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Infrastructure challenges for the built environment ☆

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ABSTRACT

The twin challenges of a lower-carbon future and national energy security are focusing attention on the most effective means of energy generation in the built environment. Efficiency gains are offered by the distribution of heat from community heating and combined heat and power (CHP) plant, which is presently underdeveloped in the UK by comparison with continental Europe. Natural gas is the preferred fuel for most of today's district energy systems which are technically developed, but proposed schemes must be tested against CHP 'quality' criteria to ensure there is not an increase in primary energy use compared to larger-scale central generation. Future district energy systems must aim to exploit local energy resources, such as biomass, wind and micro-hydro, and local thermal resources, such as solar collectors and ground source heat pumping. They may also incorporate novel forms of heat and power storage and load management.

District energy schemes must be planned within a context of increasingly efficient buildings requiring less heat while the demand for electricity increases. In addition, local power schemes will have to meet future environmental requirements, for example for air quality where waste or biomass is combusted.

1. Key challenges

The term 'infrastructure' can cover a range of services, such as transport, communications, water or waste. This review focuses on energy, in particular the distribution of electricity and heat on a local scale. Distribution is by wires for electricity and pipes for a heat exchange medium, often water. Heat is distributed to provide homes with hot water, space heating and space cooling.

The overall aim of current policy is to achieve low-carbon emissions and energy security through maximising efficiency and utilising local resources. Furthermore each scheme must be judged in terms of its economic viability. The Code for Sustainable Homes, launched in 2007, introduced the carbon-neutral 'Level 6' home, which uses a combination of very high thermal insulation and micropower from renewable technologies. Though this is a worthy goal, experience is showing that such a high target may be too expensive to replicate (Chris Twinn, Arup, private communication, 2007). In contrast, community-wide energy systems, also known as distributed or district energy, as reviewed here, may offer the cheapest way of delivering a carbon step change. UK energy security policy aims to reduce dependence on natural gas. Furthermore, the UK electricity system is heavily reliant on a small number of large power stations fuelled by natural gas, coal or nuclear fuel (Econnect Consulting, 2006). The removal from operation of one or more of these power stations represents a significant issue for security of supply. District energy can contribute to security of supply through dispersing and increasing the number of sources of electricity generation.

2. The state of current science

2.1. Basics of district heating and CHP

The physical elements of a district heating scheme consist of an energy centre with a central heat source, a heat distribution network, and space heating and domestic hot water systems within each building or dwelling (CT & EST, 2004).

Combined heat and power (CHP), known as cogeneration in the USA, is the simultaneous production of electricity and useful heat (Harvey, 2006a). All fossil-fuel-based electricity generation produces heat as a by-product. In central power plants, this heat is discarded through the cooling water and in the exhaust gases. In CHP, some of this heat is captured at usable temperatures, such as for heating nearby buildings, providing domestic hot water or for process heat. CHP has a long and extensive history of use in industrial facilities and to a lesser extent in district heating systems.

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In Denmark, district heating networks have developed on a number of scales, covering whole cities or rural settlements of only 250 inhabitants. They utilise a range of different fuels including natural gas, straw, waste wood, municipal waste and biogas (Brodies LLP, 2007; DTI, 2007; PBPower, 2006). About 57% of Denmark's electricity capacity comes from CHP and over 50% of households are connected to district heating. Other European countries have achieved up to 70% connection.

Though only 1% of households in the UK are connected to district heating, part of the reason is the comparative mildness of the British winter. 'Heating degree days' are the difference between 15.5 °C (60 °F) and the daily mean (average) temperature when the latter is less than 15.5 °C. London has about 1700 heating degree days per year, while for Copenhagen the figure is around 2900 (Brodies LLP, 2007). This represents a significant difference in the economic viability of district heating. A building of the same size and insulation levels in Copenhagen will have a higher heat demand than it would in London, making the capital investment of connection that building to CHP more financially attractive.

District heat can be economically transported several tens of kilometres, depending on the relative steam and natural gas costs, the pipeline energy loss (typically a few per cent), the pipeline cost (which is highly location dependent) and the density of the heat load (Karvountzi et al., 2002). Variable-speed pumping equipment is preferred, to reduce electricity consumption. The heat mains consist of pipes that are pre-insulated to a very high standard and buried in the ground in the same way as other main services (Energy Saving Trust, 2004). They incorporate integral leak detection systems, and are manufactured to European standards designed to ensure their reliability over at least 30 years. Some systems have a separate distribution network for centrally generated domestic hot water.

