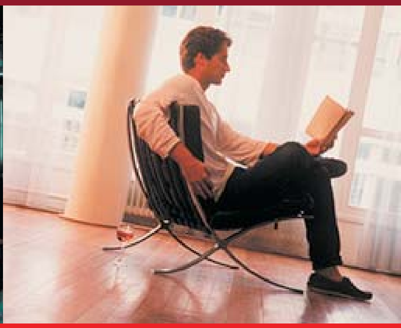
ANNEX VII | REPORT 8DHC-05.01



IEA DHC | CHP

International Energy Agency
District Heating and Cooling Project

A COMPARISON OF DISTRIBUTED CHP/DH WITH LARGE-SCALE CHP/DH

International Energy Agency
District Heating and Cooling Project Annex VII

A comparison of distributed CHP/DH with large-scale CHP/DH

Report 8DHC-05.01

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Preface

Introduction

The International Energy Agency (IEA) was established in 1974 in order to strengthen the co-operation between member countries and reduce the dependency on oil and other fossil fuels. Thirty years later, the IEA again drew attention to serious concerns about energy security, investment, the environment and energy poverty. The global situation is resulting in soaring oil and gas prices, the increasing vulnerability of energy supply routes and ever-increasing emissions of climate-destabilising carbon dioxide.

The IEA's World Energy Outlook[1] "Reference Scenario" 2004 projects that, in the absence of new government policies or accelerated deployment of new technologies, world primary energy demand will rise by 59% by 2030, with 85% of that increase from the use of coal, oil and natural gas. However, these trends are not unalterable. The World Energy Outlook "Alternative Policy Scenario" shows that more vigorous government action and accelerated deployment of new technologies could steer the world onto a markedly different energy path, where world energy demand would be 10% lower and carbon-dioxide emissions 16% lower.

DHC makes a difference

One of the key technologies that can make a difference is District Heating and Cooling.

DHC is an integrative technology that **can** make significant contributions to reducing emissions of carbon dioxide and air pollution and to increasing energy security.

The fundamental idea of DHC is simple but powerful: connect multiple thermal energy users through a piping network to environmentally optimum energy sources, such as combined heat and power (CHP), industrial waste heat and renewable energy sources such as biomass, geothermal and natural sources of heating **and** cooling.

The ability to assemble and connect thermal loads enables these environmentally optimum sources to be used in a cost-effective way, and also offers ongoing fuel flexibility. By integrating district cooling carbon-intensive electrically-based airconditioning, rapidly growing in many countries, can be displaced.

As an element of the International Energy Agency Programme, the participating countries undertake co-operative actions in energy research, development and demonstration.

One of the programmes that has run for more than 25 years is the Implementing Agreement 'District Heating and Cooling including the integration of Combined Heat and Power'.

Annex VII

In May 2002 Annex VII started.

Following is a list of the recent research projects (annexes) undertaken by the District Heating & Cooling Implementing Agreement. Ten countries participated from Europe, North America and Asia: Canada, Denmark, Finland, Germany, Korea, The Netherlands, Norway, Sweden, United Kingdom, United States.

Project title	Company	
A comparison of distributed CHP/DH with large-scale CHP/DH	**Parsons Brinckerhoff Ltd** Formerly PB Power Ltd – Energy Project leader: Paul Woods	**8DHC-05.01**

[1] The annual *World Energy Outlook* presents long-term projections for supply and demand of oil, gas, coal, renewable energy sources, nuclear power and electricity. It also assesses energy-related carbon dioxide emissions and policies designed to reduce them. The annual World Energy Outlook has long been recognized as the authoritative source for global long-term energy market analysis. This flagship publication from the IEA is produced by the agency's Economic Analysis Division with input from other internal and external energy experts as required. For more information see http://www.worldenergyoutlook.org/.

Project title	Company	
Two-step decision and optimisation model for centralised or decentralised thermal storage in DH&C	**SP Swedish National Testing and Research Institute** Project Leader: John Rune Nielsen	**8DHC-05.02**
Improvement of operational temperature differences in district heating systems	**ZW Energiteknik** Project leader: Heimo Zinko	**8DHC-05.03**
How cellular gases influence insulation properties of district heating pipes and the competitiveness of district energy	**Danish Technological Institute** Project leader: Henning D. Smidt	**8DHC-05.04**
Biofouling and microbiologically influenced corrosion in district heating networks	**Danish Technological Institute** Project Leader: Bo Højris Olesen	**8DHC-05.05**
Dynamic heat storage optimization and Demand Side Management	**Fraunhofer Institut Umwelt-, Sicherheits-, Energietechnik UMSICHT** Project leader: Michael Wigbels	**8DHC-05.06**
Strategies to manage heat losses – Technique and Economy	**MVV Energie AG Technology and Innovationsmanagement** Project leader: Frieder Schmitt	**8DHC-05.07**

Benefits of membership
Membership of this implementing agreement fosters sharing of knowledge and current best practice from many countries including those where:

DHC is already a mature industry

DHC is well established but refurbishment is a key issue

DHC is not well established.

Membership proves invaluable in enhancing the quality of support given under national programmes. Participant countries benefit through the active participation in the programme of their own consultants and research organisations. Each of the projects is supported by a team of experts, one from each participant country. As well as the final research reports, other benefits include the cross-fertilisation of ideas which has resulted not only in shared knowledge but also opportunities for further collaboration.

New member countries are very welcome – please simply contact us (see below) to discuss.

Information
General information about the IEA Programme District Heating and Cooling, including the integration of CHP can be obtained from our website www.iea-dhc.org or from:

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The project team have greatly benefited from the advice and support of the Experts Group whose members were:

Lars Gullev, Denmark

Robin Wiltshire, UK

Øyvind Nilsen, Norway

Matti Nuutila, Finland

Summary

District Heating and Combined Heat and Power are now mature and well-established technologies. They are technologies that can deliver lower energy costs, improvements in local air quality and a reduction in CO_2 emissions, which will help limit global warming. CHP systems can be implemented at a wide range of scales from city-wide by means of District Heating to individual buildings.

In a desire to improve energy efficiency and reduce dependence on imported oil, many countries looked first to see where energy was being wasted. This led to the use of heat from power stations that would otherwise be rejected to atmosphere. A ‘Scandinavian model’ became established where large District Heating networks supplied whole cities with the majority of heat supplied from major power stations.

In the 1980s small-scale CHP units were developed using spark-ignition gas-engines, and these were installed in individual buildings such as hotels and leisure centres. Small gas turbines were also used in larger building complexes such as hospitals. In recent years, developments in CHP have been directed to producing micro-CHP units suitable for individual dwellings based on the Stirling engine and including the possibility of using fuel cells.

Between these two extremes there is a continuum of CHP/DH scales of development. Gas-engines are now being produced at larger sizes up to 8MWe capacity so that, with multiple units, large District Heating networks can be supplied. In addition, the Combined Cycle Gas Turbine technology is being introduced at progressively smaller scales with a number of designs offered in the 30MWe to 70MWe range.

Energy planners are now faced with such a range of CHP/DH options that there is interest in establishing what scale of CHP/DH would be preferred both with respect to environmental benefits and in terms of overall cost. This report attempts to compare CHP/DH systems at different scales using data from a generic city. The data were derived from averaging three UK cities and the generic city has the following characteristics:

Table i Characteristics of the ‘Average City’

Population	350,900
Heat demand (MWh p.a.)	2,500,609
Electricity demand (MWh p.a.)	1,936,653
Land area (km^2)	91.1
Heat density[2] in inner city (MWh/km^2)	94
Heat density in outer city (MWh/km^2)	28

Although there is a continuum of possible CHP/DH systems and a range of fuels, comparisons were made between 4 distinct types, all using natural gas as the fuel:

A – a City-wide DH system supplied by a large CCGT power station at the city edge

B – 10 separate District level DH systems supplied by smaller CCGT power plants

C – 50 Local DH systems supplied from spark-ignition gas-engine CHP

D – individual Building CHP systems using spark-ignition gas-engines and Stirling engines for individual houses (100,208 units in total)

[2] Heat density is defined for a sector as the total estimated annual delivered heat energy demand divided by its land area

These 4 CHP/DH systems were compared to the alternative of separate heat and power production using two criteria: Net Present Value of the energy system at a discount rate of 3.5% over 25 years and the CO_2 emissions generated.

The work involved the setting up of models to determine the operation of CHP plant at the different scales to meet the energy demands of the city, using peak boilers and imports or exports from a national electricity grid as required. It was also necessary to estimate the cost of installing District Heating at each level of scheme and cost correlations with heat density were developed.

The base case results are presented in the graphs below.

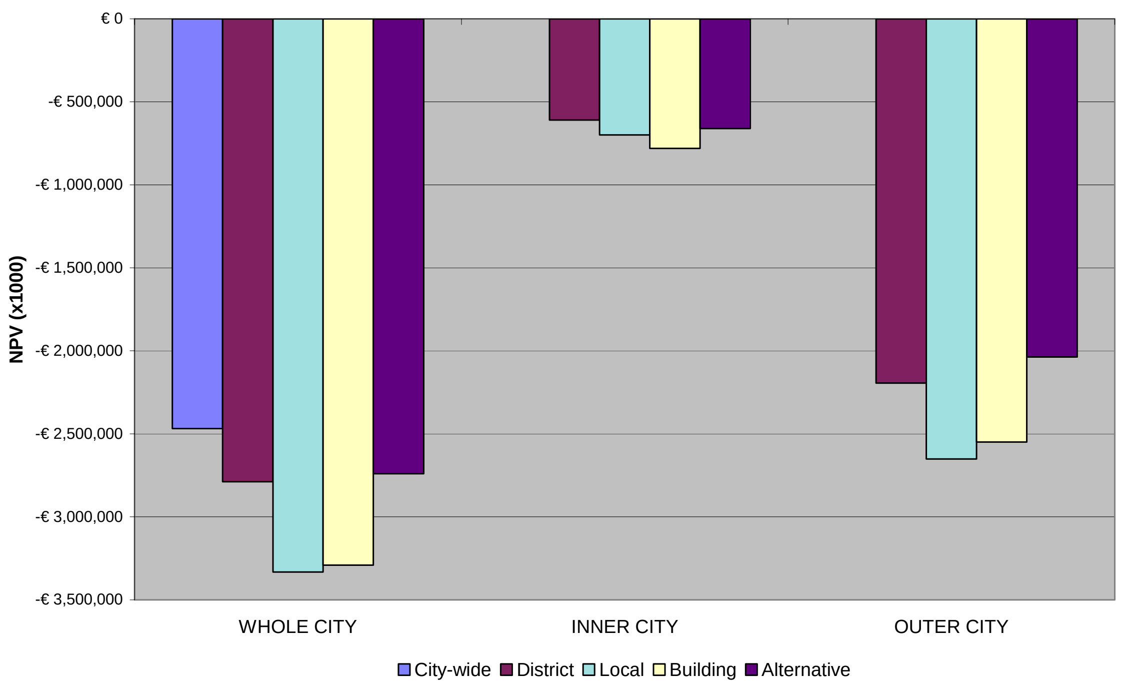

Figure i Comparison of scenario Net Present Values

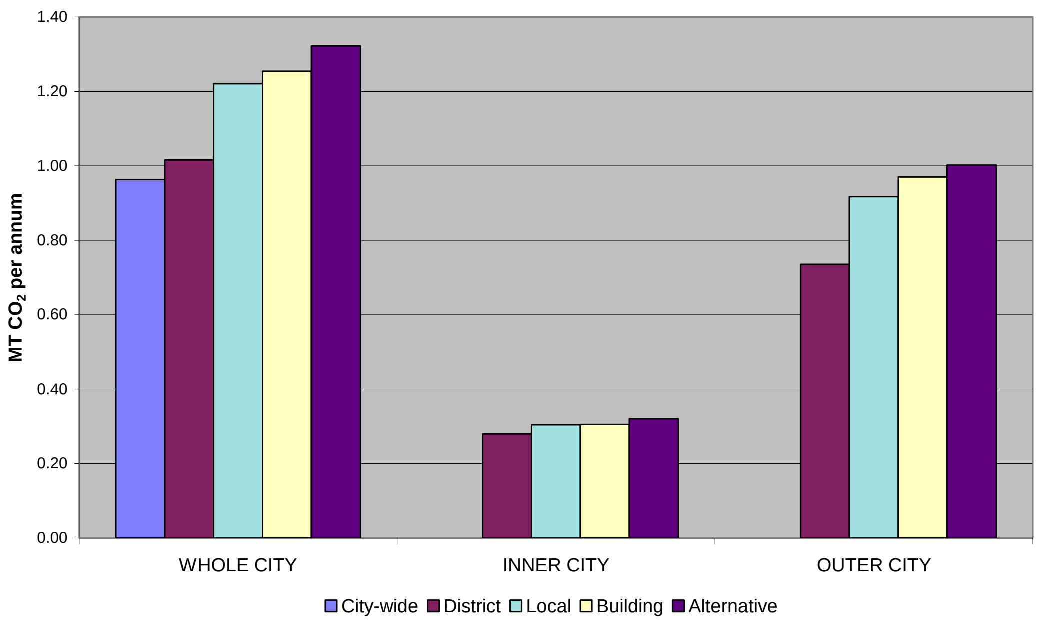

Figure ii Comparison of scenario Carbon Dioxide Emissions

The NPV represents the total cost of supplying heat and electricity to the city over a 32 year period. The comparison shows that in the whole city case the only economically viable CHP system is the City-wide scenario. In the inner city the District level CHP would be viable but in the outer city none of the CHP systems are economic. These conclusions apply even at the low discount rate used of 3.5% (UK Treasury guidance for public sector purchasing). The City-wide CHP/DH system benefits from a high efficiency, low capital cost, CCGT power plant which more than offsets the additional costs of city-wide heat distribution.

The environmental comparison also shows a clear advantage in moving to the CCGT plant at District or City-wide scale, particularly when compared to the Buildings CHP systems. This is because the CCGT is much more efficient in producing electricity than the smaller units even though electricity and heat distribution losses are higher. Even if all of the buildings were fitted with CHP systems the overall CO_2 reduction would be only 5% compared to a 27% reduction for the City-wide scheme

A further advantage of the larger-scale DH systems is the ability to obtain heat from other sources including waste to energy plants and industry. However, an estimate of the waste generated within the city shows that this would only marginally contribute to meeting the total energy demand.

