of widespread adoption of such a local approach would be the deferment of capital investment in the national electricity transmission system; this would depend on the location, rate of adoption of such a local integrated approach across the country. Hence, it would currently be difficult to quantify this economic benefit based on this case study alone, without further analysis.

To achieve ambitious carbon reduction targets, reduction in heat demand and/or providing a means of renewable energy storage is essential. Improved housing insulation levels and changes in behaviour may help with the reduction in heat demand, but examination of existing evidence suggests that anticipated heat demand reductions alone are not enough. Rosenow et al. (2018) estimated the potential for energy savings in existing domestic buildings in the UK by 2035 (as percentage of 2015 energy consumption). They found that the measures offering the greatest technical potential for energy savings over this period are installing certain specific low carbon heating systems, building fabric improvements (e.g. various types of insulation) and upgrades to condensing boilers, contributing to reductions in energy consumption of 28, 15 and 7% respectively compared to the 2015 baseline. When we compare these data against the case study group A, even if a heat demand reduction could be achieved at 50% of the current level (by implementing all 3 the measures proposed by Rosenow et al.), re-running our simulations only led to a carbon emission reduction of 77%, which is still some way off from carbon neutrality.

For group A, a considerable amount of renewable energy surplus from wind and solar is produced, hence if there were to be some form of long-term inter-seasonal storage, calculations such as shown in this study could help identify the size, type and efficiency requirements of such storage. In this group, wind generated over 95% of the surplus energy and less than 5% from solar. The accumulated surplus at the end of the year is much larger than the deficit, hence an energy storage with low efficiency or a smaller storage with higher efficiency can help address the supply-demand imbalance. This would be subject to finding some long-term and high capacity storage option that has no or very low associated carbon emissions, as the final objective of the approach is to help deliver the net zero carbon target for domestic heating. Soil energy storage and recovery is currently estimated to be around 22% efficient (Jradi et al., 2017) and would be readily available in urban areas. The annual energy surplus estimated by accumulating the hourly surpluses is approximately 716 GWh so a total of 158 GWh may be available if long term heat storage and recovery in the soil of 22% efficiency is indeed feasible. This would be sufficient to cover the sum of the hourly deficits over the year, which add up to approximately 114 GWh.

For group B, areas 1–3 have a significant amount of heat surplus for summer and autumn months, but a shortage in winter, and areas 4&5 always have insufficient heat recovery. Hence, additional low grade heat sources or storage systems would likely be needed. In the case study, no energy storage has been considered, given the amount of heat surplus (Figs. 5 and 6), it would be very beneficial if the surpluses can be stored over long time periods and then be used to cover the energy deficit in winter. If one plans to deploy sewer heat recovery applications for a location, the result from this paper could be used as a guideline for towns with similar population density, and to investigate different energy storage options. In this town, approximately 2% of houses at a sufficient density were located within a 100 m radius of a sewer with average dry weather flow >25 L/s, and no heat was recovered once sewage temperature is below 10 °C. These are both quite conservative assumptions. The influent temperature of the Wastewater Treatment Works (WWTW) should remain above 10 °C, however, the temperature in the sewer system could locally be reduced below 10 °C, as long as additional wastewater would be added into the system downstream, raising the temperature of the wastewater before the WWTW. Hence the study could be repeated on a finer spatial scale using less conservative assumptions looking at lower average dry weather cut-off flows for installing sewer heat recovery and allowing larger local temperature reductions.

The population density of the case study area is considered to be representative for many other urban areas. For example, according to the Local Administrative Units (LAU, 2020), in Germany the average population density of LAUs consisting of >10000 and < 200,000 inhabitants are 505 inhabitants per km^2, with a standard deviation of 457 and approximately half of Germany's population, just over 40 million people, lives in these areas. For Denmark, the average population density of LAUs consisting of >10,000 and < 200,000 inhabitants are 627 inhabitants per km^2, with a standard deviation of 1531 and approximately 75% of Denmark's population, or 4.4 million people, lives in these areas. This type of housing density (for small town to medium size city) is common for many European urban areas. Therefore, the results of this study are believed to be applicable to similar such areas in northern Europe. If the empirical data of wind speed, solar radiation, residential heat demand for other climates and economies are available, then this new dataset can be used directly to re-run the model. For those who do not have access to empirical data, there are forecasting models to help estimate the future wind speed, solar radiation and residential heat demand. The water infrastructures are not likely to change over a multi-decade period. The methodologies for assessing sewer flows would also be generally applicable, the vast majority of sewer systems in the developed world will have a hydrodynamic model to generate the required data on dry weather flows. In cases where a hydrodynamic model is not available, then there should still be adequate knowledge of the sewer system layout to enable a simple model to be built to estimate dry weather flows, or to estimate this manually at key locations in the catchment.

