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Modelling and mapping sustainable heating for cities

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ABSTRACT

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, CO_2, 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.

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 3000 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

Abbreviations: CFD, computational fluid dynamics; CHP, combined heat and power; ELV, emission limited value; GIS, geographical information systems; MSW, municipal solid waste; NOx, oxides of nitrogen; PM_{10}, particulate matter smaller than 10 μm.

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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 5.5 m 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 9.8 m t/a. Replacing the gas with renewable/sustainable fuels (like waste or biomass) could further minimise CO_2 emissions, saving over 19 m 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 85–120 °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 Demark 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 cogeneration 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