In the future, the conclusions could change with the advent of fuel cells as, in addition to the low emissions, they offer the prospect of higher electrical efficiencies. At present though, costs and lifetime are still significant barriers.

It is unlikely that in any city only one solution would be implemented. For example in the higher density inner city area District or Local CHP with DH may predominate and Building CHP could be introduced in the outer city lower density areas. It is unlikely that a city-wide CHP/DH system would be developed without strong regulation or legislation in view of the long time scale and the marketing uncertainty for the DH developer. This report does however indicate that the benefits are greater when moving towards this goal and that the overall economic case for city-wide DH is still strong. A good opportunity would be where there is an existing power station close to the city that can progressively supply heat as the DH scheme expands. The report indicates that in planning new power stations choosing a location near the edge of a large city could result in major environmental benefits in the future.

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List of abbreviations

CHP	Combined Heat and Power
CCGT	Combined Cycle Gas Turbine
CBD	Central Business District
CO_2	Carbon dioxide
DH	District Heating
dCHP	Domestic Combined Heat and Power
EfW	Energy from Waste
GCV	Gross calorific value
GT	Gas Turbine
HRSG	Heat recovery steam generator
km	Kilometre
kW	kilowatt
kWh	Kilowatt-hour
m	metre
NCV	Net calorific value
NOx	Nitrous oxide
NPV	Net present value
MW	Megawatt
SIGE	Spark Ignition Gas Engine
ST	Steam Turbine

1 Introduction

Parsons Brinckerhoff Ltd (PB) have been appointed by NOVEM the operating agents for the IEA District Heating and Cooling project to lead a study to compare the benefits of large-scale Combined Heat and Power (CHP) and District Heating (DH) systems with smaller-scale or distributed systems. To carry out the study, PB formed a team with the following sub-consultants:

- Ramboll from Denmark
- VTT from Finland
- W-E from The Netherlands
- University of Sussex from the UK

In addition, although not contracted to PB, Canmet of Canada have provided information and comments on the study.

The Call for Proposals against which the contract has been placed set the project brief as follows:

" Recent years have seen changes in design and manufacturing technology that promise to reduce the costs of small scale CHP equipment. Accordingly, it may become more cost effective to consider distributed smaller scale plants with smaller dimensioned distribution lines than continued use of large central plants. A report is required based on state of the art equipment that demonstrates the circumstances under which small-dimensioned piping systems served by distributed sources might be more cost effective than the current large central system model. The report should also examine issues of flexibility, reliability and secondary effects such as the impact on distribution grids (electricity, gas and thermal) and operational convenience and cost. It is also clear that new control needs will emerge. The report should consider controls and the possibilities of load management through central control or artificial intelligence approaches that may permit automated response to changes in load."

In response to this Call the following sections summarise the background, basis and objectives of the study.

In countries where CHP and District Heating has not been widely developed, there is often no clear view as to the type of CHP projects that will be developed. In the UK the Government target is for a further 5,000MWe CHP capacity by 2010. Whilst much of this development may be in industry, some 1,000-1,500MWe is expected to be in the buildings sector. Two future models of CHP/DH development can be identified:

- Firstly, the traditional, large-scale CHP/DH model, where heat is extracted from major power stations and supplied to a large-scale District-heating network. Typically the DH network is developed over time with heat only boilers used in the early years. Often the CHP station is some distance from the city and a transmission pipeline is required. To develop a DH network on this scale requires a strategic commitment to the DH concept and frequently requires some form of Government regulation or legislation. This approach has been seen in Scandinavia, Eastern Europe and South Korea. Future expansions of these schemes into lower density areas is seen as the next stage in development as well as obtaining maximum market penetration in established areas.
- Secondly, the distributed CHP/DH model involves a much larger number of smaller CHP plants, typically below 20MWe, linked to localised heat networks. The CHP plants are likely to be fuelled by natural gas or use renewable fuels and will be installed progressively from the start of the scheme often with multiple CHP units. They will generally be operated to follow the heat demand and use a thermal store to maximise the heat utilisation from the plant and target power generation at times of the day when electricity has the greatest value. A key factor in the economics of such schemes is the price that can be obtained for the relatively small quantity of electricity produced at each site. A host site may be found for the CHP plant so that some electricity can be sold directly to an electricity customer. As the heat networks are smaller, the operating temperatures and pressures are usually lower enabling direct connection and plastic DH pipes to be used. This model has been seen in recent years in smaller communities in Denmark, the UK and the Netherlands.

The aim of this study will be to review these two models with respect to economic worth, environmental benefits and other impacts. However, two further approaches have also been identified.

There is increasing interest in the use of CHP installed in individual buildings and this approach is a potential alternative to both of the CHP/DH models described above. There have been many CHP projects at sites such as hotels, leisure centres and hospitals and new technologies such as fuel cells, micro-turbines and Stirling engines are being developed to extend the market for such CHP installations even down to the individual household level. The study would therefore be incomplete if it did not take account of these recent developments.

A further CHP/DH model could be considered as an intermediate position between the large-scale and the distributed where Combined Cycle Gas Turbine (CCGT) power plants of the range 30MW to 100MW are installed to supply District Heating schemes. The advantages of high electrical efficiency and lower maintenance costs may be sufficient to offset the higher capital cost.

Hence, the range of possible applications of CHP for buildings covers a continuous spectrum from individual households to whole cities. This research study attempts to assess the best strategy for CHP and buildings and provides key information for energy planners relevant to many member countries.

This report considers CHP with District Heating; it was decided at the scoping stage not to include District Cooling in the core analysis. The consequence of this was to improve the practicality of the complex modelling required to achieve the study's objectives, and also to maximise the probability of being able to visualise key relationships underlying the results in the outcome. In most climates of IEA member countries the provision of heating is currently more important for most buildings and is likely to be the governing economic factor in the energy supply scenario, but it is acknowledged however that global demand for cooling is significant, and growing. Taken into the analysis, the potential demand for cooling could in some countries significantly alter the energy supply scenario from that considered here, particularly if electricity production and distribution networks become strained due to increasing use of electric chilling. Further analysis to investigate the impact of District Cooling is an important and necessary follow-up to this study.

It should be noted that the IEA project scope issued in the Call for Proposals identifies two other areas which have not been covered in this report:

- the impact on gas and electricity networks of distributed CHP/DH. Whilst mention of these issues is made in the report these are potentially important aspects and require further separate research.
- the issue of the need for improved controls and possible solutions using Artificial Intelligence which is considered to be the subject of a separate detailed study.

2 Experience from European Countries

Scale of CHP/DH Developments in Europe
Large-scale CHP/DH schemes have been developed in northern and eastern Europe since the 1960's, examples being the schemes in Copenhagen, Helsinki and Berlin. The large-scale model has typically been progressed through the following stages of development:

- establish local District Heating schemes based on heat only boilers
- extend these schemes by market development
- when of sufficient size connect to a large CHP station either an existing power station or purpose-built (in excess of say 50MWe)
- develop newer areas either by extension of the main network or by new heat only boiler schemes (including reuse of temporary boilers)
- incorporate other heat sources as available e.g. waste incineration, industrial waste heat
- in large conurbations, develop further transmission mains linking major DH networks together to optimise use of several heat sources

Small-scale CHP/DH schemes have been developed over the last 20 years, mainly where natural gas is available. These are typically supplied by CHP plant in the range 300kW to 10MW. Applications are usually either:

- for smaller communities in countries where the concept of District Heating has already been established in cities or
- to supply a specific group of buildings such as a public authority owned housing estate, a university campus or a hospital

The members of the project team have provided a more detailed description of the developments of CHP/DH systems in their countries. The following section summarises this work with the details provided in Appendices.

Finland
Finland has developed District Heating on a wide scale in its major towns and cities. The general pattern has been use of temporary heat only boilers to build up the heat network followed by connection to a major power station. The lack of indigenous fuels and the need to reduce oil imports have been the major drivers. Recently the use of biomass fuels in connection with the forestry industry, the use of incineration plant and the utilisation of energy from waste (EfW) for CHP systems has become more established. With the increased availability of natural gas, a large-scale 430MWe Combined Cycle Gas Turbine CHP plant has recently been built to supply the Helsinki DH system; this plant forms the basis for our modelling of the large-scale CHP/DH systems. Further details of Finland's experience are given in Appendix A.

Denmark
Denmark has a long history of District Heating development using CHP as a heat source. The need to reduce imports of oil after the oil price rises in the 1970s was a big driver. More recently, as natural gas became more widespread, small-scale systems have been introduced in Denmark to supply smaller towns and villages and some of these have incorporated renewable and waste fuels such as straw burning. Further details of Denmark's experience are given in Appendix B.

The Netherlands
The Netherlands has had the benefit of its own natural gas fields and although some CHP systems were installed in the 1970s it is only recently that CHP systems have been introduced more widely. This has been largely driven by the need to improve the environment rather than for economic reasons. The planning of energy supplies is considered at an early stage in the development of new housing districts. As a result, the scale of CHP systems will be determined by an analysis of the costs and benefits of each technology on a case-by-case basis. The tools developed for the typical analysis in the Netherlands have been used in this project. Further details of the Netherlands' experience are given in Appendix C.

UK

Less than 1% of buildings in the UK are supplied from DH, most of these being built in the 1970's with heat supplied from boilers; a small proportion of the country's electricity is met by CHP (6%), most of which is in industry. The CHP/DH schemes that exist are based either on waste to energy plants or on smaller scale gas-fired CHP systems. Although larger-scale CHP systems were investigated in the late 1970s and early 1980s, only a few major schemes were constructed, such as those at Sheffield, Nottingham and Southampton. Renewed interest in the technology has emerged in the last few years as the environmental impact of fossil fuel combustion has become more widely acknowledged. Future planning policies and regulations on new building design will encourage the use of CHP and renewable energy. There is significant interest in developing District Heating schemes for new-build areas and for the existing high-density inner city residential areas. The Community Energy Programme has provided £43m of development and capital funding to a number of CHP, District Heating and/or cooling projects since 2001 resulting in 44MWe of new CHP capacity. Further details of UK's experience are given in Appendix D. In other applications, buildings are more likely to be supplied from dedicated CHP installations. There is considerable activity in the development of domestic CHP units (for single dwellings) and significant government and private industry research funds have been directed in this area using both Stirling engines and fuel cells.

3 Factors Influencing CHP/DH Developments and Overall Methodology for the Study

As discussed in the Introduction there is potentially a continuum of scales of CHP/DH developments extending from CHP systems designed for individual buildings and even individual dwellings at 750We up to large-scale power stations of 1000MWe. Clearly to analyse a complete range of schemes would be very complex and time consuming. The approach taken is to identify scales of development where there will be a distinct step change in technology that may therefore result in a distinct advantage or disadvantage. The scales of development that will be analysed are defined as follows:

Type A - City-wide District Heating

In this scheme a single DH network extends across the whole city and the heat demand is supplied by a single large power station. This is assumed to be a high efficiency Combined Cycle Gas Turbine (CCGT) plant operating continuously with an extraction-condensing steam turbine to supply heat. The heat distribution network can be considered in three parts: **Local** mains supplying buildings, **District** mains interconnecting the Local node points and a **transmission** main connecting the District level nodes to the CHP station. The CCGT will typically be of the order of 500MWe. It is assumed that heat-only boilers for top-up and standby are installed at the Local network level.

Type B - District Level CHP/DH.

In this scheme the CCGT plant is assumed to be smaller and at the lower limit at which such plant is currently marketed. The **District** and **Local** level heat networks exist but there is no need for the transmission main. Several large networks exist within the city, each supplying heat to a particular district of the city from a CCGT CHP plant typically in the range 30MWe to 100MWe.

Type C - Local level CHP/DH.

In this scheme the spark-ignition gas engine (SIGE) type of CHP plant is used to supply the **Local** DH network. The District level heat mains are not required. The typical CHP size is assumed to be 1MWe to 30MWe (with multiple units), which is generally above the size that would be described as packaged CHP units.

Type D - Building CHP

In this scheme each building has its own CHP unit and there are no DH networks. Individual dwellings will have a domestic CHP unit but apartment blocks and non-domestic buildings will have a small SIGE or a micro turbine. Typical CHP unit sizes range from 750We to 1MWe.

There is the potential for some overlap between these schemes however they are sufficiently different to justify their separate analysis. Finally, as a comparator, there is the production of heat and power from separate facilities:

Alternative – Separate Heat and Power

In this scheme heat is produced by boilers in each building and power is generated at a large-scale CCGT power station at the boundary of the city. The fuel in both of these scenarios is considered to be natural gas.

The comparisons of the cost and environmental impact of each type or scale of CHP/DH scheme needs to take into account a number of factors:

- CHP electrical efficiency
- CHP overall energy efficiency
- CHP capital cost
- CHP maintenance cost
- Peak/standby boiler capital cost
- Peak/standby boiler efficiency
- Value of electricity

- Cost of fuel
- Capital cost of DH network
- Market penetration
- Heat losses from DH network
- Pumping energy for DH network
- Operation and maintenance of DH network
- Cost of consumer connections
- Electrical network losses
- Environmental constraints and costs
- Administration and management
- Potential for renewable and waste fuels
- Marketing and implementation
- Gas network costs within the area
- Electricity network costs within the area

These factors were initially considered on a qualitative basis as defined in the matrix of factors given as Table 3-1. Most of these factors were amenable to a quantitative treatment, the few that were not are discussed in section 10.

The methodology for modelling the five schemes for energy supply involves three elements:

- Defining a generic city and assessing its energy demands so that the various scales of CHP/DH scheme can be costed and analysed
- Identifying the CHP and boiler plant for each type of CHP/DH development, estimating the capital cost and modelling its outputs over the year
- Defining the heat mains networks and customer connections required for each type and estimating the capital cost, heat losses and pumping energy needed

These three elements are the subject of the next three sections.