There are also other promising emerging opportunities to further utilise urban water systems to deliver the required storage of heat energy. As described by Dacquay et al. (2020) ground source heat recovery could be made more efficient by implementing it near sewer pipes as these can heat the surrounding soil. This may be even more enhanced by incorporating phase changing material near the sewer system for heat storage (Sharma et al., 2009), although considerable research would be needed in how to practically implement this. Sustainable drainage systems can enhance thermal conductivity of soil and may therefore also be useful to enhance ground source heat recovery (Ali et al., 2017). Furthermore, open urban surface water may also be used to provide both cooling in summer, and heating in winter, combined with using urban aquifers as a low efficiency but large scale low grade heat energy storage as described by De Graaf et al. (2008). Spriet et al. (2020) described utilizing WWTW effluent heat to feed into a district heating system, and also found both daily and seasonal mismatches between heat source availability and heat demand, with daily surplus and shortages in both winter and summer, and a winter deficit. They discussed that for mitigating daily mis-matches, excess heat may be fed into the district heating system, by increasing flow or temperatures to mitigate daily shortages. To help mitigate seasonal mis-matches they suggest excess heat may be utilised at the WWTW, to create biogas which can be stockpiled. They concluded that an integrated planning approach, considering both spatial and temporal demand mis-matches is essential to ensure best possible use of WWTW effluent heat.

5. Conclusions

This paper studied the spatial and temporal considerations when implementing sewer heat recovery and integrating wind turbines and solar PV as local renewable energy sources, and a drinking water reservoir as pumped energy storage, in order to cover domestic heat demand. The energy supply and heat demand were simulated hourly for one year, based on actual meteorological data and heat demand data.

The case study area contained a population of just over 80,000 within just over 33,000 households. The housing density is typical for small towns to medium sized cities for many European urban areas. Therefore, the conclusions of this study are believed to be applicable to a broad range of urban areas in northern Europe.

In the case study area of 33,334 households, spatial analysis identified 614 households (Group B - 2% of all households in case study area) to be within 100 m radius of a sewer with enough dry weather flow for sewer heat recovery - making this low carbon heat technically feasible. For the Group B households, sewer heat is able to meet domestic heat demand for at least 43% of the time across the whole year studied. For

85% of the time a mixture of renewables (sewer heat, wind, solar) is able to cover their heat demand. The remaining households in the case study area form Group A where the heat demand is met by a combination of wind, solar, energy stored in the water service reservoir and a non-renewable back-up supply. In this group, heat demand can be fully satisfied for 71% of the time using the optimised renewable energy source mix.

For the whole case study area, adopting the integrated water-energy systems would lead to a 60% reduction in annual carbon emissions when compared to a situation in which domestic heat demand is satisfied by natural gas. If the optimised integrated system is adopted, the size of peak PV output is unlikely to lead to the need for reinforcing the local electricity distribution grid, whereas the maximum wind output would require either reinforcement to the local electricity grid or a cap on the amount of wind output that could be fed into the integrated system. Without including any energy storage, a non-renewable electricity back-up is still required although its use would be limited and intermittent.

Due to the intermittent nature of the renewable energy sources and peaks in heat demand, even in periods of low heat demand such as in the summer months there remain short time periods of several hours duration where there is not enough renewable energy supply to meet the domestic heat demand. This imbalance is significantly larger in the winter months. A ‘blanket’ heat demand reduction, such as increased home insulation was found to be insufficient to mitigate short temporal imbalances between supply and demand. The simulations in group A indicate that a non-renewable energy source with peak supply of 245 MW (7.3 kW/household) would be required to ensure that there was no hourly supply-demand imbalance within the year. The simulations also showed that over the space of the year, the surplus renewable energy is considerable and local inter-seasonal energy storage with relatively low efficiency (around 20%) may be suitable as a heat storage option to cover any hourly demand-supply imbalance.

The simulation methods described in this paper can be used by engineers and land use planners to explore how different types of local energy sources could optimally be combined and at what space-time scales. The method also informs when and where there is surplus renewable energy, and can be used to explore what efficiency and type (heat or electrical) energy storage would be needed.

In this study, only one year of UK heat demand data was available and geographical information on the regional variability of household demand was not available. However, local heat demand will be influenced by factors such as poverty and house insulation levels. Weather data for 3 years was considered which is unlikely to contain periods of persistent low wind speed. For future work on analysis of other case study areas local heat demand data should be obtained, including information on anticipated changes in residential insulation if possible and wind speed data should be considered over 1-2 decades to better understand the impact of these uncertainties over the time periods required to justify investment in such synergistic water energy systems. These uncertainties would have an impact on the anticipated carbon emissions savings.

