Decentralised energy in the UK is rare. Cities in the north of England however lead the UK in terms of sustainable, low-carbon, local/district heating, through the implementation of combined-heat-and-power (CHP) facilities; substantial schemes are installed in several cities, including Barnsley and Sheffield. This paper presents the results from extensive experimental and theoretical feasibility studies, in which the merits of these were explored. Barnsley has a number of biomass-fuelled community energy generators, where pollutant monitoring and mathematical modelling were conducted to assess combustion characteristics and overall system performance. Measured pollutant levels were within the relative emission limits, though emission concentrations (CO, CO₂, NO and particles) in the flue gas from the coal boiler were higher than the wood pellet boiler. Sheffield already has a citywide district energy network, centred around a sustainably-sourced waste-to-energy facility; an expansion of this scheme was investigated here. This focuses mainly on the link to a 30 MW wood-fired CHP plant, which could be a significant provider of additional thermal capacity (low-grade heat) to an expanded network. Through identifying heat sources and sinks – potential suppliers and end-users – key areas were identified where a connection to the heat network would be feasible.

**Keywords:** low-carbon heating; biomass fuel; waste-to-energy plant; low-grade heat.
1. INTRODUCTION

The UK Government has set targets for reductions in carbon dioxide emissions and an increase in the percentage of electricity and heat generated from renewable sources [1-4]; these provide an opportunity to develop new systems of energy provision. Most electricity generation here is both large-scale and centralised, produced using fossil fuel resources, like coal and gas, and does not recover any of the low-grade waste heat. District heating/cooling through the use of combined-heat-and-power (CHP) systems however offer a substantial increase in overall plant efficiency from approximately 55%, for the best ‘electricity-only’ generating plant, to approximately 85% for a CHP plant that produces electricity and then recovers the heat. CHP-based district heating can also significantly reduce CO$_2$ emission [5]. Moreover, local resources can be used in such plants. CHP can be provided by incinerating local municipal solid waste (MSW), which can represent almost 20% of the total energy needs of a city, resulting in further reductions to net CO$_2$ emissions. Such MSW-fuelled schemes have been reported to be able to reduce carbon emissions by up to 76% compared to the conventional (separate) generation of heat and power [6,7]. The use of locally-sourced biomass can also minimise carbon emissions, among others, as explored below.

These locally planned and operated systems follow a rational approach to energy conservation and environmental protection, and have operated successfully in tandem with traditional electricity and gas supply systems to meet the main energy (thermal and electrical) demands of local communities. More than 3,000 towns and cities across Europe have such systems, including large-scale schemes in Paris and Vienna, among others, but the UK is somewhat behind, since there are just a handful of relatively small projects currently in operation here.

In addition to the government targets for carbon emissions and renewable energy/electricity, there are also policies which are aimed at increasing the amount of energy in general, and heat specifically, from such distributed sources of generation in the UK. The Renewable Heat Incentive, for example, offers financial support for the installation of renewable heat technologies, such as district heating; various monetary support levels are offered for different scales of heat production and also for a range of heat generating technologies, such as solid biomass combustion [8]. The Heat and Energy Saving Strategy also aims to focus on district heating in suitable communities [9]. A key policy proposal is to identify communities where district heating can be economically viable – namely areas with a high heat density (>3000 kW/km$^2$). In these regions, it is thought that a 6+% return on investment could be achieved. If district heating was utilised in all these areas, it would account for 5.5m properties and contribute about 20% of the overall heat demand in the UK. Large, high-efficiency gas-fired cogeneration heating schemes would result in CO$_2$ savings in the region of 9.8m t/a. Replacing the gas with renewable/sustainable fuels (like waste or biomass) could further minimise CO$_2$ emissions, saving over 19m t/a of CO$_2$ [9].

As a result, there is now much more interest in district energy and community heating in the UK. Consequently, the main aims of this research were to perform extensive experimental and
theoretical studies in two UK cities currently using decentralised energy; this will predominantly highlight the benefits of such schemes and encourage further installations in other areas of the country. Firstly, experimental pollutant monitoring and numerical modelling was performed in Barnsley to assess the performance of community biomass heating. Secondly, potential expansions to the existing district energy network in Sheffield were investigated, to evaluate their feasibility. These different case studies represent different stages in the progressive development of the city-wide integration of networked decentralised energy generation and use.

2. FUNDAMENTALS OF DISTRICT HEATING/COOLING

District heating often forms part of a total energy system that includes CHP, which produces energy at greater efficiencies than single, ‘electricity only’ generation, as detailed above. District and community heating schemes have three main elements: the heat source(s), the distribution system and the customer interfaces, which are discussed below. Examples of such schemes in Europe and beyond are also considered herein.