Table 3-1 Matrix of factors which influence CHP/DH Systems

	City-wide CHP/DH	District CHP/DH	Local CHP/DH	Building CHP	Notes
Type	A	B	C	D	
Min CHP capacity (electrical output)	100MW	30MW	1MW	750W	indication only
Max CHP capacity (electrical output)	500MW	100MW	30MW	1MW	indication only
CHP CAPEX / kW installed	low	medium	medium	high	indication only
CHP electrical efficiency (%)	48-58	44-48	33-42	10-33	
CHP total efficiency (%)	80-85	80-85	80-85	75-90	
CHP maintenance	low	low	medium	high	
CHP staffing	low	medium	low	low	
CHP/boiler fuel price	low	low	medium	high	
CHP utilisation (proportion of total heat)	medium	medium	medium	high	depends on storage and diversity
Peak/standby boilers	medium	medium	medium	low or nil if existing retained, or dCHP	
Peak/standby boiler efficiency (%)	80	80	80	84	
DH Network capex	high	medium	low	nil	depends on diversity assumptions
DH technology	Higher pressures/temps	Higher pressures/temps	Low temps/press PEX pipe	none	
DH network heat losses and pumping	high	medium	low	nil	
DH network operation and maintenance (relative to extent of DH mains)	medium	medium	high	nil	
DH admin (relative to extent of DH mains)	medium	medium	high	nil	
Consumer connections capex	medium	medium	low	nil	pressures/temps influence
Electricity network impact	low	low	medium	medium	fault levels, reinforcement
Electricity network losses	high	medium	low	low	
Gas network impact	high	med	medium	high	
Local environmental impact e.g. NOx, noise	low	low	high	medium	larger plants can afford mitigation
Implementation and marketing	needs regulation	needs regulation	needs group action	single customer decision	
Build-up period	long	long	medium	short	
Potential for renewables	high	medium	low	low	
Security of supply for electricity	low	low	medium	high	
Security of supply for heat	high	high	medium	medium	

4 Modelling the Energy Demands of a Generic City

The 'Average City'

To carry out the analysis of the energy flows for each type of CHP scheme a generic city has been defined. This generic city is intended to be representative of cities of developed countries, however as data was most readily available for the UK from previous studies the city characteristics have been derived from an average of three UK cities. To determine what size and type of UK city would be most representative of an international average, the population data of the largest 500 cities in Europe was assembled and studied. This data is represented as a frequency distribution histogram in Figure 4-A. It can be seen that the majority of cities have a population of between 150,000 and 600,000 people, with relatively few metropolises exceeding this size. For this reason it was decided that very large cities such as London (population circa 7 million) and Birmingham (population circa 1 million) were atypical and would not be suitable for the base data of the study. Three cities were selected to form the basis of the study which, as well as falling in the desired size range, were familiar to members of the project team:

- Leicester (population 279,900 in 2001)
- Newcastle (population 259,600 in 2001)
- Sheffield (population 513,200 in 2001)

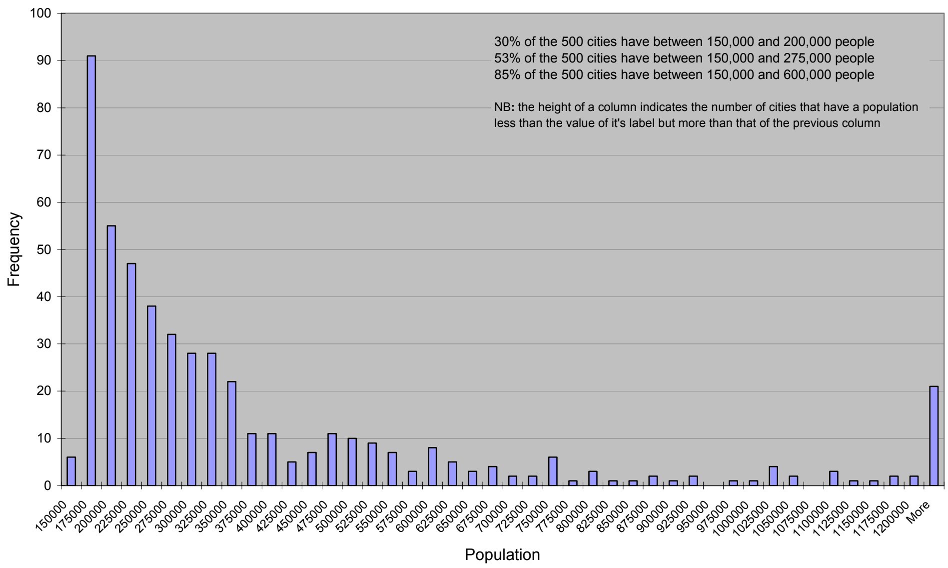

Figure 4-A Population frequency distribution of the 500 largest cities in Europe

Database by postcode

Previous work carried out in the UK to assess the potential for CHP/DH had created a database of information on buildings [1]. The basis for the residential sector of the model is the 2001 UK population census. Non-domestic floor space data was obtained from records used to determine local authority business taxation. The data has been assembled as a set of totals for each 'postcode sector' - a discrete area of land typically 0.5 to 4 square kilometres denoted by a unique alphanumeric code, originally defined for the postal service. The following information was available from the database for each postcode sector within each city:

1. Sector land area (km^2)

2. Number of dwellings: sub-divided by tenure type (i.e. detached, semi-detached, terraced, purpose built flats etc.)

3. Quantities of non-domestic buildings: sub-divided into categories and measured by floor area (prisons, factories, commercial offices, local government offices, retail, industrial, hotels), number of beds (hospitals) or number of pupils (universities and schools).

A sample of the database for the postcodes LE3 9 and LE4 0, areas of the suburbs of Leicester, is given in Table 4-1.

Table 4-1 Sample UK Census data

Postcode Sector	AREA (km^2)	Hospitals 1998 (No. of Beds)	Factories (m^2)	Commercial Offices (m^2)	Secondary and Middle Schools (no. pupils)	Detached houses: number of dwellings	Semi-detached houses: number of dwellings	Purpose Built Flats: number of dwellings
LE3 9	4.43	120	10970	1453	0	256	2087	631
LE4 0	3.09	0	107153	7863	2790	462	2228	1210

The postcode sectors do not align exactly with city boundaries and at the margins of the city it was necessary to select only those postcode sectors where it was judged that there was a significant density of dwellings or commercial development. Only the postcode sectors that were considered actually part of the 3 cities (132 sectors in total) were included in the analysis.

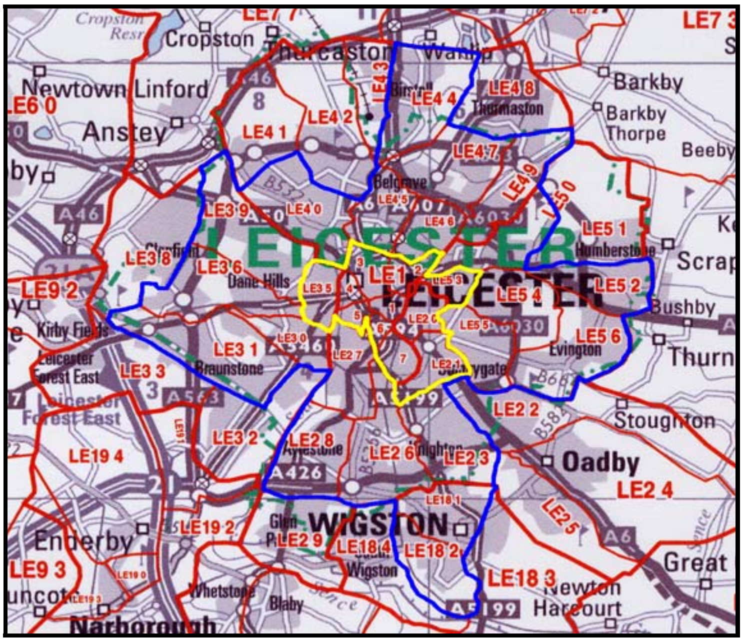

Figure 4-B City and inner city postcode boundaries as defined for Leicester

Further, it is important to recognise that a city is not homogeneous: the type of building, population density and energy demand profiles vary geographically. In general, the major differences can be found in a central area, known as the central business district (or CBD) or inner city, which is distinct from the rest of a city. Certain postcodes within the each city were identified as constituting the inner city on the basis of geographical location, type of building and knowledge of the layout of the city.

Energy consumption benchmarks

In order to estimate energy demands from this data, typical annual gas (for space heating and hot water) and electricity (for appliances and lighting) consumption figures were defined for each dwelling or building type identified above. Such figures are published in the UK by advisory bodies such as the Building Research Establishment (BRE) and the Chartered Institution of Building Services Engineers (CIBSE). They were manipulated into benchmarks giving energy consumption per dwelling (domestic properties), or per square metre of floor space (non-domestic consumers), per bed (hospitals) or per pupil (schools). The complete set of benchmarks used is listed in Appendix G. By applying these benchmarks to the statistical data, the total domestic and non-domestic energy consumption of each postcode sector was estimated. This data was consolidated to form the energy demand for the notional average city.

Heat demand profiles
In order to model CHP and DH schemes it is necessary to consider heat demand variations both seasonally and over the day. A given building will not have a constant heat demand, but one that varies according to the time of day, creating a unique daily demand profile. For example, the heat demand profile that might be exhibited by an average dwelling in a block of communal housing on a given day is represented in the plot below. This instance assumes that the dwelling has time control and heat meters.

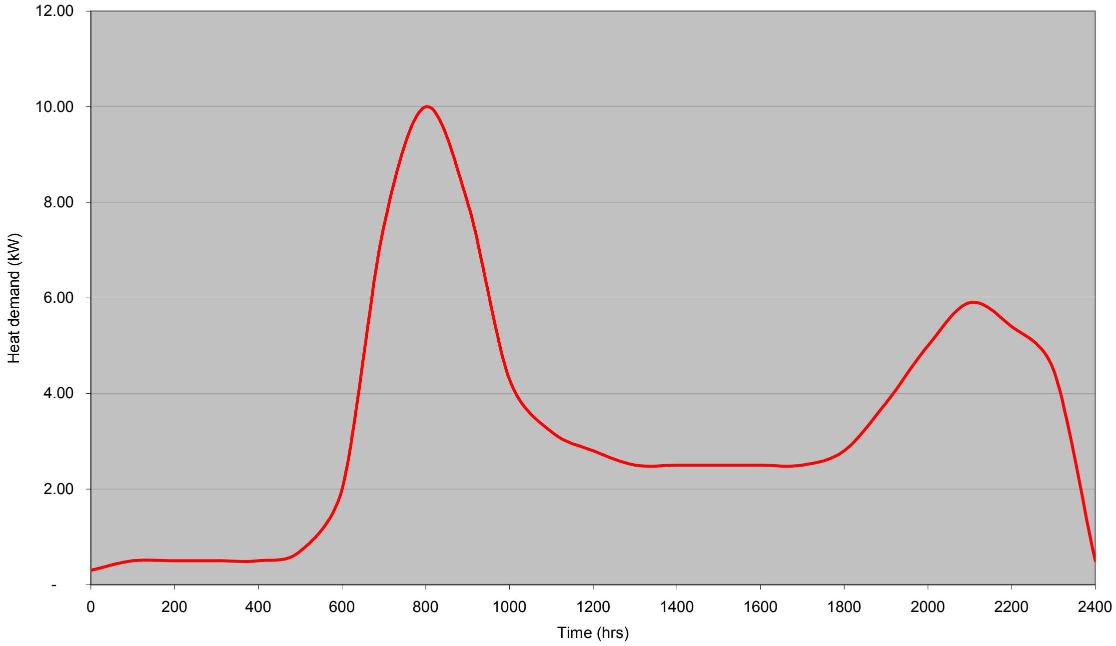

Figure 4-C Example notional daily heat demand profile for a family dwelling in communal housing

In the example given in Figure 4-C there is a clear heat demand peak in the morning, as the homes are heated and hot water is required for washing. During the daytime hours the majority of the houses are empty and the demand falls until occupants return from work, when a second peak is seen.

A generic daily heat demand profile was generated to represent each building type: the shapes of these profiles were based on predicted operating hours and heating patterns, and previous experience. The heat demand of a building not only varies according to the time of day but also to the time of year: it is directly related to the ambient temperature. Historical records of seasonal variation in ambient temperature are available for many locations in the UK, presented as monthly heating degree day totals. Degree days are a measure of accumulated temperature difference during a given month: one degree day is registered when the outside air temperature falls one degree below a reference temperature (15.5˚C is used as standard) for one day. Thus the number of degree days accumulated in a month indicate the severity of the heating season, and can be interpreted as a measure of the amount of heating energy required in that month to maintain a constant temperature in a given building. The degree-day curves for the three cities are shown below.

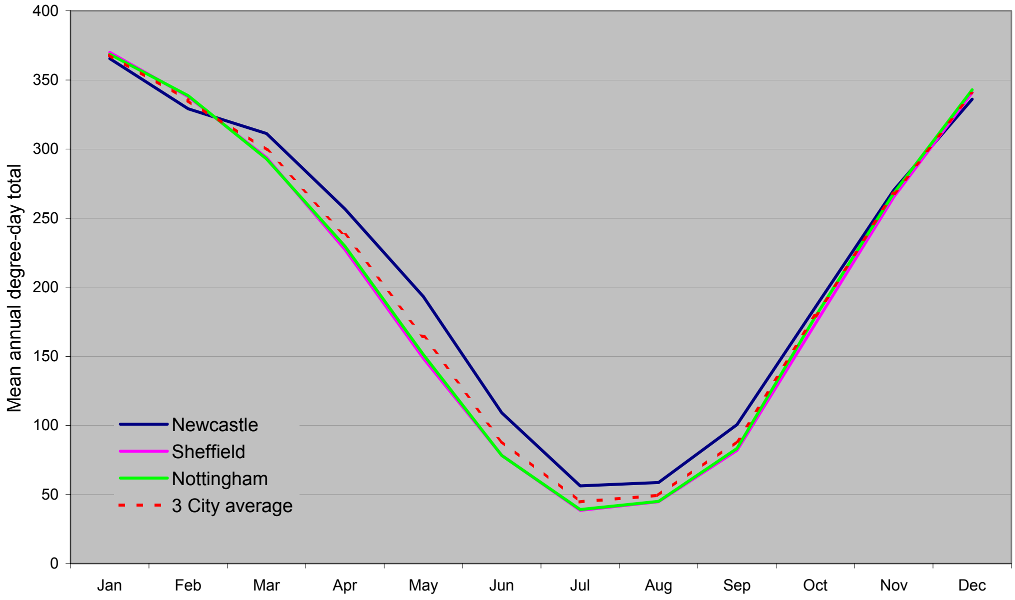

Figure 4-D Mean annual heating degree days (15.5C base temperature)

Combining the daily heat demand profile of a building with the seasonal variation in heating energy produced a profile with hourly variation for each weekday and weekend, with an applied seasonal variation, an example of which is given below for a typical dwelling.