In the Southampton District Energy Scheme, the pipes have a heat loss of 1 °C at a 1 km radius from the heat station, roughly the extremity of the scheme (IEA DHC/CHP, 2004). (While this is a low value for small schemes, it would give rise to appreciable thermal losses for schemes more than a few kilometres in size.) The water is distributed at a seasonally variable temperature of 70–82 °C with a design return temperature of 50 °C. This low return temperature is very important to maximise heat recovery from the CHP plant and from the geothermal well unique to this system.

District heating systems generally provide heat to dwellings in the same way as heating systems, substituting for their own individual boilers, but otherwise using the same pipes and radiators (IEA DHC/CHP, 2004). The owners use the same controls, such as programmers to set daily and weekly heating and hot water requirements. One option is to use a hydraulic interface unit within a building. This unit includes a plate heat exchanger, as in a combination boiler, which can provide instantaneous domestic hot water and eliminate the need for hot water storage.

2.2. *Efficiency of natural gas CHP*

Most CHP systems are fuelled by natural gas for its convenience, efficiency and cost. However, gas is less desirable in terms of future UK energy security.

Critical parameters for the assessment of gas-powered CHP are the proportion of the output produced as electricity, and the overall efficiency of the system for electricity and useful heat. For example, a 1 MW simple-cycle gas turbine might have an electrical efficiency of 22% and a thermal efficiency of 43%, which sum to an overall efficiency of 65%. This compares very favourably to existing central power plants with an overall average electrical efficiency of about 33–35%, further decreased by 90–95% transmission efficiency. Where a CHP system is configured for power rather than heating in district energy systems, the challenge is to ensure that the heat is fully utilised whenever electricity is being generated.

A further test for natural gas CHP follows from a comparison to natural gas domestic boilers (Harvey, 2006b) in order to ensure there are savings in primary energy. This is because the useful thermal energy obtainable from CHP systems is constrained by the fact that not all the by-product heat can be extracted at temperatures high enough to be put to use in most applications. The critical parameter for this aspect is the marginal electrical efficiency, also known as the effective efficiency of electricity generation. This is the electricity produced divided by the extra fuel energy used compared with the generation of heat alone, as given in the following equation:

$$\eta_{marginal} = \frac{\eta_{el}}{1 - \eta_{th}/\eta_b}$$

where η_{el} and η_{th} are the CHP electric and thermal efficiencies, respectively, and η_b is the boiler efficiency. The more efficient a boiler system is for stand-alone heat production, the greater the additional fuel use by CHP compared with heating alone, and the lower the marginal electrical efficiency. For η_b, comparison is made to a condensing boiler at 92% efficiency, the current state-of-the-art. The resulting marginal electrical efficiency should be compared to new state-of-the-art combined-cycle plants using natural gas of at least 55%.

Harvey (2006a, b) provides an extensive list of CHP technologies available for use in district heating networks, including their marginal electrical efficiencies and other characteristics. For marginal electricity efficiency, the list shows that micro-turbines of 30–100 kW are the worst at about 44%, consuming more primary energy than some central generation, while combined-cycle CHP units of 20 MW and higher perform the best at about 88%.

So, to ensure that a gas CHP system achieves primary energy savings involves making comparison to appropriate alternative generators. A methodology for this is called 'good quality CHP' which has a precise definition according to the CHPQA programme operated on behalf of the UK Government (CHPQA, 2003). The EU has given some very specific values for the harmonised reference efficiencies of various fuel types. Under European Directive 2004/8/EC, the UK's CHPQA will be required to calculate the Primary Energy Savings against a 'same fuel source' (Defra, 2007; EU, 2004) in which each fuel type is given its own reasonable target. Furthermore, energy-efficiency improvements should be calculated against new efficient central power plants.

2.3. *Efficiency of natural gas district heating*

While district heating networks offer the prospect of significant energy savings for electricity production if they are combined with high-efficiency natural gas CHP, there can still be efficiency advantages to producing heat alone with district heating from natural gas (Harvey, 2006b).