CRediT authorship contribution statement

F. Liu: Designed the model, analysed data, took the lead to draft and revise the manuscript. **A. Schellart:** Supervised the work, helped to shape the research, analysis and the manuscript. **W. Shepherd:** Provided comments of this work, helped to prepare some of the data and verify some of the findings. **J. Boxall:** Supervised the work and provided comments of this work. **M. Mayfield:** Supervised the work. **S. Tait:** Supervised the work, verified the findings of this work, helped to shape the manuscript.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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References

Abdel-Aal, M., 2015. Modelling the Viability of Heat Recovery from Underground Pipes – Deterministic Modelling of Wastewater Temperatures in a 3000 Sewer Pipe Network. PhD thesis. *University of Bradford*, UK.

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

Abdel-Aal, M., Tait, S., Mohamed, M., Schellart, A., 2021. Using long term simulations to understand heat transfer process during steady flow conditions in combined sewers. Water 13 (4), 570.

Ali, A., Mohamed, M., Abdel-Aal, M., Schellart, A., Tait, S., 2017. Analysis of ground-source heat pumps in north-of-England homes. Energy 170, 105–113.

Arnaudo, M., Dalgren, J., Topel, M., Laumert, B., 2021. Waste heat recovery in low temperature networks versus domestic heat pumps - a techno-economic and environmental analysis. Energy 219, 119675.

Arnaudo, M., Topel, M., Laumert, B., 2020. Techno-economic analysis of demand side flexibility to enable the integration of distributed heat pumps within a Swedish neighbourhood. Energy 195, 117012.

BEIS, 2018. Department for Business, Energy & Industrial. 2018 UK Greenhouse Gas Emissions, Final Figures. https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/862887/2018_Final_greenhouse_gas_emissions_statistical_release.pdf. (Accessed 12 February 2021).

BEIS, 2019a. Department for Business, Energy & Industrial. Energy Consumption in the UK (ECUK) 1970 to 2019. National Statistics. https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/928350/2020_Energy_Consumption_in_the_UK_ECUK_.pdf. (Accessed 21 February 2021).

BEIS, 2019b. Department for Business, Energy & Industrial Strategy. Conversion Factors 2019 - Condensed Set (For Most Users). https://www.gov.uk/government/publications/greenhouse-gas-reporting-conversion-factors-2019. (Accessed 21 March 2021).

BEIS, 2020. Department for Business, Energy & Industrial. Energy Consumption in the UK (ECUK) 1970 to 2019. National Statistics. https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/820843/Energy_Consumption_in_the_UK_ECUK_MASTER_COPY.pdf. (Accessed 23 March 2021).

Bertasiene, A., Borg, R., Azzopardi, B., 2015. A Review of Life Cycle Impact Analysis of Wind Turbines. *Workshop On Trends and Challenges for Wind Energy Harvesting.* Coimbra, Portugal.

Cecconet, D., Raček, J., Callegari, A., Hlavínek, P., 2020. Energy recovery from wastewater: a study on heating and cooling of a multipurpose building with sewage-reclaimed heat energy. Sustainability 12 (1), 116.

CEDA, 2018. Centre for Environmental Data Analysis. Hourly Wind Speed and Solar Radiation for 2018. http://wps-web1.ceda.ac.uk/ui/home. (Accessed 21 February 2021).

Cipolla, S., Maglionico, M., 2014. Heat recovery from urban wastewater: analysis of the variability of flow rate and temperature in the sewer of Bologna, Italy. Energy Proc. 45, 288–297.

Dacquay, C., Holländer, H.M., Kavgic, M., Maghoul, P., Liu, H., Fujii, H., 2020. Evaluation of an integrated sewage pipe with ground heat exchanger for long-term efficiency estimation. Geothermics 86, 101796.

DECC, 2014. Estimates of Heat Use in the United Kingdom in 2013. Department of Energy and Climate Change Statistics. https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/386858/Estimates_of_heat_use.pdf. (Accessed 21 February 2021), 2014.

De Graaf, R., Van De Ven, F., Mitenburg, I., Van Bert, E.E., Van De Winckel, L., Van Wijk, G., 2008. Exploring the technical and economic feasibility of using the urban water system as a sustainable energy source. Therm. Sci. 12 (4), 35–50.

EIA, 2020. US Energy Information Administration: Consumption & Efficiency – Energy Consumption Estimates by Sector. https://www.eia.gov/consumption/. (Accessed 20 February 2021).

Eurostat, 2018. Energy Consumption in Households. https://ec.europa.eu/eurostat/web/products-eurostat-news/-/DDN-20200626-1#:~:text=In%202018%2C%20households%20accounted%20for,and%20derived%20heat%20(8.7%25). (Accessed 20 February 2021).

Foxon, T., Hammond, G., Pearson, P., 2020. Socio-technical transitions in UK electricity: part 1 – history, actors and pathways. Proceedings of the Institution of Civil Engineering – Energy 73 (3), 109–122.