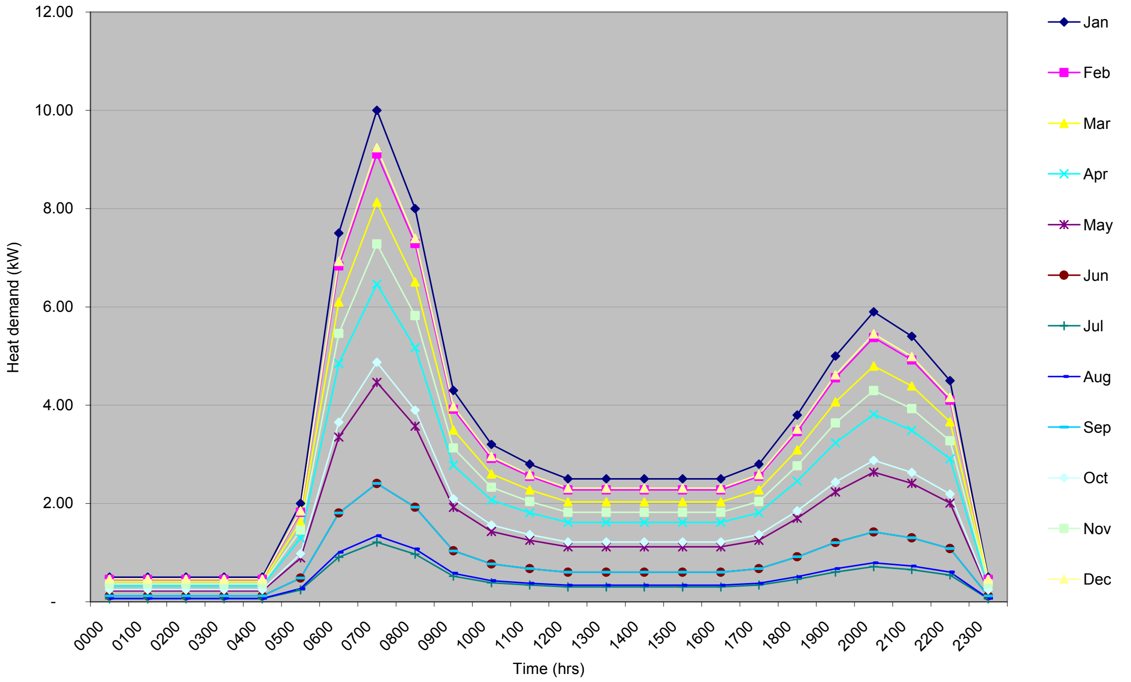

Figure 4-E – Example annual heat demand profile for an average dwelling

A unique heat daily demand profile was estimated for each building type. In order to assess the heat demand of the whole city, these heat demand profiles were combined with the previously derived breakdown of heat demand data for the city. Thus a combined profile of the overall heat load was assembled for the whole city, presented in Figure 4-F.

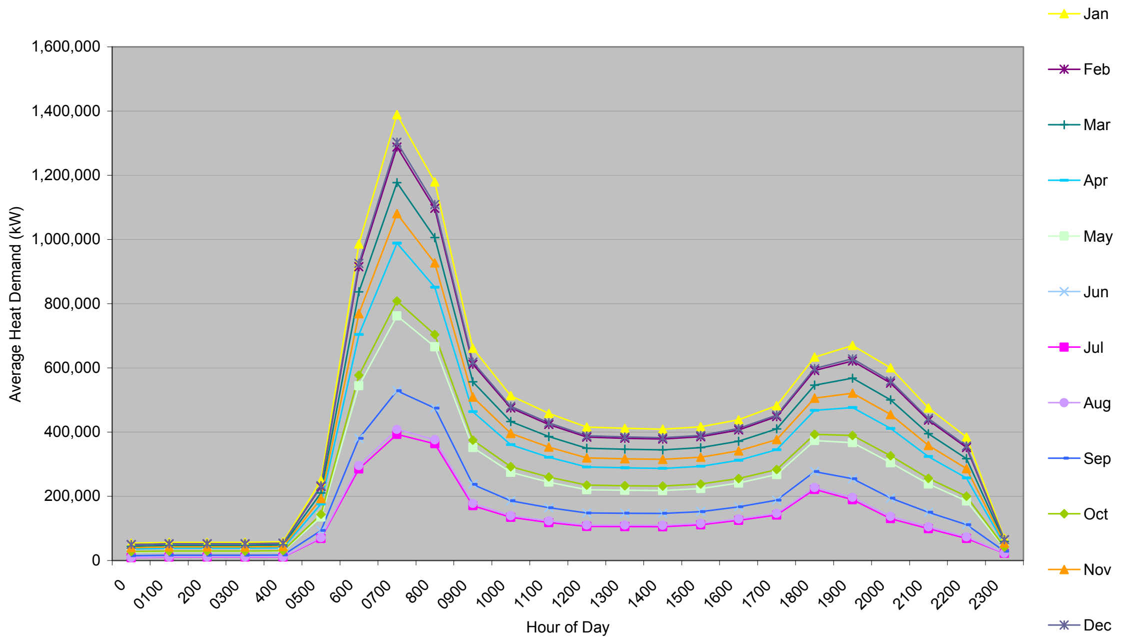

Figure 4-F Undiversified theoretical Whole city heat load profile

Electricity demand profile
The total annual electricity demand for each postcode sector was estimated using benchmark data. Discrete electricity demand profiles are not as important to forecast as heat demand profiles, because a national grid distribution system allows transfer of electricity in and out of the city. To create a notional overall profile for the city, the shape of an average overall UK electrical demand profile was matched to the derived annual consumption data. A degree of seasonal variation was applied to the profile to account for the higher proportion of electricity used in lighting in winter. In some climates electrical demand for air conditioning can be significant in summer.

City energy demand summary
A summary of the derived energy demand for the city is presented in Figure 4-G. It shows that although the inner city consumes less heat than the outer city, due to its smaller area, the proportion of non-domestic consumption is considerably higher. The higher consumption of electricity in the central business district causes the inner city peak electrical demand to be relatively high.

	Total heat demand (GWh p.a.)	Total elec demand (GWh p.a.)
Whole city	2,501	1,896
Inner city	451	549
Outer city	2,050	1,336

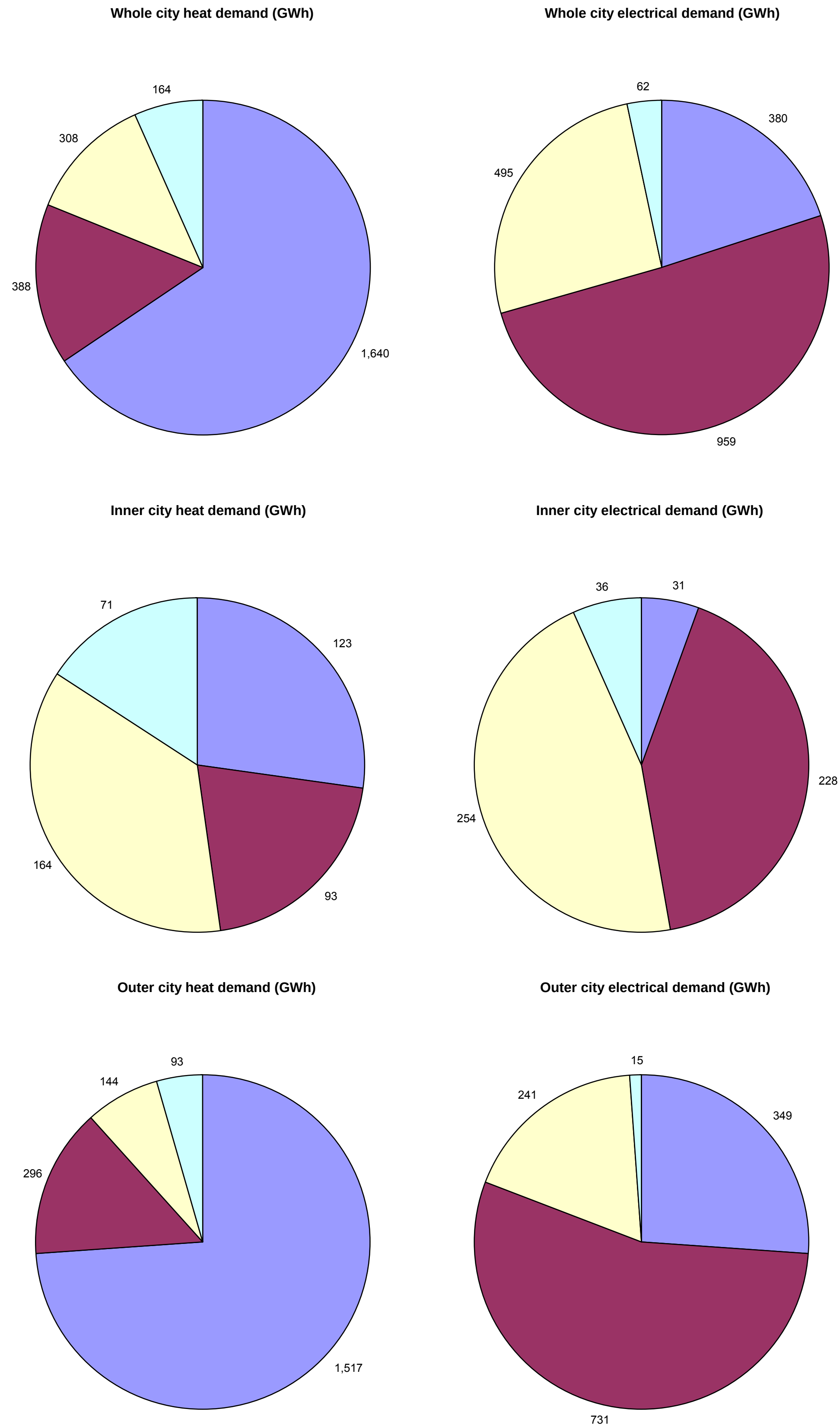

Figure 4-G Energy demand variation in average city

5 Supplying the Energy Demands of a Generic City

CHP Technologies
As discussed in section 3, the CHP technologies selected define the main schemes to be analysed:

Type A the City-wide scheme is defined as a large-scale CCGT and the modelling is based on the information provided by VTT on the new CCGT CHP plant recently constructed in Finland (see Appendix A).

Type B – the smaller CCGT plant is typically around 60MWe. Two gas turbine options are appropriately sized: the Siemens GTX100 and the GE LM6000. Both can be used in a small-scale CCGT plant.

Type C is a spark-ignition gas-engine (SIGE) CHP plant and there are number of suppliers depending on the size considered (e.g. Jenbacher, Caterpillar, Waukesha, Rolls Royce and Wartsila). The modelling is based on mid range values from these suppliers.

Type D is the Building CHP and here there are a number of issues. For larger buildings the packaged SIGE CHP units are well-established technology however micro-turbines are also a possible contender. For domestic CHP the Stirling engine is currently being offered in the market but in the future, fuel cells may become available. The University of Sussex carried out a review of available and future technologies and their report is given in Appendix E. For the purposes of the modelling we have assumed a Stirling engine CHP for domestic properties and a packaged SIGE for the larger buildings.

Alternative – the non-CHP option assumes individual gas-fired boilers at average seasonal efficiencies of 86% and power imported to the city derived from large-scale CCGT plant.

The assumptions used for the CHP plant are given in Appendix F.

Diversity on heat demand
The combined city load profiles discussed in section 4 are summations of the individual load profiles of all the consumers in the area (be it the whole city, inner or outer areas). The figure below shows for example the un-manipulated theoretical heat load profile for the inner city area.

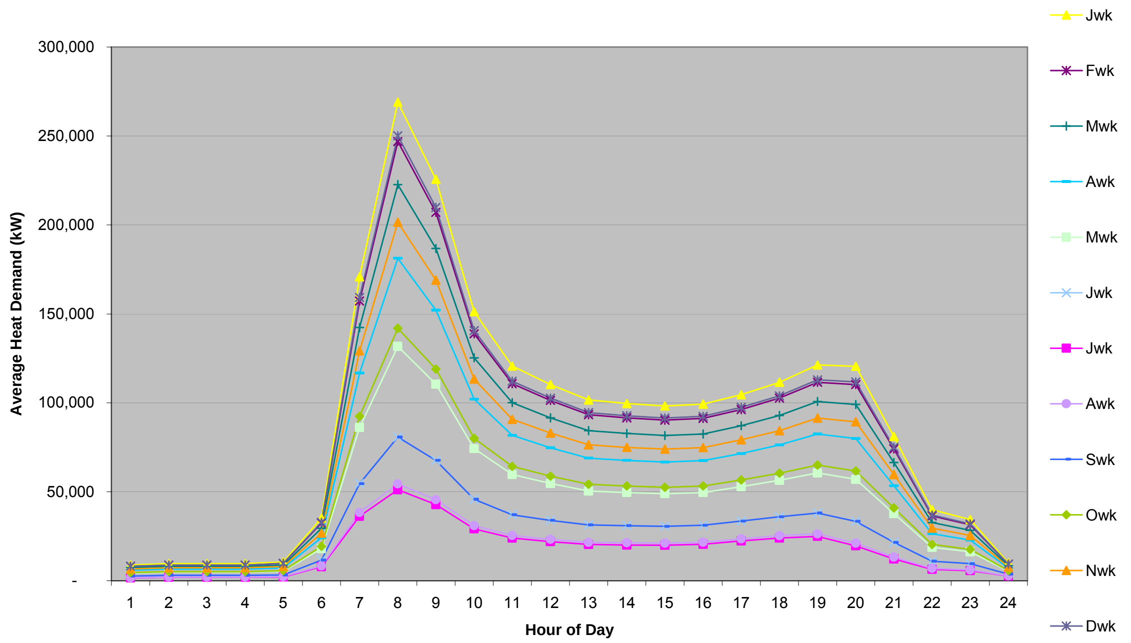

Figure 5-A Undiversified theoretical inner city heat load profile

The heat demand peak is relatively sharp and narrow because the model uses a single generic profile for each type of consumer. This is unrealistic; it is obvious that the likelihood of, for example, all dwellings in the inner city area incurring their peak heat demand simultaneously is very small. The peak heat demand seen by the DH production facilities will be somewhat less: this phenomenon is known as diversity, and the effect of diversity increases the more consumers are connected. Diversity was simulated on the load profile shapes by applying a ‘smoothing factor’; a moving average function adjusts each half-hourly demand figure nearer to the levels that precede and follow it. The annual consumption figures are retained, but the overall effect is to soften sharp changes in loading, and reduce peaks. The effect of the smoothing factor was adjusted to simulate a level of diversity between 60% and 80% depending on the scheme size in accordance with the experience of the study team. Examples of the results are shown in Figure 5-B to Figure 5-F for the heat load seen per plant under the different CHP/DH scenraios. The main format for displaying the profiles is a load duration curve, which shows every hourly heat demand figure from the year rearranged in descending order, for both the undiversified heat demand (red) and the diversified demand (blue). It can be seen that the effect of simulating diversity is to reduce the peak of these curves and fill out the sloping ‘toe’.