2.1 Heat Sources

There are number of different thermal energy sources that can be used for district heating, including heat pumps, solar thermal energy, geothermal systems and the recovery of industrial waste/low-grade heat, in addition to conventional boilers and cogeneration technologies, which can utilise a range of renewable and non-renewable fuels. Using a low return-water temperature of 30-65°C in district heating systems not only enables the efficient use of low-grade energy sources, but also means that more thermal energy can be absorbed. The majority of heat sources that are available tend to come from gas-fired CHP systems or from locally-sited conventional gas-, oil- or coal-fired boilers.

2.2 Distribution Systems and Customer Interfaces

Such heat sources can be either directly connected to the distribution system or indirectly connected through a heat exchanger. The direct system is limited to use water as the distribution medium; the water quality and pressure requirements need to be the same for the heat source and the building’s internal distribution system. An indirect connection allows the heat source and the distribution system to be controlled separately, with different temperatures and pressures, allowing more design and operational flexibility for both.

District heating water is distributed from the heat source through a network of supply pipes to the customers’ interface and is returned after heat has been extracted, through the use of individual heat exchangers installed in each home or building. Heat delivery is accomplished through the use of circulating pumps that create a pressure differential between the supply and return pipes. Pumps are selected to overcome the flow resistance in the pipes and also the pressure differential in the customer installation at the end of the system. The use of variable
speed drives to control the pumps ensure that the power consumed is minimised. Direct district heating systems typically operate with flow and return temperatures of 85/65°C and pressures of below 6 bar, whereas indirect systems often use temperatures of 110/65°C and pressures of below 16 bar. The greater the temperature difference between the flow and return pipes, the lower the flow rate required. A common supply temperature range is 85 to 120°C [10]. The low end of the range is normally the temperature required to meet domestic hot water needs during the summer. By reducing the normal operating temperature and by reducing the effects of pressure fluctuations, the life of the pipework can increase dramatically. The type of pipework used limits the district heating flow water temperature. The majority of medium to large systems use steel pipes as they can withstand higher operating temperatures and pressures and thus offer increased flexibility in design and operation. Most systems have a maximum operating temperature of 140°C and a maximum pressure of 25 bar. The size of pipework ranges, typically, from 25 mm up to 1000 mm in diameter.

2.3 Combined-Heat-and-Power and District Heating in Europe

Considering electricity production, Denmark and Slovenia produce 52.9% and 37.7% of electricity via CHP respectively, similar to much of Scandinavia and Eastern Europe [11]. A substantial element of the Netherlands production is associated with process industries, whereas in Denmark and Finland the balance is in favour of urban scale district heating. Conversely, France, Greece and Ireland only generate a tiny fraction of their present total electricity demand by CHP. Looking at heat production, which in fact should be the focus when evaluating CHP against energy efficiency aims, the picture is a little different. In this respect, Iceland has the highest percentage of district heating used to satisfy the heat demand in the residential and service sectors, with 93.9%; many other countries also have high percentages, including Russia (63%), Sweden (55%), Lithuania (50%), Finland (49%) and Poland (47%) [11]. The most common type of CHP plant in Europe is traditional steam-cycles, representing 52% of production, but the more efficient combined cycle co-generation plants have now reached a level of 30% of the market. Fossil fuels are used for ~70% of the electricity production in the CHP plants [12]. The minority share of power production stems from renewable energy, mainly from the use of wood wastes, paper and waste incineration. The largest integrated CHP system for district heating/cooling in the EU is to be found in Paris, whereas the largest scheme in ‘Greater Europe’ is in Moscow. Large-scale systems are found across Germany, Sweden, Finland, Denmark and Austria, as well as in all Eastern European countries. Although there are examples of fairly large-scale CHP district heating in the UK, they are rare compared to their prevalence in the rest of Europe and are dwarfed by other European systems. The share of district heating in the heat markets in Belgium, France, Greece, Ireland, Italy, Luxembourg, Holland, Portugal, Spain and the UK is low, often less than 3% [11]. There are clear opportunities therefore to incorporate residential and industrial/commercial areas into new schemes across the UK and Europe.

There are many examples across the world where there are partnerships between the local district heating utility and local industry, where waste heat from process industries is supplied to the nearby district heating network for redistribution. Further added value of the network is created by the ability to deliver heat to produce ‘cooling’ or to deliver chilled water, whilst at
the same time reducing pollution. Presently, demand for cooling is included along with the projections showing increasing demand for electricity. However, in the future, district cooling (based on the integration of absorption chillers into CHP plants – thus becoming combined heat, cooling and power) with district heating as an energy input would slow the rise in electricity consumption. In city areas that have a heat demand during winter and a cooling demand during the summer, the combination of CHP, district heating and absorption refrigeration can be an optimal solution for ensuring the efficient use of capital invested in production capacity. If CHP generating capacity is balanced to meet the local heating and cooling loads, then energy efficiency would be improved and the electricity would be more environmentally friendly, although electricity-only stations would still be needed [13].