Hao, X., Li, J., van Loosdrecht, M., Han, J., Liu, R., 2019. Energy recovery from wastewater: heat over organics. Water Res. 161, 74–77.

IEA, 2018. International Energy Agency. https://www.iea.org/countries/china. (Accessed 20 February 2021).

Ilisei, G., Catalina, T., Alexandru, M., Gavriliuc, R., 2019. Implementation of a geothermal heat pump system in a solar passive house. In: E3S Web Conference, vol.8, 07014.

Jradi, M., Veje, C., Jørgensen, B.N., 2017. Performance analysis of a soil-based thermal energy storage system using solar-driven air-source heat pump for Danish buildings sector. Appl. Therm. Eng. 114, 360–373.

Kretschmer, F., Simperler, L., Ertl, T., 2016. Analysing wastewater temperature development in a sewer system as a basis for the evaluation of wastewater heat recovery potentials. Energy Build. 128, 639–648.

Koffi, B., Cerutti, A., Duerr, M., Iancu, A., Kona, A., Janssens-Maenhout, G., 2017. Covenant of Mayors for Climate and Energy: Default Emission Factors for Local Emission Inventories. Joint Research Centre (JRC) Technical Reports. EUR 28718 EN. Publications Office of the European Union, Luxembourg. https://op.europa.eu/en/publication-detail/-/publication/278ae66b-809b-11e7-b5c6-01aa75ed71a1/language-en. (Accessed 20 March 2021).

LAU, 2020. Eurostats. https://ec.europa.eu/eurostat/web/nuts/local-administrative-units. (Accessed 27 June 2021).

Liu, F., Tait, S., Schellart, A., Mayfield, M., Boxall, J., 2020. Reducing carbon emissions by integrating urban water systems and renewable energy sources at a community scale. Renew. Sustain. Energy Rev. 123, 109767.

Lund, H., 2018. Renewable heating strategies and their consequences for storage and grid infrastructures comparing a smart grid to a smart energy systems approach. Energy 151, 94–102.

Millar, M., Burnside, N., Yu, Z., 2019. District heating challenges for the UK. Energies 12 (2), 310.

Mondol, J., Jacob, G., 2018. Commercial scale solar power generation (5MW to 50 MW) and its connection to distribution power network in the United Kingdom. Journal of Solar Energy Research Updates 5, 25–38.

Nagpal, H., Spriet, J., Murali, M., McNabola, A., 2021. Heat recovery from wastewater–A review of available resource. Water 13 (9), 1274.

ONS, 2019a. Office for National Statistics. Population Estimates for the UK, England and Wales, Scotland and Northern Ireland: Mid-2019. https://www.ons.gov.uk/peoplepopulationandcommunity/populationandmigration/populationestimates/datasets/lowersuperoutputareapopulationdensity. (Accessed 27 November 2020).

ONS, 2019b. Office for National Statistics. Families and Households. https://www.ons.gov.uk/peoplepopulationandcommunity/birthsdeathsandmarriages/families/datasets/familiesandhouseholdsfamiliesandhouseholds. (Accessed 13 November 2020).

Postnote, 2016. Carbon Footprint of Heat Generation. House of Parliamentary Office of Science & Technology. https://post.parliament.uk/research-briefings/post-pn-0523/. (Accessed 18 March 2021).

Rosenow, J., Guertler, P., Sorrell, S., Eyre, N., 2018. The remaining potential for energy savings in UK households. Energy Pol. 121, 542–552.

Sayegh, M., Jadwiszczak, P., Axcell, B., Niemierka, E., Bryś, K., Jouhara, H., 2018. Heat pump placement, connection and operational modes in European district heating. Energy Build. 166, 122–144.

Self, S.J., Reddy, B.V., Rosen, M.A., 2013. Geothermal heat pump systems: status review and comparison with other heating options. Appl. Energy 101, 341–348.

Spriet, J., McNabola, A., 2019. Decentralised drain water heat recovery: a probabilistic method for prediction of wastewater and heating system interaction. Energy Build. 183, 684–696.

Spriet, J., McNabola, A., Neugebauer, G., Stoeglehner, G., Ertl, T., Kretschmer, F., 2020. Spatial and temporal considerations in the performance of wastewater heat recovery systems. J. Clean. Prod. 247.

The Green Age, 2014. Air Source Heat Pump vs. Ground Source Heat Pump. https://www.thegreenage.co.uk/air-source-heat-pumps-vs-ground-source-heat-pumps/. (Accessed 18 March 2021).

UK Data Service, 2009. Energy Demand Research Project: Early Smart Meter Trials, 2007–2010. https://beta.ukdataservice.ac.uk/datacatalogue/studies/study?id=7591&type=Data%20catalogue. (Accessed 18 March 2021).