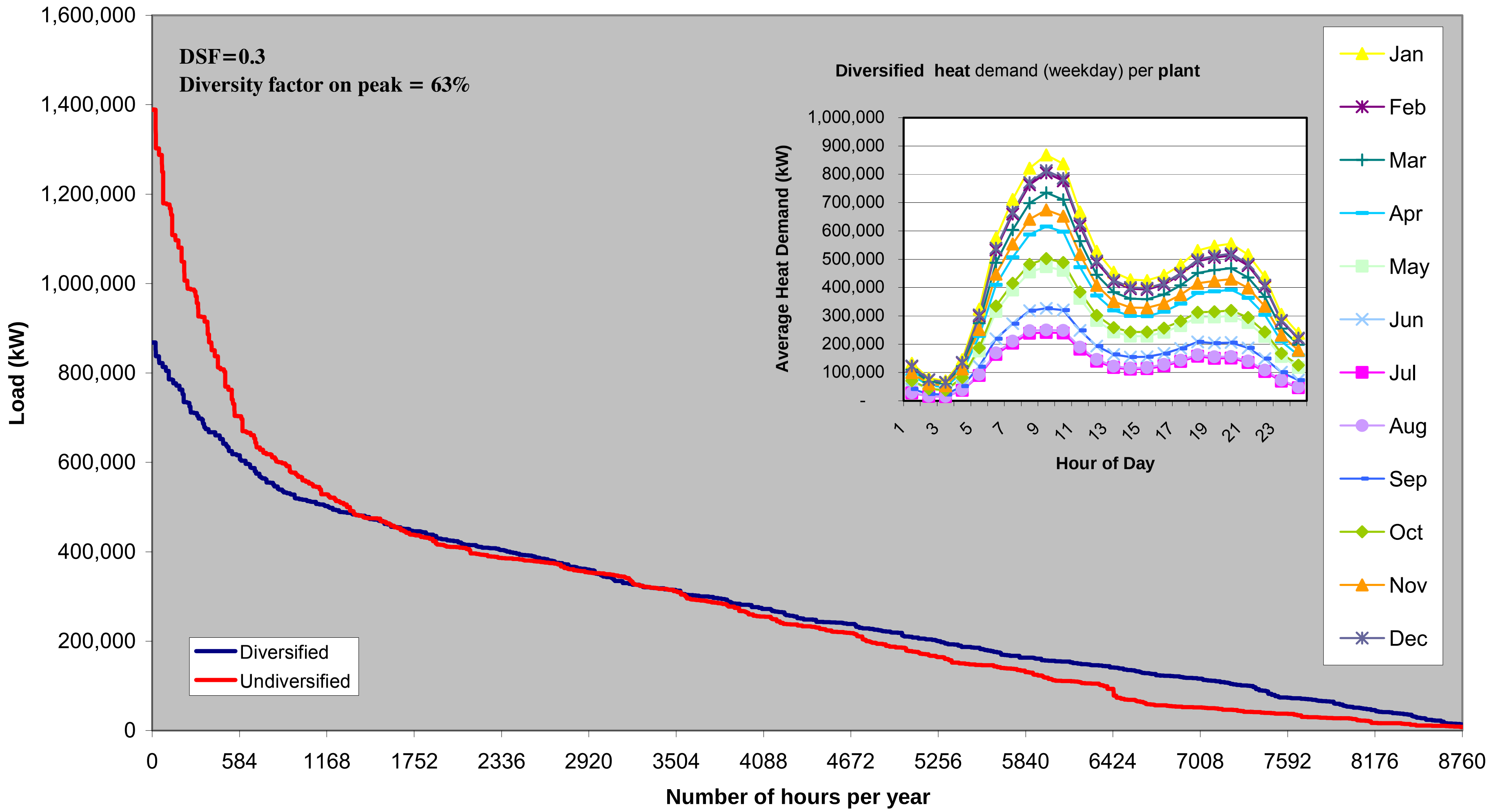

Figure 5-B Whole city CHP (1 plant) diversified heat load profile

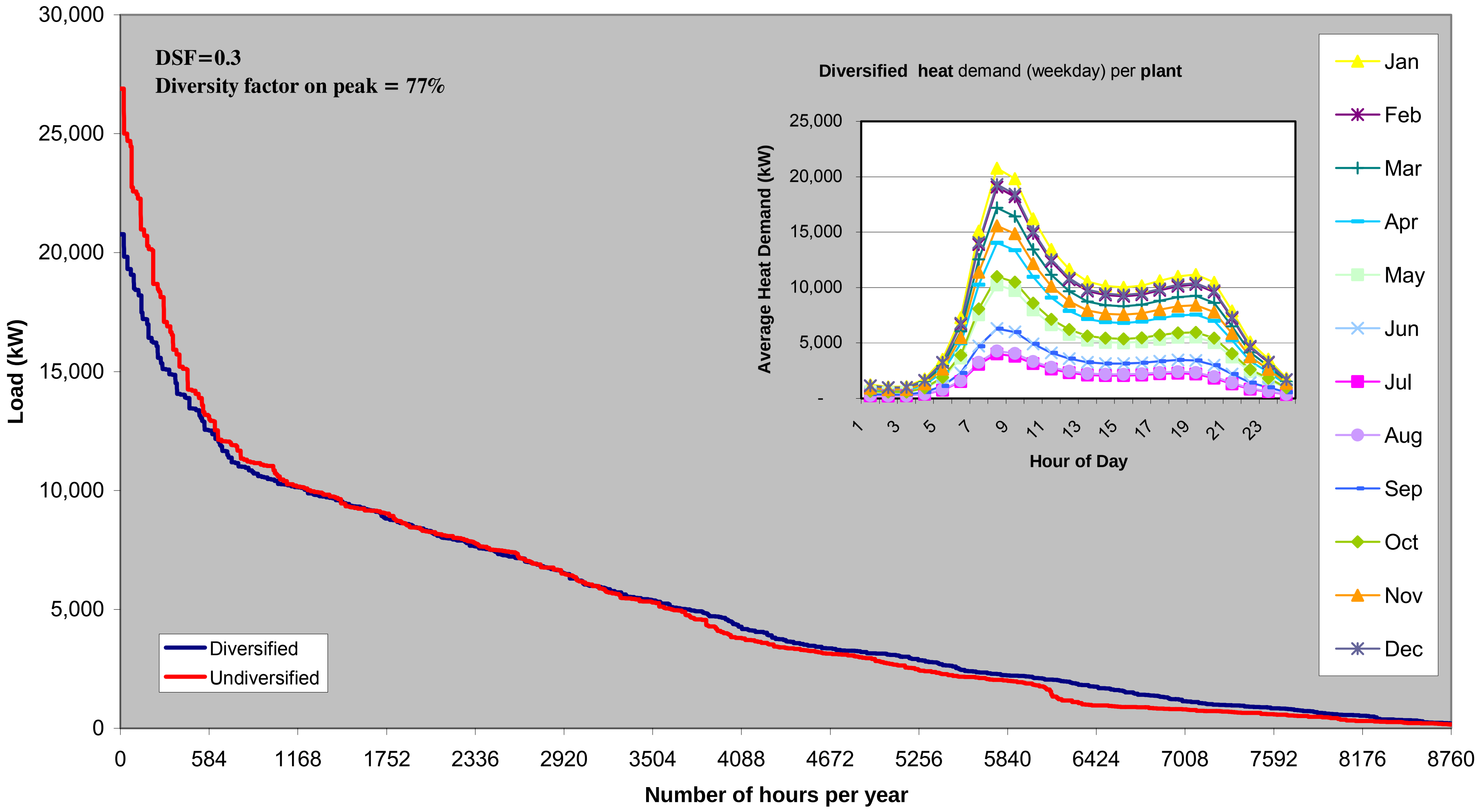

Figure 5-C Inner city Local level per plant (10 plants) diversified heat load profile

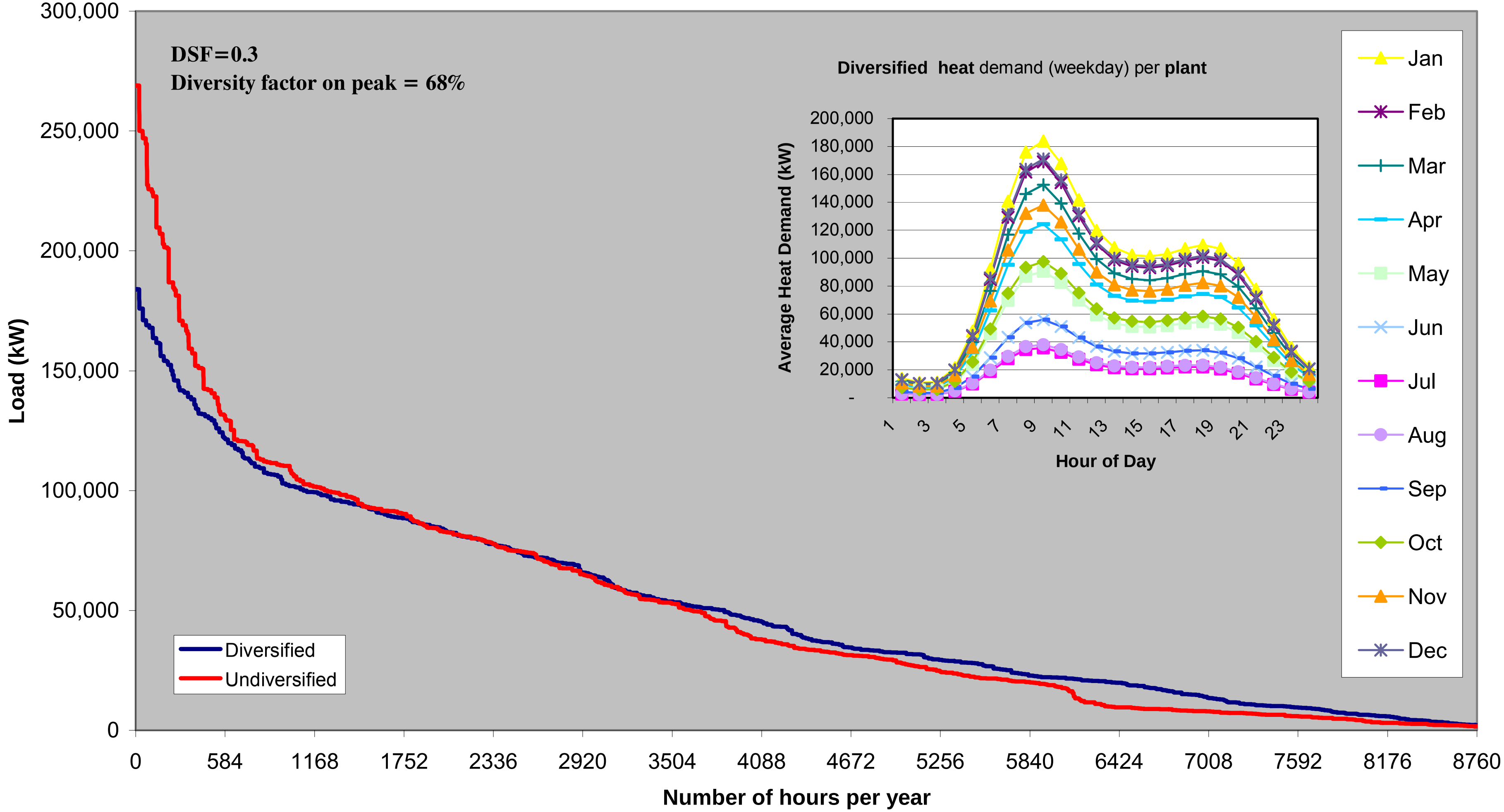

Figure 5-D Inner city District level (1 plant) diversified heat load profile

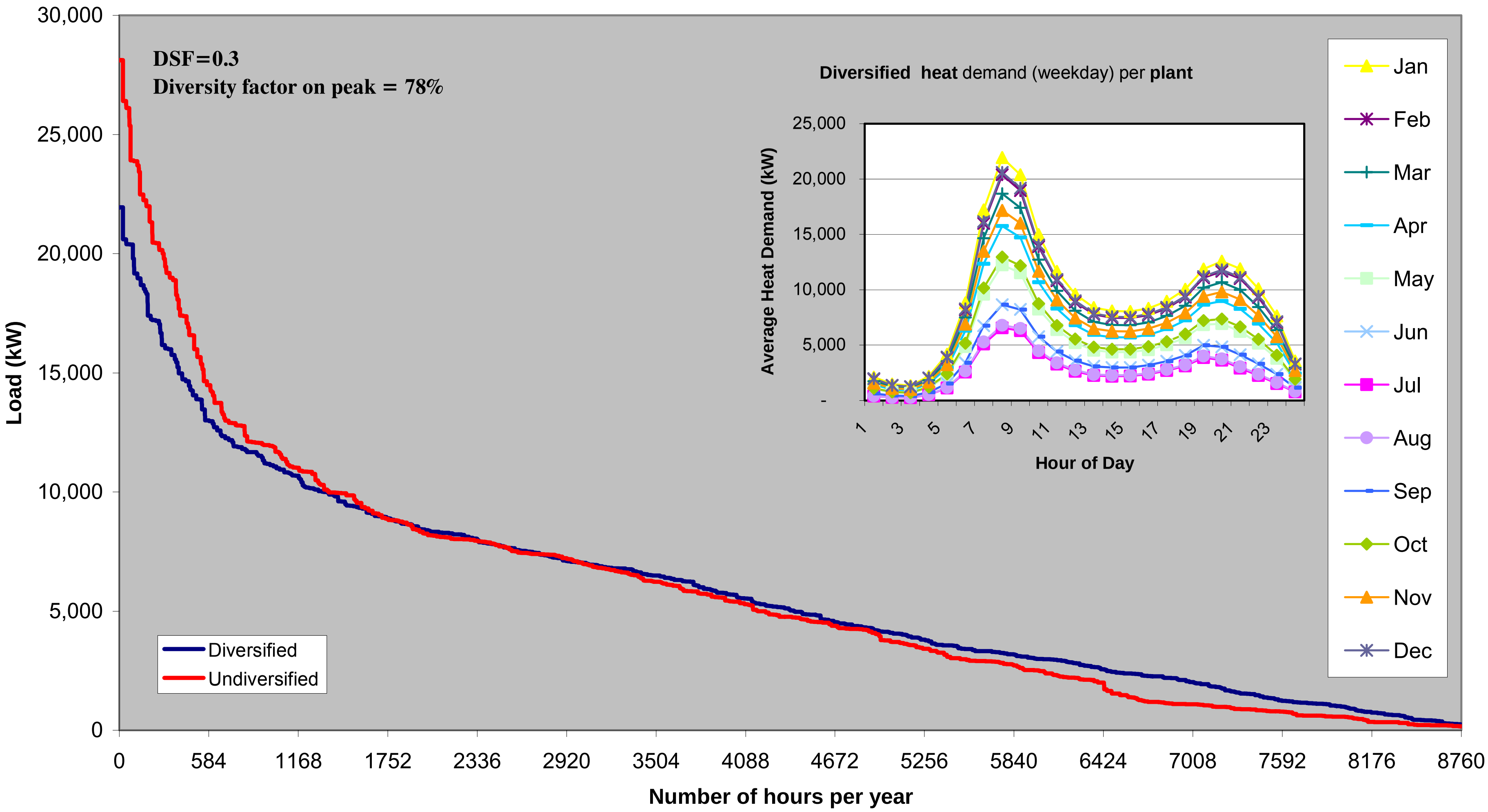

Figure 5-E Outer city Local level per plant (40 plants) diversified heat load profile