2.4 Analysis of District Heating in the UK

As demonstrated above, the use of CHP technologies, especially for district heating purposes is common in Europe and across the world, however the picture is starkly different in the UK. In 1996, both Nelson, et al. [14] and Babus’Haq and Probert [15] evaluated the current state and future prospects of CHP and district heating in the UK. Nelson, et al. [14] state that such schemes in a number of European cities offer a range of social and commercial benefits that are overlooked in the UK, which, according to Babus’Haq and Probert [15], has consequently resulted in very slow deployment rates. The fact that these systems tend to produce fewer environmentally-damaging emissions (from the range of fossil and renewable/sustainable fuels they can use), in addition to being, at the time, economically justifiable, highly efficient and thermodynamically attractive, appear to have been neglected then – and this is clearly still a problem now. Further barriers discussed in these papers include unfavourable governmental legislation/initiatives and the high capital costs [14,15]. Even in 1996, it was identified that increased amounts of CHP and district heating will be needed in the UK to mitigate the impacts of the decline in fossil fuels, the generation of atmospheric pollutants and the population increases that will lead to a dramatic rise in the overall energy demand [15]. It would appear that relatively little progress has been made on a national scale since the publication of these articles.

Since these papers, which also discuss the schemes implemented in Sheffield, Nottingham and Leicester, among others, some developments have been made with regards to CHP generation, although not so much with district heating. It has been reported that although the CHP capacity of the UK has increased significantly (almost doubling in the 10 years since the publication of the above papers, to ~6000 MW), the vast majority of heat and power generated is used in situ at large industrial sites, meaning that less than 0.1% of households are connected to a CHP district heating scheme [16]. Hinnells [16] identifies several publications by various government-funded bodies that present data for the potential of CHP-based district and community heating schemes in the UK; these are often huge estimates – some suggesting that up to 20% of UK homes could benefit from such local installations, which would be an almost insurmountable increase compared to the current <0.1%. Nonetheless, increasing the amount of distributed energy in the form of district-/community-scale heat and power generation, especially from renewable and sustainable fuels, is vital to ensure a secure and reliable supply of energy, with limited environmental impacts [17]; such systems will need to form an integral
part of the entire energy mix, which will also need to include a range of other fuel and energy sources, like heat pumps, wind turbines, solar power and micro-CHP generation. The integration of thermal energy storage technologies into these, particularly CHP operations will also be necessary for the future [18]. These later and more recent papers still delineate that the poor governmental approach to CHP remains a significant barrier to future developments, along with the infrastructural challenges [16,18].

Cansino, et al. [19] investigated how 27 EU countries, including the UK, are promoting heating and cooling production from renewable sources of energy through various policy implementations, inclusive of subsidies, tax incentives, feed-in tariffs and other financial support mechanisms. The UK uses specific subsidy measures to support heating and cooling from biomass sources (heat-only boilers). Other countries have implemented subsidies for a range of other renewable energy sources, including solar thermal and geothermal. Tax incentives in the form of exemptions are also used the UK, for example, the revenue acquired from the Feed-In Tariff scheme and the Renewable Heat Incentive for installations of heat generating technologies will not be taxed. Furthermore, the UK has brought in reduced levels of value-added tax rates (of 5%) on certain components and materials for specific heating/cooling systems. Zero-carbon homes can also be eligible for reduced (and sometimes no) stamp duty. Feed-in tariffs only tend to be widely used in the EU for electricity production, but a small number of EU member states also apply this to heat generation – including the UK. Despite these various incentives, the adoption of renewably-sourced heating in the UK, especially at a decentralised scale remains limited.

Westner and Madlener [20] assessed the economic impacts on CHP-based district heating of the modification to the EU Emissions Trading System for the third emission trading period, which will be enforced in 2013. They found, through Monte Carlo simulations, that the net present values of large-scale CHP plants used for district heating could be reduced significantly with the implementation of this third emission trading period, compared to the current second period, thus increasing the operational risks and decreasing the economic viability. They conclude therefore that these new rules may result in the replacement of high-efficiency, large-scale CHP plants by less efficient separate generation technologies – ‘heat-only’ and ‘electricity-only’ facilities – potentially disincentivising CHP installations.