Where many non-condensing boilers serve individual buildings, each boiler has a lower efficiency at part load than at full load, and most of the time the boiler is operating at only a small fraction of full load. By contrast, modern condensing boilers have constant or even higher efficiency at part load, down to 10–30% of their full load. In summer, when the only load might be for domestic hot water, the part-load penalty of the ageing non-condensing boilers will be particularly severe. By connecting the heat demand of individual buildings together with a district network and centralised multi-boiler plant, all of the boilers can be modulated and sequenced with those not needed being shut down. The annual energy savings can be 10–20%, even after distribution losses of 5–10%.

A further advantage of a district heating network could be to collect heat from scattered sources. Examples include sewage treatment works, bakeries, some manufacturing facilities and electrical transformer stations. Since the heat from these sources will usually be at a lower temperature than that at which heat is distributed by the district heat system, heat pumps will be needed to transfer heat from them to the heat distribution grid. The ratio of total heating provided to electrical input is called the coefficient of performance (COP). In Tokyo, sewage has a stable temperature of about 16 °C in February and is used as a heat source for production of hot water at 47 °C with a COP of 3.9 in one small district heating network.

Schemes can start a heat network by installing a centralised energy centre and 'energy linking' buildings, initially utilising fossil fuels (CT & EST, 2004). Once a viable heat network is established, the energy centre is fuel-flexible and can introduce renewable fuels such as biogas, woodchip and other alternative fuels.

2.4. Trigeneration, electric chillers and district cooling

Trigeneration is the simultaneous production of electricity, heat and chilled water, where some of the by-product heat from power generation drives an absorption chiller (Harvey, 2006b). This would use by-product heat during the summer months when there is no space-heating load. However, this is not necessarily the most efficient configuration, as described below. A project-specific approach to the assessment of trigeneration is necessary, together with detailed modelling. In mixed-use developments it should only be considered where there is genuine seasonal surplus heat available from the CHP prime mover alone and where there is a marginal efficiency benefit.

The COP for a chiller is the ratio of cooling provided (joules of heat removed) to energy input. Absorption chillers can be either single effect ($\mathrm{COP} = 0.7$) or double effect ($\mathrm{COP} = 1.2$). They require a minimum input temperature of about 80 °C for single effect or 120 °C for double effect. Taking one type of steam turbine as an example, for every unit of thermal energy withdrawn at 80 °C, about 0.11 units of electricity production are lost; at 120 °C, 0.185 units of electricity production are lost. From this it follows that more cooling would be achieved for a given energy input if electricity production is maximised, the low-grade by-product heat is thrown away and the extra electricity production is used in an electrical chiller. The break-even electric chiller COP is only 5.3–5.8 in this example, something that can easily be exceeded with large centrifugal chillers.

Large centrifugal chillers are more often part of a centralised district cooling system. A district cooling system consists of a network of insulated pipes carrying cold water (typically at 4–6 °C), an ice–water slurry or an alternative thermal transfer fluid (Harvey, 2006a).

Like centralised heat production, centralised chilling with electric chillers also has inherent advantages in terms of energy efficiency over on-site chilling. The efficiency gains arise from the greater efficiency of large units (easily a factor of two to three higher than small room air conditioners) and from the ability to avoid inefficient part-load operation. The central chilling plant built for Expo '98 in Lisbon reduced chilling energy use by 45% compared with meeting the same loads with chillers in each building (Harvey, 2006b).

Additional efficiency benefits for district cooling arise from the use of heat sinks that could not otherwise be used. Potential media for receiving the heat from a cooling system include sewage water, lake water or sea water, or the ground itself. District cooling networks can also be linked to large above- or below-ground cold water tanks that can be used to store chilled water, or even ice produced at nights when electricity rates are lowest (IEA DHC/CHP, 2004).

2.5. Non-fossil fuelled district heating and CHP

District heating systems lend themselves easily to alternative local fuel sources. These reduce the use of fossil fuels, in particular natural gas, and use an energy source that might not be feasible for large central generation plant, such as low-density biomass.

The use of biomass boilers for heating is an established technology. The only constraints are the availability of suitable fuel and storage space, and increased labour costs for maintenance and operation compared to conventional gas boilers (PBPower, 2006). The technology of biomass CHP using steam turbines in the 10–50 MWe (megawatts of electricity output) is well established in Scandinavia, Germany, the Netherlands and Austria. However, most UK experience has been with heat-only boilers or electricity-only production, for instance a straw-burning plant at Ely. Slough Heat and Power has, however, been using a biomass fluidised bed boiler for CHP for some years.