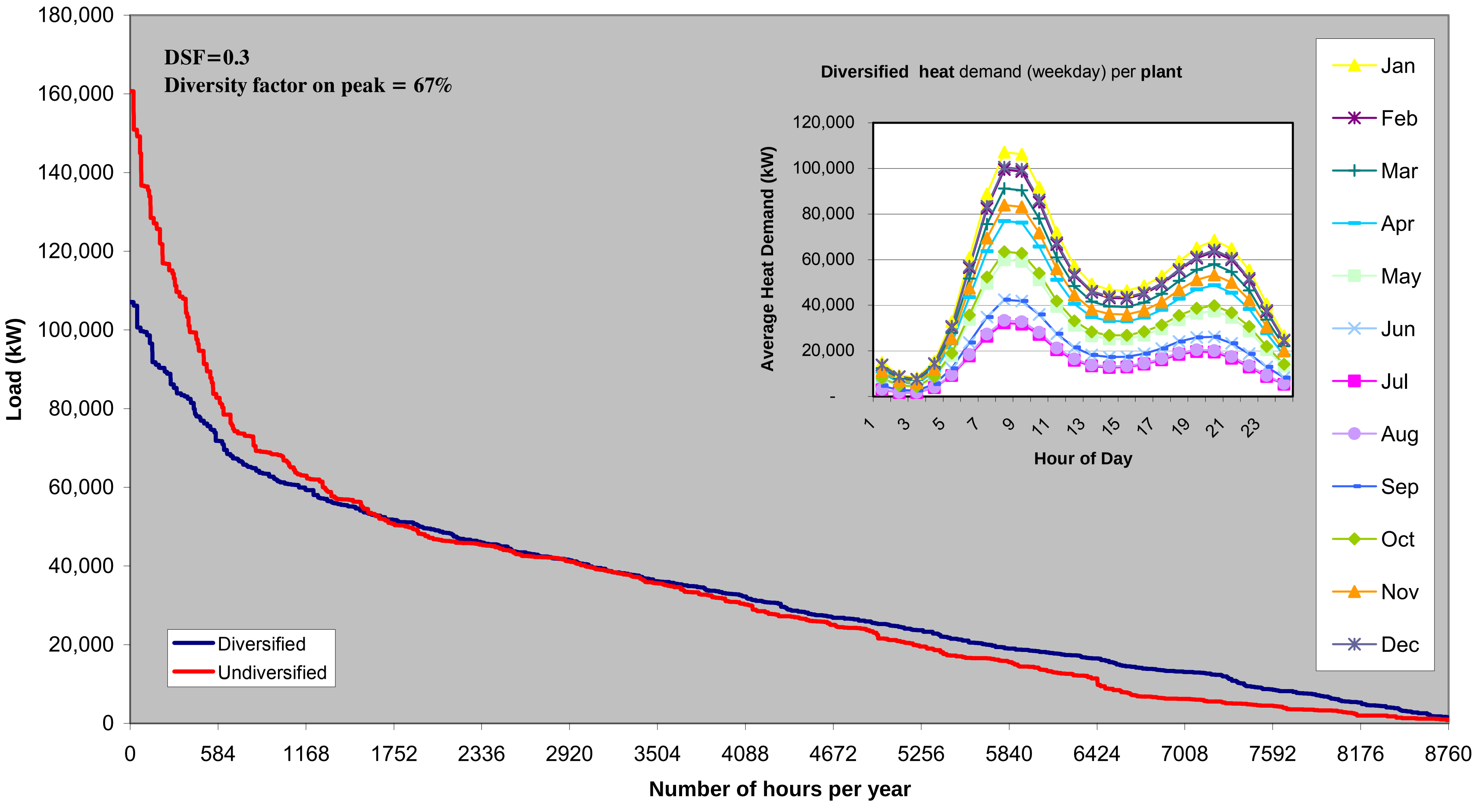

Figure 5-F Outer city District level per plant (7 plants) diversified heat load profile

CHP Operating Models

Bespoke spreadsheet models were used to simulate the annual operation of a range of CHP plant against each loading scenario. The software inputs allow the user to define key parameters of a CHP plant such as electrical efficiency and heat to power ratio. The mode of operation of the plant can be selected (i.e. running continuously, running above a certain heat demand, thermal load following etc) as can an option to model thermal storage in the system. The other inputs required include the consumer annual heat and electricity demand profiles in the form of hourly demand data for an average day in each month.

Types A and B - District & City-wide (CCGT) CHP and District (CCGT) CHP

The model for the larger CCGT based plant was an arrangement whereby the steam raised by the GT waste heat boiler feeds an extraction condensing steam turbine (ST). The gas turbine runs at constant load and hence consumes fuel at a constant rate. A heat exchanger for the DH system is supplied by a steam feed taken from the low pressure ST, which may be varied between zero and its maximum design output, resulting in a reduction in the electrical output of the system. The heat output of the CCGT CHP therefore exactly matches the heat demand of the consumer at all times when the demand falls between zero and 100% of the system's heat output. At higher levels of heat demand, similarly, boilers supply the 'top-up' heat demand remaining after the CHP has contributed 100% of its maximum heat output. The decrease in electrical generation for a corresponding increase in DH energy supply, known as the Z-factor, was assumed to be constant over the operational range between the known performance limits.

Type C - Local (SIGE) CHP

The SIGE plant were modelled both with and without the use of thermal storage, in order to evaluate whether thermal storage has the potential to significantly improve the economic or environmental performance of the schemes.

With thermal storage: under this scenario, the CHP units were allowed to run at full load for continuous periods, assuming that sufficient demand was available either from on-site heat demand or from charging the thermal store, to ensure that no heat would have to be rejected. Thus if the thermal store is fully charged, and there is an on-site heat demand of less than the maximum output of the CHP unit, the CHP unit would then turn off, and allow the heat demand to be met by the energy stored in the thermal storage vessel.

Without thermal storage: the CHP engines were modelled to run in a heat load following mode under this scenario. For any given hourly heat load, the CHP engine will attempt to supply as much of the heat demand as it is able, up to its maximum heat output but only above a minimum operating level of 50%. The heat output of the CHP, therefore, exactly matches the heat demand seen by the system at all times when the demand falls between 50% and 100% of the CHP's heat output. When demand falls below the 50% level, the engine no longer runs, and boilers supply the necessary heat to the circuit. At higher levels of heat demand, similarly, boilers supply the 'top-up' heat demand remaining after the CHP has contributed 100% of its maximum heat output.

The use of thermal storage was found to be beneficial and the economic modelling was based on the inclusion of a store.

Type D - Building CHP

Two different CHP types were used to model this scenario:

1. Stirling engine micro-CHP: to supply heat and power to individual dwellings
2. SIGE CHP: to supply heat and power to non-domestic buildings and communal housing (e.g. apartment blocks).

The census data provided the number and geographical distribution of dwellings within the city. In the Building CHP scenario over the Whole City 14% of domestic heat load is attributable to communal apartment blocks, and the remaining 86% to self-contained dwellings; in the Inner City the communal proportion rises to 35%.

In reality, every building is unique and with the exception for domestic CHP, which is becoming available off the shelf, Building CHP is typically sized on a case-by-case basis given a building's anticipated heat load and demand pattern. However, the census data does not provide data on discrete buildings, only total quantities of building stock in each postcode. Therefore some methodology was required to estimate the distribution of building size and type, predict heat load patterns for this range of building sizes and model SIGE CHP units to suit. The first step was to estimate the size of a single building of each type in terms of the unit of measurement used in the census data, e.g. 4,000m^2 constitutes a single office, or 750 students constitutes one school. In some cases such as the "commercial" category, a single building size would not adequately represent the range of office sizes encountered in real life, so several sizes were chosen and a distribution was assumed between them. Using the heat demand database and assumed heat load factors (see Appendix F), the peak heat requirement for an individual building of each type was calculated.

An ideal CHP unit for each connection was sized on the basis of the typical percentage contribution of useful heat from the CHP, and expected annual operating hours of the unit (based on the heat demand profiles); this process is shown in Table 5-1. A packaged CHP unit of suitable size was matched to each building type, resulting in a distribution of Building CHP sizes for each supply scenario, which is given in Table 5-2. This distribution was used to derive:

- Building CHP performance and operating parameters, in order to calculate a CHP energy balance for each scenario
- Total capital costs for the Building CHP scenarios, given costs for each individual type of unit.

Table 5-1 Building CHP sizing assumptions for whole city scenario

WHOLE CITY	Derived heat peak per building (kW)	Load distribution (if split category)	Sector heat demand (MW)	Useful heat from CHP	Proportion of sector heat demand supplied from CHP (kW)	CHP anticipated annual operating hours	Equivalent utilisation	Peak CHP unit size (combined kW)	Number of CHP installations (calculated)	CHP Unit ideal thermal size (calculated)	Nearest known CHP unit thermal size (kW)	Nearest known CHP unit electrical output (kWe)
Residential dwelling	9.8	86%	1,413,169	51%	720,716	1,135	13%	634,992	102,757	6.2	6.4	0.9
Residential communal	287.3	14%	226,948	65%	147,516	2,920	33%	50,519	451	112	197	122
Hospitals	1007	100%	48,797	75%	36,597	6,205	71%	5,898	16	373	427	305
Education	999	100%	114,992	75%	86,244	2,080	24%	41,463	57	726	750	625
Prisons	1005	100%	593	75%	445	2,000	23%	222	0	759	750	625
Commercial small	300	50%	50,946	60%	30,567	1,560	18%	19,594	129	152	197	122
Commercial medium	999	30%	30,567	65%	19,869	2,190	25%	9,072	23	390	427	305
Commercial large	3001	20%	20,378	68%	13,857	2,920	33%	4,746	5	918	1,003	836
Retail small	301	50%	102,948	65%	66,916	2,190	25%	30,555	260	117	197	122
Retail large	2994	50%	102,948	75%	77,211	2,920	33%	26,442	26	1,010	1,003	836
Warehouse/Industrial small	299	30%	116,497	65%	75,723	1,560	18%	48,541	148	327	427	305
Warehouse/Industrial large	3001	70%	271,827	70%	190,279	2,080	24%	91,480	34	2,654	2,344	2,188

Table 5-2 Distribution of Building CHP sizes

CHP size (kWe)	NUMBER OF PLANT		
	WHOLE CITY	INNER CITY	OUTER CITY
0.85	99,314	5,632	93,682
122	510	193	357
305	149	42	107
625	56	-	25
836	31	39	15
2188	39	9	30

Electrical losses

The electrical network was modelled in two parts. A high voltage (HV) transmission network transfers electricity from outside the city into the city and vice versa, and incurs a loss of 3% on energy transmitted. A low voltage (LV) network distributes electricity within the city and incurs a loss of 6% on energy transmitted. The following coefficients were applied to these base-case loss factors to reflect the flow of electricity through the networks under the different CHP/DH scenarios. The resultant loss factors were applied to the total electrical demand of the city, and the resulting shortfall made up with additional import.

Table 5-3 Losses on transmitted electricity

	City-wide	District	Local	Building	Alternative
Utilisation coefficient on HV loss factor	100%	100%	0	55%	100%
Utilisation coefficient on LV loss factor	100%	100%	100%	55%	100%
Resultant HV loss factor	3%	3%	0%	2%	3%
Resultant LV loss factor	6%	6%	6%	3%	6%

Energy balance results

The energy balance for the city is shown in Figure 5-G and Figure 5-H for the different CHP scenarios; in each case the consumer demand is constant. The various energy transmission losses can be seen to increase as the CHP plant moves away from the customer and becomes bigger. All scenarios require top-up boiler heat during times of peak heat demand. Variation in the amount of heat recovered by the different plant is due to small differences in the loading conditions and plant characteristics leading to different economically optimum CHP sizes. Under the Building CHP scenario, the small SIGE CHP systems in communal housing and non-domestic buildings have high heat-to-power ratios. The Stirling engine CHP units in dwellings incorporate a supplementary burner to meet heat demand peaks, resulting in a system with high thermal efficiency, low electrical efficiency and high heat-to power ratio. Overall, the Building CHP units are able to supply a large proportion of heat demand, but the city as a whole requires significant import of electricity. The City-wide CHP at the other extreme is electrically efficient and being sized for the heat demand, generates a surplus of electricity, resulting in a net export from the city. The alternative solution of gas-fired boilers obviously requires 100% boiler heat and 100% imported electricity.