3. EVALUATING THE PERFORMANCE OF BIOMASS-FIRED COMMUNITY HEATING SYSTEMS IN BARNSLY

In the UK, approximately 49% of the final energy consumed is in the form of heat [13]; since this accounts for about 47% of UK CO₂ emissions, there is a clear need to decarbonise heating. Barnsley Metropolitan Borough Council was the first local authority in the UK to adopt a ‘biomass fuel heating policy’. They have successfully installed and operated over twenty wood-fuelled ‘mini’ district heating systems since 2005, combusting both wood pellets and wood chips in place of coal. Extensive experimental measurements and numerical simulations have
been conducted at these wood-fired heating systems, in order to investigate pollutants emissions and assess overall performance; the methodologies and results of two case studies are presented here.

3.1 Case Study 1: Biomass Heating System at a Primary School

The first plant consists of three cast iron hot water boilers for heating a primary school. Two boilers were tested: a 190 kW Beeston Robin Hood Senior Boiler and a 146 kW Hartley-Sugden White Rose Boiler. Both were originally designed to burn coal, although the former was retrofitted to burn wood pellets. Measurements were carried out in the stack of each boiler. This involved monitoring the gas temperature and composition (CO, CO$_2$, O$_2$ and NOx – oxides of nitrogen), as well as the mass size distribution and concentration of PM$_{10}$ (particulate matter smaller than 10 µm) in the flue gas. The concentrations of CO, CO$_2$ and O$_2$ in the gas were measured with a MGA 3000 Multigas Analyzer and the NOx concentration by a Signal 4000 VM NOx Analyzer. The mass size distribution and total concentration of particulate matter in the flue gas was isokinetically measured using an eight stage Nonviable Andersen Impactor (Series 20-800, Thermo Electron Corporation). Detailed information on the measurement techniques used can be found in Chen, et al. [21]. Table 1 presents the measured emission data for both case studies.

<table>
<thead>
<tr>
<th>SCHOOL: CASE STUDY 1</th>
<th>HOUSING: CASE STUDY 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wood pellet boiler</td>
<td>Coal boiler</td>
</tr>
<tr>
<td>CO (ppmv)</td>
<td>300-700</td>
</tr>
<tr>
<td>O$_2$ (% vol)</td>
<td>12.6-16.2</td>
</tr>
<tr>
<td>CO$_2$ (% vol)</td>
<td>5.6-8.2</td>
</tr>
<tr>
<td>NO (ppmv)</td>
<td>44-97</td>
</tr>
<tr>
<td>PM$_{10}$ (mg/m³)</td>
<td>27.8</td>
</tr>
<tr>
<td>Flue Gas Temperature (°C)</td>
<td>300-367</td>
</tr>
</tbody>
</table>

Table 1. Experimental results from monitoring the flue gas emissions for Barnsley case studies [14,18].

To obtain more detailed information on wood pellet/coal combustion in the boiler and the pollutant emissions, computational fluid dynamics (CFD) modelling was undertaken. The combustion of wood pellets/coal lumps consists of in-bed combustion and out-of-bed combustion. Here, an in-house code, FLIC, was employed to predict in-bed combustion, and the FLUENT code (version 6.3.26) was used to simulate gas-phase reactions in the freeboard region above the bed. FLIC assumes that the fuel bed is a one-dimensional bed (perpendicular to the grate) of packed particles with gas voids, and tracks the history of the combustion in the bed. The sub-processes consist of equations for conservation of mass, momentum, energy and chemical species for both the gas- and solid-phases in the bed, together with equations for moisture evaporation, devolatilization and volatile/char combustion. Details of the model development, governing equations, numerical schemes and sub-models for reactions and heat transfer were presented in previous papers [22,23]. For both boilers, the computational domain of the fixed bed was discretized into 200 cells along the bed height. The initial bed height was 212 mm in the pellet boiler, and 302 mm in the coal boiler. The particle size was set to be 5 mm for wood pellets and 15 mm for coal.
The FLIC simulation of the in-bed combustion provided the profiles of gas temperature, velocity and composition at the bed top, which were used as the boundary conditions for the over-bed combustion modelling in FLUENT, to determine the temperature profiles and flow fields. The boundary conditions used for this case are detailed in Table 2. The interface between the FLIC and FLUENT modelling is a rectangle at the bottom of each boiler with fine grids. In the FLUENT modelling, conservation equations for mass, momentum and energy, together with various gas reactions were solved with a standard $k$-$\varepsilon$ model for turbulence and a P1 model for radiation being selected. The finite rate/eddy dissipation model was used to calculate the chemical reaction rates. The total number of cells was 197,897 for the wood pellet boiler and 363,696 for the coal boiler. Since NOx is an important pollutant produced during combustion, the formation of NOx was considered carefully in the modelling. In this case, it was assumed that the ratio of volatile-N to char-N equals that of the volatile to fixed carbon content ratio in the fuel samples. The FLUENT post-process modelling simulated the NO formation from the HCN intermediate by the De Soete mechanism.