For waste, there are several different technologies available to generate electricity (Econnect Consulting, 2006; PBPower, 2006). The most prevalent are the combustion of raw and processed waste, landfill gas, and gas produced from the anaerobic digestion of waste. The mechanical biological waste treatment process results in a solid recovered fuel that has a high calorific value and consistent properties, and is suitable for gasification.

Anaerobic digestion is the digestion of organic wastes in the absence of air. The enclosed system results in the production of biogas. Anaerobic digestion biogas production is very well established across northern and central Europe, with biogas used for both transport and electricity production. It can be used equally easily for CHP or for the production of electricity only. It is gaining a foothold in the UK with plants such as that at Ludlow in Shropshire. It processes source-segregated household waste into biogas for electricity generation.

District heating systems designed for relatively low distribution temperatures (35–70 °C) can also make use of solar thermal energy, and lend themselves to seasonal underground storage of thermal energy collected during the summer, as in many projects in Europe and the Drake Landing Solar Community in Canada (Harvey, 2006b).

The use of geothermal energy for CHP is very dependent on local conditions. The Southampton District Energy Scheme started off using its geothermal resource, but this did not perform as had been hoped. It became a catalyst for a district heating scheme, with geothermal sources now supplying only 15% of the heat (CT & EST, 2004; IEA DHC/CHP, 2004).

2.6. Scale of district heating schemes

District heating has suffered from a poor image based on the experience of outdated technologies and systems that are 20–40 years old and have not been adequately maintained (CT & EST, 2004). But in appropriate developments, especially dense urban developments, well-configured modern systems such as those common in Scandinavia offer one of the most effective ways to reduce buildings-related carbon emissions. Up-front costs are higher than other options, but CHP often has the lowest whole-life cost.

In residential developments, the number of dwellings and the density of the development are important since demands tend to be peaky and, for new build, increasingly strict building regulations progressively diminish heating demands. The housing density for fruitful CHP integration will preferably approach 50 dwellings or more per hectare, with the CHP unit sized to run usefully for at least 5000 h/year. Greenwich Millennium Village is a good example of a high-density development where the high number of dwellings also provides some load diversity. The prime candidates for district heating will be high-rise buildings, defined as more than six storeys. For smaller developments of 100 homes or less, typical of infill projects, densities may need to be around 75 dwellings per hectare to be cost-effective.

In many urban areas, the ideal scheme would link those adjacent buildings with differing patterns of heat demand, such as adjacent schools, hospitals, student accommodation, government or local authority buildings. For example, the same energy centre can serve flats predominantly in the morning and evening, but a school during the day.

Of UK households, 20% are not on a gas network and the number of dwellings for a district energy system is less critical in off-gas grid locations where options are limited. In areas where a cohesive community exists, the best alternative to electric heating, solid fuels or oil heating would be renewables in an energy centre serving the community through a heat network. Even though such networks are unlikely to be as dense as those in urban areas, the fact that renewables are displacing electric heating, solid fuels or oil heating means this may make them attractive in cost and carbon terms.

2.7. *Local power generation*

Distinct from the power provided from CHP, a community energy system could have purely electricity generation. If capacity is sufficient, the electrical distribution system can be private wire with the option to operate as an ‘island’ separated from the national network, though there are regulatory and licensing hurdles to their development. There are 80 island energy sites in the UK of which the Woking energy system is the largest comprising four CHP systems, a fuel cell CHP system, wind turbines and the largest concentration of solar photovoltaics in the UK (Brodies LLP, 2007).

Wind resource is used extensively for electricity generation in regions of the country that have reasonable wind speeds. The characteristics of power network operation with distributed generation have been addressed and largely solved through experience with clusters of wind turbines formed into wind farms (Econnect Consulting, 2006). For a district energy scheme, the turbines used are in the range 500 kW–3 MW, local wind conditions and space permitting. These are much more effective than micro-turbines on individual buildings.

There are two main types of small-scale hydro generators: low head and medium head (Econnect Consulting, 2006). Low head small-scale hydro generators utilise the existing ‘run-of-river’ water flow, that is, they use the flow of water from existing weirs or locks using a penstock to divert the water through a turbine. Most small-scale hydro is low head. Medium head systems most usually take water from dams, again via a penstock. The amount of civil work needed is key to hydro viability. If a site has previously been used for hydro-power (e.g. an old water mill) then it is far more likely to be viable.