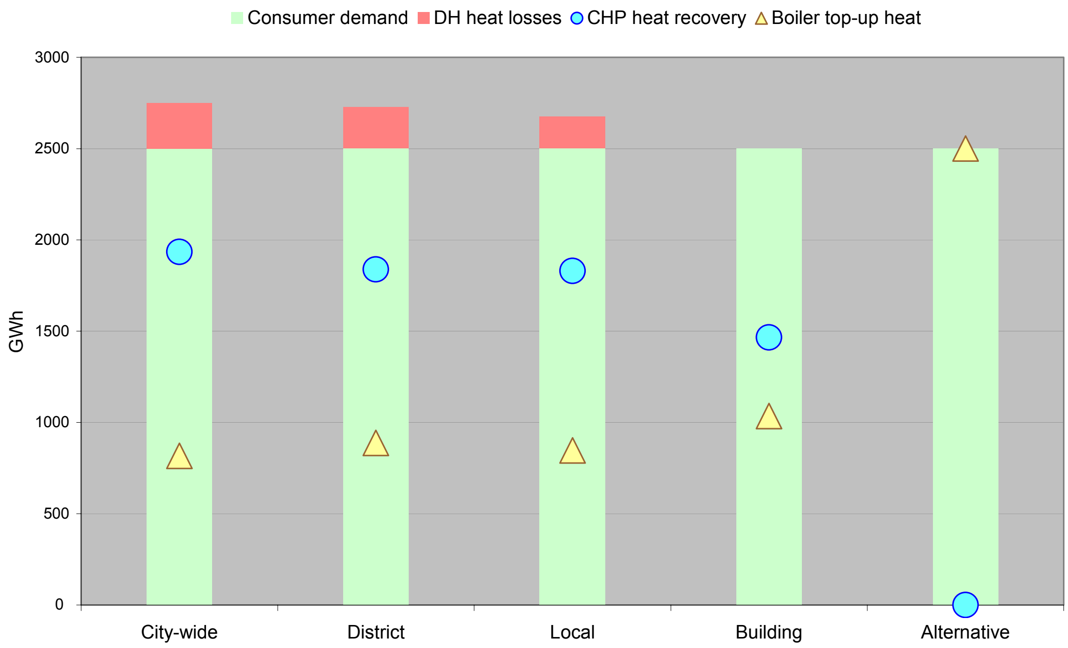

Figure 5-G Heat energy balance results summary

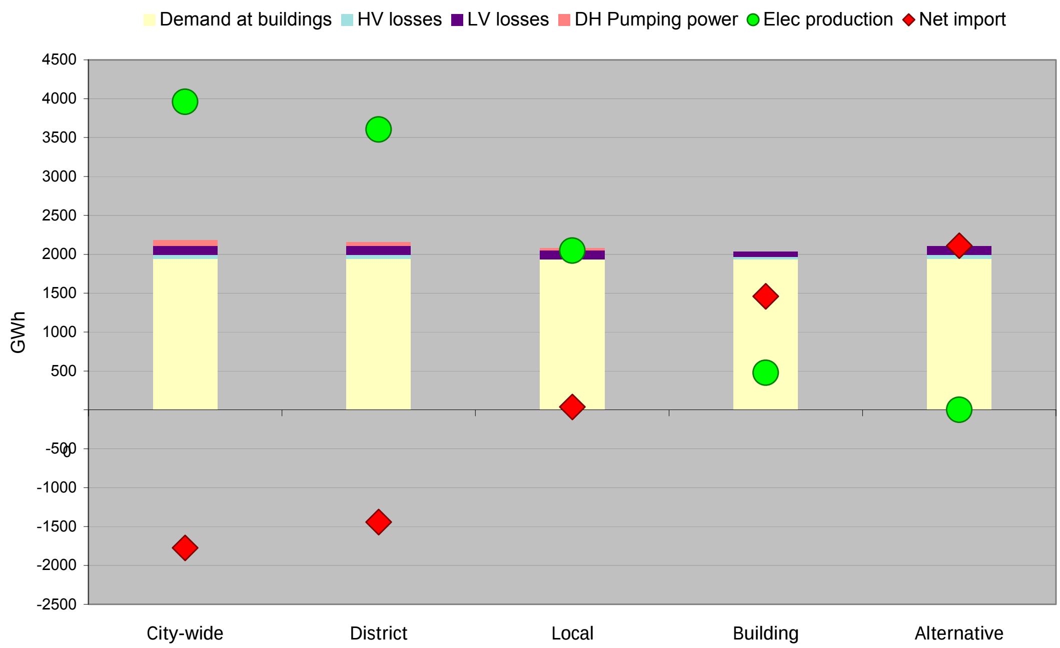

Figure 5-H Electrical energy balance results summary

Table 5-4 Energy balance results example for the Whole City

		WHOLE CITY				
		A City-wide	B District	C Local	D Building	Alternative No CHP
CHP unit electrical output	kW	450,000	51,888	5100	Various	N/A
Indicative individual thermal store size	m3	N/A	N/A	682	Various	N/A
CHP availability		98%	97%	92%	Various	N/A
Number of CHP installations		1	8	50	100,038	N/A
Sector heat demand	MWh	2,500,609	2,500,609	2,500,609	2,500,609	2,500,609
DH heat losses	MWh	250,061	225,055	175,043	0	0
Thermal store charging	MWh	0	0	325,490	0	0
CHP heat recovery	MWh	1,933,615	1,838,418	1,829,562	1,471,443	0
LT (top-up) boiler heat	MWh	817,055	887,246	846,089	1,029,166	2,500,609
Thermal store discharge	MWh	0	0	325,490	0	0
DH Loss as % heat demand		10.00%	9.00%	7.00%	0.00%	0.00%
Sector electricity demand	MWh	1,936,653	1,936,653	1,936,653	1,936,653	1,936,653
DH pumping electricity	MWh	74,938	50,089	30,421	0	0
CHP electricity generation	MWh	3,959,796	3,605,037	2,046,909	478,876	0
CHP electricity exported	MWh	1,989,077	1,703,327	532,067	0	0
HV transmission losses on CHP electricity	MWh	38,733	38,733	0	21,303	38,733
LV transmission losses on CHP electricity	MWh	116,199	116,199	116,199	63,910	116,199
Grid net import demand	MWh	-1,793,273	-1,463,363	36,365	1,457,777	1,936,653
CHP fuel	MWh	7,689,677	7,200,166	5,295,113	2,321,284	0
Boiler fuel	MWh	1,021,319	1,109,058	1,057,612	1,228,011	2,983,750
Total fuel	MWh	8,710,996	8,309,224	6,352,725	3,549,294	2,983,750
CHP Average total efficiency (GCV)		77%	75%	74%	84%	N/A
CHP Elec Efficiency (GCV)		51%	50%	40%	21%	N/A
Boiler Efficiency (GCV)		80%	80%	80%	84%	N/A
Annual CHP Equivalent operating hours (at full load)		6624	6371	7041	Various	N/A
Useful heat from CHP		70%	65%	65%	59%	N/A
CHP Thermal efficiency (GCV)		25%	26%	35%	63%	N/A

6 DH Network design

Overview
The design of the heat network that would supply heat to connected properties under the Local level, District level and City-wide District Heating scenarios is critical, as it represents both a significant capital investment and incurs ongoing operational costs. The mains were modelled in three stages, corresponding to these three supply scenarios, as illustrated in Figure 6-A, Figure 6-B and Figure 6-C. It should be noted that the geometric layout of the networks in these figures is illustrative and not accurately representative of what was modelled; this is discussed later in this section.

- The Local level network includes the branches and connections to supply each connected dwelling or building, and the necessary heat mains to link them to the Local energy centres.
- The District level network includes all of the connections and pipework of the Local networks. At the Local energy centre however a heat exchanger and pumping station replaces the prime mover. Additional District heat mains supply heat to these Local supply points from the District energy centres.
- The City-wide network includes all of the connections and pipework of the Local and District networks in addition to a transmission ring main. At the District energy centre the prime mover is replaced by a pumping station, supplied via the transmission main from the City-wide power station

The cost of installing heat mains in a given area depends upon four factors:

A. The design operating temperatures and pressures: These factors have a significant impact on the design of a DH network and generally are assessed for each DH application on a case-by-case basis. Here they have been assessed for each supply scenario to represent typical design practice, based on our experience.

B. The complexity of existing services: The impact of the complexity of existing services is difficult to quantify but it is clear that the same length of pipe installed in city centre locations will be more expensive than in less congested areas, partly because of the difficulty in finding routes around existing services and partly because of the need for traffic management and related safety requirements. The following factors on capital cost have been assumed[3]:
- average heat density less than $8MW/km^2$ 0.95
- average heat density between $8MW/km^2$ and $12MW/km^2$ 1.00
- average heat density more than $12MW/km^2$ 1.30

C. The length of the heat mains: The heat mains must extend to connect all of the required loads in an area.

D. The peak heat demand: the heat demand to be supplied will determine the pipe diameter.

All of the DH networks analysed have assumed that pre-insulated pipe systems to EN 253 will be used with the pipes buried directly in the ground. There is limited scope for capital cost reductions in the future although other IEA studies have identified possible routes for cost improvements, i.e:

- reuse of excavated material [2]
- use of plastic carrier pipes [3]

The selection of routes for the larger diameter district and transmission mains that minimise the need to excavate in major roads is the most important factor to be considered and the extent to which such routes are available will be very city specific. Consequently the cost estimates for the larger diameter heat mains are subject to a greater level of uncertainty. This may modify the conclusions in that cities where such heat mains will be relatively expensive to install will clearly tend towards smaller-scale CH/CHP schemes.

The other main determinant in the cost of the heat mains is the pipe diameter, which is determined by the temperature difference between flow and return (from which flow rates are calculated) and the available pressure drops.

[3] *The UK Potential for CHP/DH* [1]

In order to determine the pipe diameters and hence costs for each element of the heat mains models, assumptions on operating temperatures and pressures need to be made. In addition there are linked assumptions regarding the position of heat exchangers to achieve hydraulic separation, the type of consumer connections and the position of peak load boilers. These assumptions are set out below and are considered to be typical for most CH/CHP developments installed to supply existing buildings.

Local DH schemes

The Local DH networks will be designed as low temperature systems with flow and return temperatures of 95ºC flow 65ºC return. A wider temperature difference would be preferable however the return temperature will be limited by the temperatures of existing heating systems, which typically will be 80ºC flow 60ºC return unless designed specifically for DH. Higher flow temperatures than 95ºC are not achievable from spark-ignition gas-engine CHP plant without either additional costs or loss of efficiency. Indirect connection of buildings has been assumed with a plate heat exchanger with a 5ºC approach temperature. Where dwellings are in apartment blocks the heat exchanger will add little to the cost of the project and will have advantages to the DH operator of hydraulic separation. Connections to row houses would ideally be through direct connection if there is pressure compatibility. The low temperatures would allow plastic carrier pipes to be used if there was a cost advantage, particularly for final connections to buildings. For both these reasons peak pressures in some parts of the network may need to be limited to 6barg. In other parts of the network pressures of up to 10barg would be permitted.

Peak boilers are assumed to be located at the supply points of the Local DH networks. This reduces the diameters of the district and transmissions mains which only need to be sized for the delivery of the CHP capacity not to supply the peak demand. Some of the larger non-domestic buildings (e.g. hospitals) may retain their own boilers to provide a peak and/or standby facility.

District mains system

The District mains system which connects a number of Local DH systems together to supply enough load for a small CCGT plant is assumed to operate at higher pressures and temperatures. A flow temperature of 110ºC and return temperature of 70ºC is assumed. Heat will be transferred to the Local DH mains through heat exchangers installed at the Local network supply point where the peak boilers are also located. This hydraulic separation will enable higher pressures to be used on the District network, up to 25barg. An economic analysis will establish the optimum pressure level, however the benefits of minimising diameters by using higher velocities and pressure drops will be of relatively greater value with the larger diameters needed for the District level mains.

Transmission main system

The transmission main conveys heat from a major CCGT plant at the edge of the city to each of the District level nodes. The transmission main system will be designed for a direct connection into the District level network; hence the maximum pressure is 25barg. At the District level nodes it is assumed that pumps are installed to supply the District networks. This means that the temperatures on the transmission main will be the same as for the District level network (110ºC/70ºC). This method of distributed pumping enables pipe sizes to be minimised within economic constraints and the direct connection avoids the need for higher flow temperatures that would impact adversely on the electrical efficiency of the CCGT plant (lower z-factor).

For simplicity, it is assumed that flow temperatures are kept constant in all cases, which has the advantage of minimising pumping energy. It is recognised however that the larger CCGT schemes may benefit from a reduction in flow temperature under part-load conditions as additional electricity could then be generated assuming multiple steam extraction ports are used. The additional electricity generated would be offset by the increase in pumping energy that would result.

Clearly some variation in these assumptions would be possible without materially affecting the conclusions in the report.