<table>
<thead>
<tr>
<th>MASS FLOWRATE (kg/s)</th>
<th>TEMPERATURE (K)</th>
<th>CO</th>
<th>O$_2$</th>
<th>CO$_2$</th>
<th>N$_2$</th>
<th>H$_2$O</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wood Pellet Boiler</td>
<td>0.050</td>
<td>931</td>
<td>2.75</td>
<td>18.20</td>
<td>6.45</td>
<td>71.62</td>
</tr>
<tr>
<td>Coal Boiler</td>
<td>0.267</td>
<td>981</td>
<td>0.83</td>
<td>21.01</td>
<td>1.50</td>
<td>76.66</td>
</tr>
</tbody>
</table>

Table 2. Boundary conditions at the fuel and air inlet of case study 1 – comparison of the wood pellet- and coal-fired operation of the boiler [14].

The mathematically modelled CFD results agreed reasonably well with the measured data shown in Table 1 [21], where both indicated that pollutant emissions were within the relative emission limits specified in BS EN 303-5:1999 [24]. The pollutant levels in the flue gas from the coal boiler, however, were higher than those from the wood pellet boiler. CO emissions from the wood pellet boiler were 500-1650 mg/m$^3$ at 10% O$_2$, lower than that from the coal boiler (2000-9000 mg/m$^3$). This is most likely due to: (i) the poor mixing of the combustion air with the combustible gases released from the coal bed, and (ii) the shorter residence time of flue gas in the furnace. NOx emissions from the wood pellet boiler were 40-120 mg/m$^3$ at 10% O$_2$, again lower than that from the coal boiler (240-390 mg/m$^3$). This is because the higher char fraction in coal leads to a higher bed temperature (up to 1500 K for the coal boiler, shown in Figure 1b, compared to a maximum temperature of ~1000 K for the wood pellet boiler, shown in Figure 1a) and consequently contributes more char-N NO during combustion. The average mass concentrations of PM$_{10}$ were around 46 mg/m$^3$ (10% O$_2$) and 182 mg/m$^3$ (10% O$_2$) from the wood pellet and coal boilers, respectively. Results obtained from this research show that biomass with a high volatile fraction could be an ideal solid fuel for small-scale fixed bed boilers, resulting in higher combustion efficiencies and lower pollutant emissions.

### 3.2 Case Study 2: Wood-Fired Heating System at a Residential Building

A residential building in Barnsley has been refurbished and equipped with a small-scale residential biomass heating system to increase energy efficiency and improve the residential environment. Two Froling wood chip boilers with thermal capacities of 320 kW and 150 kW were installed for space and water heating. Experimental and theoretical investigations were
conducted to characterise both the combustion and the emissions generated. Measurements of flue gas emissions (concentrations of CO, CO$_2$, O$_2$, NOx, SO$_2$ and particulate matter) were carried out at the exit of the 320 kW boiler, operating at approximately 65% of its maximum continuous rating during the measurements. The experimental methodologies and procedures were identical to those used in case study 1 above. In addition, mathematical modelling work using FLIC and FLUENT codes was carried out in order to simulate the combustion process of wood chips in the boiler and subsequently evaluate overall systems performance. The selection and settings of the models were same as those in case study 1.

The boundary conditions utilised for this case are overviewed in Table 3. The FLIC and FLUENT codes interacted through their respective boundary conditions, as before. The measured emissions data were used to validate the modelling work. In the in-bed FLIC modelling, the initial bed height was 183 mm, which was discretized into 60 cells. The average particle size of the wood chips was assumed to be 15 mm. In the FLUENT modelling, a total of 217,249 cells were employed for the 3D simulation of the furnace. The meshes were finer at the inlets of the fuel and air and coarser towards the exit in order to save on computation time. More detailed information of the mathematical modelling can be found in Zhang, et al. [25].

<table>
<thead>
<tr>
<th>MASS FLOWRATE (kg/s)</th>
<th>TEMPERATURE (K)</th>
<th>AVERAGE GAS COMPOSITION (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fuel/Primary Air Inlet</td>
<td>0.219</td>
<td>540</td>
</tr>
<tr>
<td>Secondary Air Inlet</td>
<td>0.068</td>
<td>288</td>
</tr>
<tr>
<td>Tertiary Air Inlet</td>
<td>0.068</td>
<td>288</td>
</tr>
</tbody>
</table>

Table 3. Boundary conditions at the fuel and air inlets of case study 2 – the wood-chip boiler [18].
Table 1 presented the measured pollutant concentrations in the flue gas of case study 2. The mass concentration of CO was 550-1600 mg/m$^3$ (10% O$_2$); both the experiments and simulations found that CO emissions from the boiler were below the emission limited value (ELV) specified in BS EN 303-5:1999 [24] and were within the relative emission limits. NOx concentrations in the flue gas from wood chip combustion varied between 28 and 60 ppmv. The emission factor for NOx was 113 mg/MJ, lower than the DEFRA Technical Guidance of 150 mg/MJ [26]. The mass concentration of PM$_{10}$ in the flue gas was around 205 mg/m$^3$ at 10% O$_2$, matching the in BS EN 303-5:1999 ELV of 200 mg/m$^3$ [24]. The emission factor of PM$_{10}$ however was 126 mg/MJ and therefore significantly lower than the outlined ELV of 240 mg/MJ, as specified in the DEFRA Technical Guidance [26].