3. The future

Since new buildings can be built to require almost no winter heating, the trend will be to needing less heat while electricity use continues to increase, so the scope for the effective use of CHP in future high-performance buildings will decline (Harvey, 2006a).

As availability of natural gas becomes more difficult, with possible disruption to supplies, the design of district energy schemes will have to focus on renewable fuel sources in their locality. Where the source is biomass or general waste, combusting technologies will have to meet emission requirements, such as for NO_x. Furthermore design of district energy installations will need to take into consideration efficient collection of these fuels.

For electricity, there is likely to be an increasingly diverse mix of district and microgeneration technologies with the grid providing an important balancing role. Developments in power handling devices will be essential to maximise generation efficiency and network stability.

3.1. *Low-energy buildings, fuel cells and hydrogen*

Compared with typical practice in current new construction, future buildings will have a high-performance envelope (high levels of insulation, high-quality windows, minimal uncontrolled leakage and heat recovery from ventilation exhaust) (Harvey 2006a, b). Peak space-heating loads can be reduced by 50–90%. Reduced space-heating load also reduces the required distribution temperature for heating. When low-temperature heating systems are used in the house, then the whole heat distribution system can be designed to low temperatures (45–70 °C), which may have positive influence on the whole energy chain (UNEP, 2007). Reduced temperature leads to improvements in boiler or CHP efficiencies and reduces heat losses in the district heating network.

As less winter heating is needed, hot water heating loads will dominate. The annual average hot water to electricity use ratio is typically about 1.0 in US households (Braun et al., 2004). This matches the output ratio of fuel cells, which have a high electricity generation efficiency of 40–50%. Development of the high-temperature fuel cells will be particularly beneficial for district CHP applications.

District energy systems could facilitate the eventual transition to a hydrogen economy as only one or a small number of central heating and power plants will need to be converted to hydrogen fuel, rather than individual buildings. A ‘European Partnership for the Sustainable Hydrogen Economy’ has been formed to mobilise a broad range of stakeholders and structure a coherent effort on advancing sustainable hydrogen and fuel cell technologies (European Commission, 2003).

3.2. *Thermal storage and heat pumps*

Rather than aim for maximum electrical power, there are other strategies for using the thermal output.

Seasonal underground storage of heat is an effective way of storing solar thermal energy, plentiful during the summer, and using it during the winter for heating purposes (Harvey, 2006a). Solar thermal energy can be stored in underground aquifers, in subsurface rock using pipes in a series of vertical boreholes, in insulated steel or concrete tanks or in gravel–water pits with waterproof liners. Winter coldness can also be stored in underground aquifers or in subsurface rocks. Many projects have been built in Sweden, Germany and elsewhere in Europe, in which solar thermal collectors collect heat that is stored underground and used for space heating and domestic hot water purposes. Such systems are most viable economically at a scale of many buildings, connected by a district heating network.

To make use of excess wind energy, district energy heating and cooling systems can be used as a buffer where electricity generation during low demand powers heat pumps

(Harvey, 2006a). This in turn will allow wind energy systems to be sized to meet a larger fraction of total electricity demand with minimal economic penalty due to capping the power output when the wind electricity potential exceeds total demand.

3.3. SiC-based power control

Imagine a device that automatically detects demand for power and delivers processed electricity in the required form (AC or DC) at the correct voltage and frequency. Such a device, termed an 'energy router', analogous to the familiar data and communications routers, could improve reliability, efficiency and safety at every level of the electrical power system (Arnedo and Wang, 2006). Businesses, factories and homes could better use greener and more efficient energy sources and loads, such as different equipment and appliances with variable-speed motors. The power grid could employ intelligent 'energy routers' to quickly isolate problems while still providing necessary power.

A key technology for an 'energy router' would be systems based on the new semiconductor silicon carbide (SiC) that are currently being developed to operate in harsh environments or at high temperatures (Schupbach and Lostetter, 2007). SiC has one-tenth the switching losses of silicon, ten times the blocking voltage, four times the thermal conductivity and ten times the switching speeds. SiC technology also provides a junction temperature threshold in excess of 600 °C. All of these physical advantages that SiC has over current silicon technology will greatly enable increased power density, which is the chief limiting factor of today's power electronic systems. It will also significantly enhance energy efficiency, and shrink the size of power electronics systems by an order of magnitude. All of these factors will also result in cost savings.

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