The FLIC/FLUENT modelling results showed that due to the high flue gas temperatures in the furnace, up to 1200 K (Figure 2a), most of the fuel was burnt inside the furnace and little CO was released, as confirmed by the experimental results. The injection of secondary air (the small circles on Figure 2) provided adequate mixing and thus favourable combustion conditions in the wood chip-fired boiler, as demonstrated by the flow fields in Figure 2b; the added air at these locations enhance mixing, giving rise to regions of reverse flow above the secondary jets, as shown, to facilitate efficient combustion. These areas of intensive combustion result in high temperature zones, as identified in Figure 2a. The outlet temperature also remains high. This study has shown that the use of biomass (wood chips) heating is a low-carbon heating solution, since it produces much lower net CO$_2$ emissions in comparison to a fossil fuelled heating system. The implementation of such schemes will help to meeting government targets regarding carbon emission reductions and renewable energy generation.

Figure 2. Modelled results for (a) temperature profiles (the inclined, dashed line indicates the location of the wood chip bed) and (b) flow fields (small circles are secondary air jets; the big circle is the exit) inside the furnace of the wood-fired heating system at the residential building – case study 2 [18]. The x-axis (Z) shows the distance along the grate (in m) and the y-axis is the height above the burning bed (also in m).
4. POTENTIAL EXPANSIONS OF SHEFFIELD’S DISTRICT ENERGY NETWORK

Sheffield’s district heating network is one of the largest and most successful CHP schemes operating in the UK. It has been developed around a MSW incinerator located close to the city centre. The plant is designed to handle ~225,000 t/a of local, non-recyclable MSW and generates up to 60 MW<sub>th</sub> for the citywide district heating system and 21 MW<sub>e</sub> for the National Grid; the production of sustainable energy mitigates the generation of 21,000 t/a of CO<sub>2</sub>, hence this too is a low-carbon form of heating [27,28]. Around 120,000 MWh/a of low-grade heat is distributed throughout the city via a 44-km pipeline network to 3000 residences and over 140 other buildings, including shops, offices and both universities. The plant and heat distribution network are identified in Figure 3 within the context of Sheffield. An overview of the plant and its district heating system is given in Table 4. Although this is already an extensive system, there are potential expansion opportunities, which have been preliminarily investigated here.

![Figure 3: The initial GIS base map layer, identifying the area enclosed within the Sheffield City Council Boundary, the energy recovery facility and the district heating network.](image)

4.1 Reasons for Expanding the Network

Although district heating is rare in the UK, many policies, including the Renewable Heat Incentive and the Heat and Energy Saving Strategy, discussed above, are aimed at increasing the amount of heat from distributed sources of generation; it is thought that these will positively influence decision-making in this area in the future. The rationale for expanding the
network in Sheffield therefore is: (i) providing sustainable/secure energy, (ii) reducing CO$_2$ emissions, (iii) generating heat in proximity to where it is used, (iv) providing reasonably-priced heat, critical to the fuel poverty agenda, (v) aiding Sheffield in becoming a low-carbon city and (vi) helping to meet legislation regarding renewable energy and CO$_2$ (e.g. UK Low Carbon Transition Plan and the Renewable Energy Strategy). This work aimed to discover the expansion possibilities of Sheffield’s district energy system through identifying the existing and emerging heat sources and sinks – the potential suppliers and end-users in an expanded energy network. These were mapped utilising ESRI ArcGIS software – a geographical information systems tool – to locate the key sites and identify areas where a link to the existing heat network would be feasible, as well as environmentally and economically beneficial.

### OPERATING PARAMETERS OF THE SHEFFIELD WASTE-TO-ENERGY PLANT

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fuel (municipal solid waste, MSW) Feedrate</td>
<td>28 tonne/hr</td>
</tr>
<tr>
<td>Calorific Value of the Fuel</td>
<td>9.21 MJ/kg</td>
</tr>
<tr>
<td>Grate Design</td>
<td>Martin reciprocating, 5 rows, 13 steps</td>
</tr>
<tr>
<td>Steam Flowrate</td>
<td>86 tonne/hr</td>
</tr>
<tr>
<td>Steam Temperature and Pressure</td>
<td>400°C and 40 bar</td>
</tr>
<tr>
<td>Chimney Height</td>
<td>75 m</td>
</tr>
<tr>
<td>Gas Fired Auxiliary Burners</td>
<td>2 × 20 MW</td>
</tr>
<tr>
<td>Hot Water Temperature in the Pipeline Network</td>
<td>120°C</td>
</tr>
<tr>
<td>Water Pressure in the Pipeline Network</td>
<td>16 bar</td>
</tr>
<tr>
<td>Pumps in the Distributed Pipework System</td>
<td>15</td>
</tr>
<tr>
<td>Total Capacity of 3 Stand-By Backup Boilers</td>
<td>84.6 MW</td>
</tr>
</tbody>
</table>

**Table 4.** Technical data for Sheffield’s waste-to-energy plant and the associated district heating system [20,21].

### 4.2 Producing the Base Maps of the City

Firstly, a series of base maps were produced. The first of these incorporated the existing energy and transport infrastructures within the city council boundary. The different buildings types were then added, including domestic, educational, governmental, health care, commercial, industrial and leisure. Figure 4 contains a composite of these multiple-layered GIS maps that were generated.

### 4.3 Heat Mapping: Identifying and Linking Heat Sources and Sinks

#### 4.3.1 Existing and Emerging Heat Sources – Potential Suppliers

A number of potential heat sources were recognised; these are mapped on Figure 5 and currently have a total capacity of at least 6-11 MW. The primary source is the proposed biomass power station at Blackburn Meadows, near Tinsley [29,30]. This is the site of a former coal-fired power station and should be redeveloped by E.ON UK plc, starting in 2012, with a new energy facility: Blackburn Meadows Biomass Power Station. This renewable energy plant will combust locally-sourced, clean recycled wood waste (~180,000 t/a); it currently has an envisaged capacity of 30 MW (20-25 MW for electricity, plus 5-10 MW of heat), although it is hoped that the thermal capacity can be increased. This should generate power for about 40,000 nearby homes and the prospect of recovering and using the low-grade ‘waste’ heat generated by electricity production
for district heating (to supply local residential and industrial/commercial premises) is being investigated; there is consequently a clear opportunity to integrate this facility into an expansion of the district energy network in Sheffield.

Figure 4. The final GIS base map, identifying the infrastructure and different building types within the city boundary. The city centre and narrowed target area based on the initial base mapping is also shown as an inset.
In addition to this plant, low-grade waste heat from numerous steelworks in the city could also be recovered and fed into the network. Most of these are located in the Lower Don Valley, as shown on Figure 5. The low-grade waste heat recovery potential from the two circled plants on this map is reported to be at least 1 MW, although it is likely to be considerably more. Renewable energy sources currently in use were also highlighted on this map; these have a thermal output that could be increased to provide surplus heat to the network.

Figure 5. Heat map of the existing and emerging heat sources – potential suppliers that could be incorporated into an expansion of the current district energy network.

4.3.2 Existing and Emerging Heat Sinks – Potential End-Users

A large number of heat sinks were also discovered. This can be broken down into different buildings types. Residential areas contribute significantly to this as they have significant heat loads (~1.5 GW), particularly those with a high population density. There are also 26 new domestic development areas in the city, which will have around 1500 new homes; the estimated heat load for these has been calculated to be in excess of 10 MW. Another residential development just over the border in Waverley, Rotherham will have around 4000 new homes, which could have a heat load of 25 MW. Data for 157 buildings has also been collected; these heat loads total 34 MW, mainly for educational and industrial buildings, but these also include
leisure centres, residential care homes, sports/entertainment venues, hotels and libraries. The heat loads for these are mapped on Figure 6. A number of additional buildings that may be significant heat sources or sinks have also been identified and data is being sought for these.

4.3.3 Linking Heat Sources and Sinks

As stated above, data is not known for all buildings that are of interest. Based solely on the information outlined herein though, it can already be seen that there are key areas in the city where an expansion to the existing district energy network would be feasible. These can be identified by linking the heat sources (Figure 5) that would supply additional heat through new pipelines to the heat sinks (Figure 6), which would benefit from a connection to the district energy network. Once more information is gathered for the other buildings, this picture will become even clearer. The main area where an expansion/extension would be both feasible and beneficial is the Lower Don Valley, including an extension across the City Council Boundary into Rotherham. Outlined as one of the key spatial development areas, this region of the city contains both a significant number of heat sources and heat sinks. The heat sources include the proposed biomass-fuelled energy plant (E.ON facility, Blackburn Meadows), which will form the main heat supply, as well as many steelworks that are likely to have low-grade waste heat. There are also a diverse range of heat sinks located here, comprising existing and emerging residential areas, industrial sites, council/governmental buildings, educational complexes and leisure facilities.

Even if a connection to the existing energy network proves not to be possible, there is still a strong case for a separate district heating network for the Sheffield-Rotherham Don Valley, centred on the E.ON facility as the main provider of heat to a second network. There are other
areas in the city where there is a considerable heat demand and thus where there are other expansion possibilities. Pipeline extensions in these areas could be linked to both the existing network and those for the proposed scheme in the Lower Don Valley. With the additional data for the buildings outlined, it is hoped that the development opportunities in these other areas will become more apparent and therefore also more promising.

5. DISCUSSION AND CONCLUSIONS

The use of local renewable and sustainable fuels (biomass and municipal waste) for energy generation on a decentralised scale can be hugely beneficial. These offer lower-cost heating and electricity for local populations, coupled with widespread environmental benefits in terms of reduced emissions compared to conventional energy generation utilising coal and other fossil fuels. Moreover, existing small-scale coal-fired heating schemes can be easily converted to be fuelled by renewable resources to further minimise CO₂ emissions for low-carbon heating. Furthermore, other emissions that can have detrimental health and environmental implications, like NOx and particulates, can also be lowered through using wood (pellets or chips) instead of coal. Technologies, such as district-scale cogeneration can achieve much greater overall efficiencies (~70%+) compared to single, ‘electricity-only’ generation at large, centralised power stations, which rarely exceed 35-40%. Such systems are used extensively in Europe and across the world, with high-profile schemes in Vienna, New York and Paris, as well as many others. Whilst there are some examples of the use of community and district-scale energy projects in the UK, such as in Barnsley and Sheffield, as considered herein, these are rare here. These places in the north of England are leading the UK in terms of sustainable, low-carbon, decentralised heating. Currently, these schemes have reached their network capacity – all the heat that is generated has a consumer and additional end-users cannot be accommodated. There is however the potential to further develop such schemes by incorporating a range of additional existing and emerging energy sources to provide more thermal capacity to an expanded network; the extra heat can then be redistributed throughout the city to connect to additional heat sinks and provide sustainable and low-carbon heat.

This work has identified the stages in transition from local, small-scale community heating projects to city-wide CHP-based district heating that will require the heat mapping techniques described herein. Barnsley and Sheffield each represent different phases in the development and integration of networked, city-wide decentralised energy deployment. Barnsley is in an early (first) stage in the formation and development of district energy generation, having a number of separate ‘mini’ district heating projects in operation throughout the town. The adoption of these in place of coal has lead to the environmental and cost benefits outlined above; the work here has demonstrated that further optimisation of these is possible through CFD modelling, which is vital to enhance its profile. Sheffield has gone a stage further into the following phase of development, where a more holistic, networked approach has been taken, linking different areas and buildings across the city through a larger, integrated CHP-based district heating scheme to redistribute the heat from the main plant. This identifies how the
gap can be closed between small-scale low-carbon heating, which is slightly more prevalent in
the UK, and sustainable city-wide energy provision, which has been so far largely neglected.

The subsequent stages for each location were outlined above, where this investigation has
presented how these two phases can be bridged. The next stage (initial mapping) in the
analysis of heat for the example city were also detailed, dealing with more in-depth
investigations of a range of pertinent aspects. Comprehensive heat mapping can be used to
link smaller systems to create a CHP-based city-wide network of energy generation and delivery.
Further examinations of related factors would also be required, especially regarding local
environmental aspects and relevant economic issues.

The amount of energy, and specifically heat, from distributed sources of generation clearly
needs to be increased significantly to comply with policies, such as the Heat and Energy Saving
Strategy and the Renewable Heat Incentive, ensuring these have a positive impact. This will
help meet the fuel poverty agenda and decarbonise residential energy use – in particular,
domestic heat generation. This will include the installation of many new schemes across the
UK, in addition to the expansion/upgrading of existing networks. The successful schemes used
in the north of England, in both Barnsley and Sheffield, have demonstrated to decision-makers
that such projects can be hugely beneficial in the UK and that there are apparent opportunities
in these cities and in other areas to integrate existing heat sources and sinks into a distributed
energy network or install a separate facility or plant to serve the high heat demands, often in
densely populated areas. The examples of these highly-effective schemes in both the UK and
Europe need to be showcased more extensively to overcome the negative perceptions
associated with them and publicise the benefits these heating systems can have. There are still
other additional barriers (such as the current unfavourable governmental legislation and
initiatives) that need to be addressed in the UK to promote further the adoption of
decentralised energy technologies. A more coordinated approach to pertinent policies and
initiatives is required to achieve this.

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