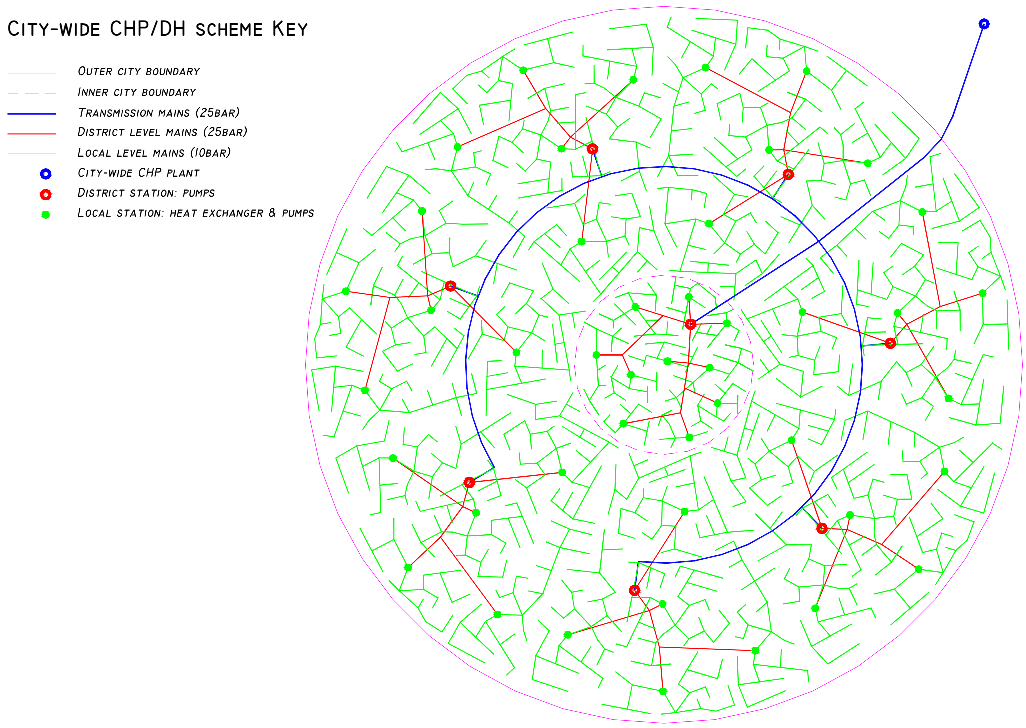

Figure 6-A Schematic diagram of the heat distribution network in the City-wide CHP/DH scenario

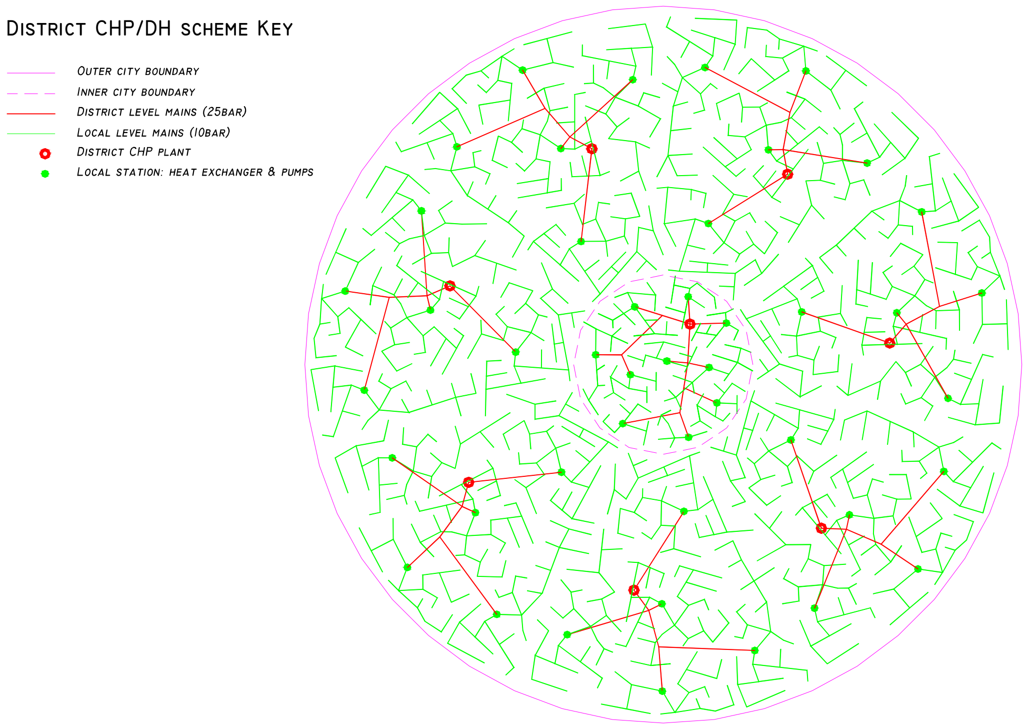

Figure 6-B Schematic diagram of the heat distribution network in the District CHP/DH scenario

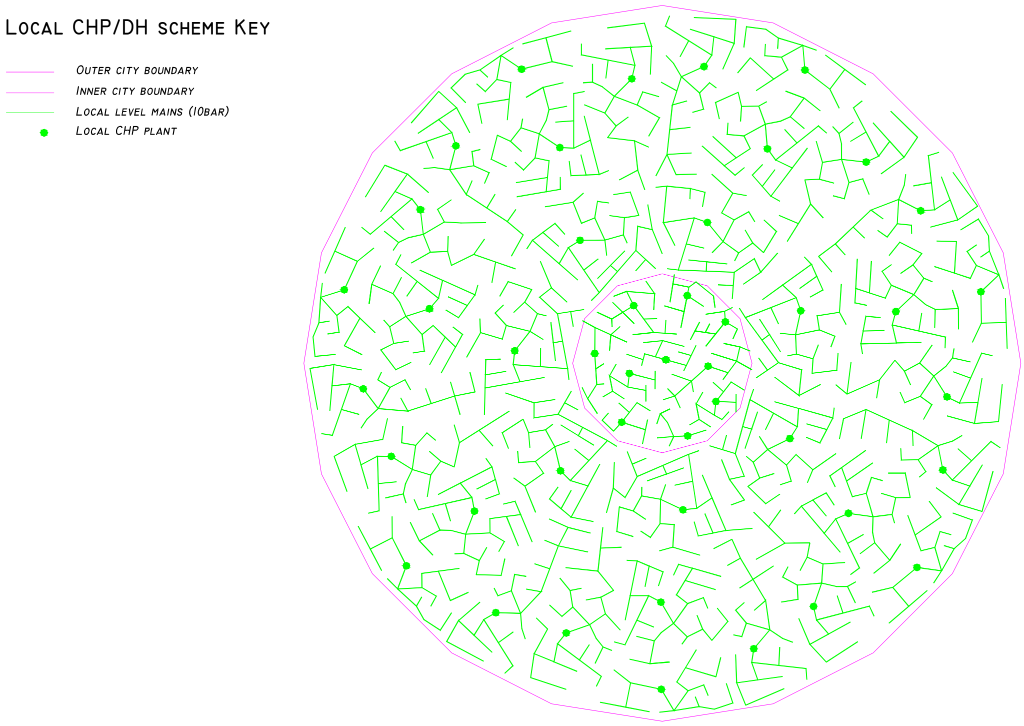

Figure 6-C Schematic diagram of the heat distribution network in the District CHP/DH scenario

Local level heat mains design methodology

Geometry

The Local heat mains are the pipes that supply heat to individual buildings and dwellings. In practice the pattern of heat mains serving a given area will be unique; the actual lengths and layout of the pipes depend on the distribution of the supply points, the diameter of the pipes would be designed to supply sufficient load to each connection whilst optimising pumping costs, and branch and bend fittings would be specified as appropriate to the particular application. Typically many different loads would be connected to a DH system, ranging in capacity from tens of kilowatts for an individual dwelling, to several hundred kilowatts for a large office or school.

In order to estimate the cost of the network over the extent of a city, a model was developed to create a single Local DH mains structure for each postcode sector area. The design of each network is based on a notional supply grid, as shown in Figure 6-D, employing branches to link every load within an equivalent square area to the postcode sector area to a single supply point. It is assumed that the geographical distribution of loads (heat load density) within a postcode sector area is homogeneous.

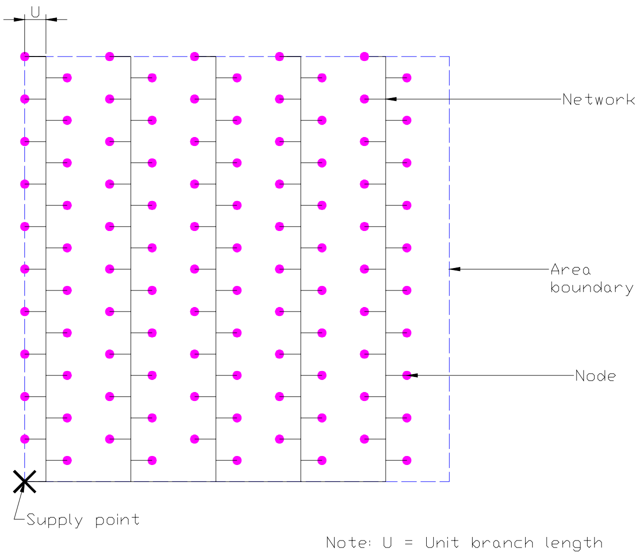

Figure 6-D Notional grid geometry (100 equispaced nodes)

The capital cost of each postcode sector area network is a function of its land area and the number of nodes it contains (which affect the total length of the pipes) and the load at each node (which affects the diameter of the pipes).

The peak heat load for each postcode sector area was assessed in from benchmark data, but there is no statistical breakdown available of the number or size of building connections. It was assumed that each postcode sector grid would contain 100 supply nodes of and that all of the 100 nodes would be of equal capacity, i.e. that the total peak load for that postcode sector area is divided equally between 100 nodes. This was considered a reasonable assumption as variations in pipe sizes about the mean due to larger or smaller actual connections will tend to cancel out over the area of the city.

The number of nodes per grid was selected after studying the frequency distribution of the peak heat loads of all 132 postcode sector areas. This shows that most postcode sector areas have a combined peak heat demand of between 20MW and 40MW, because with the original definition of postcode sectors, each aimed to contain a similar number of addresses. With 100 nodes per grid, the notional grids supply between 200kW and 400kW to each node, as shown in Figure 6-E, a size range that corresponds to typical non-domestic loads or apartment blocks. In addition to the grid heat mains, some allowance must be made for extra, smaller branches to account for connections to individual dwellings: this is detailed in the capital cost section later.

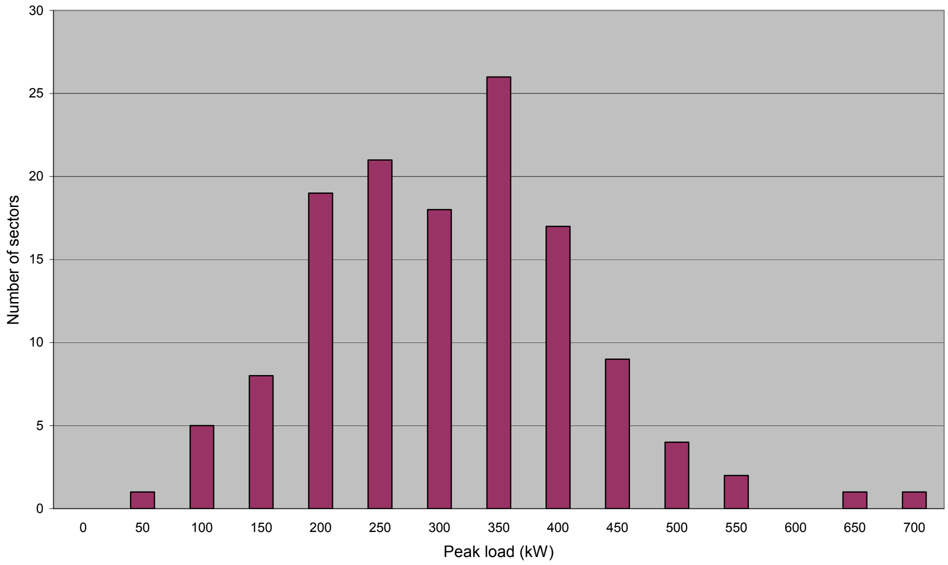

Figure 6-E Histogram showing distribution of the average load per node of a 100-node notional grid for each postcode sector area modelled

Thus the capital cost of each postcode sector area network is a function of the load at each node and the length of pipes in the network, which is approximately proportional to the sector area.

Network optimisation

The actual optimisation of design of the notional grids was performed using a suite of hydraulic analysis software called System RØRNET developed by Ramboll. Given a set of parameters defining the network geometry and operational constraints, the software calculates the economic optimum sizes of the pipes, taking account of pumping energy, heat losses and capital costs. For the Local level grids, the following design criteria are assumed:

- a static head of 3bar
- a factor of 1.1 on pressure drop through the network over and above pressure losses resulting from the roughness of pipes, to account for bends, branches and valves[4].
- a 1bar differential pressure allowance at each customer connection to allow for the hydraulic interface heat exchangers and control valves.
- maximum system working pressure of 10bar based on an analysis of a range of working pressures from 6bar to 16bar and the effect on network design and cost implications.
- Primary DH flow temperatures of 95°C and an average return temperature of 65°C, giving a 30°C temperature difference across the network.

Capital cost

It was not feasible to perform a design optimisation analysis on every one of the 132 notional grids created for the postcode sector areas, each having different geometry and peak load requirement. Instead, 10 networks were analysed, with combinations of loading and total pipe lengths to cover at intervals the range of loads and sector areas in the data. The unit used to express the length of pipe in a network is “unit branch length”, as shown in Figure 6-D, a fixed fraction of the total pipe length which is derived from the land area of the postcode. The results are expressed in Figure 6-F as an average specific pipe cost for a given network e.g. if the total length of piping in a given network is 100m and the combined capital cost of the pipes required is €91,000 then the average pipe cost is €910/m. The schedule of pipe costs used is typical of those experienced in the UK for similar projects, and is shown in Figure 6-G

[4] This is considered typical for DH networks.

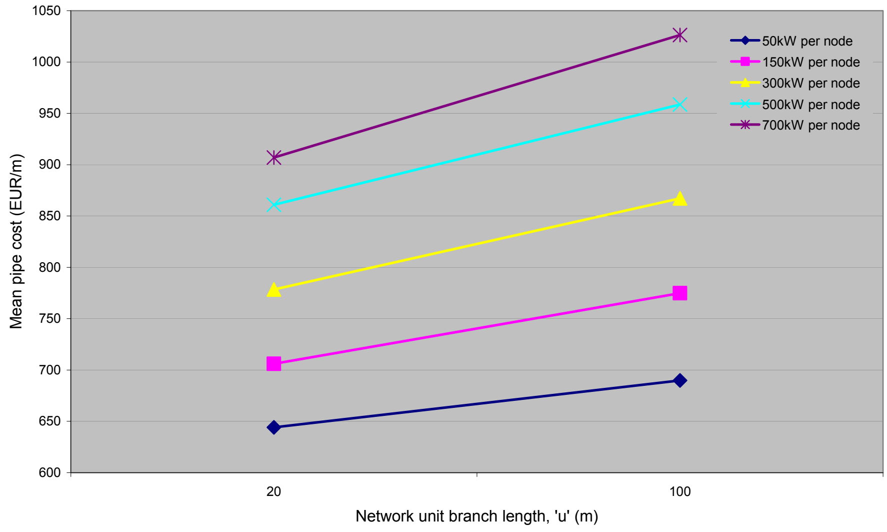

Figure 6-F Variation in average pipe capital cost with loading and network size for the notional grid network

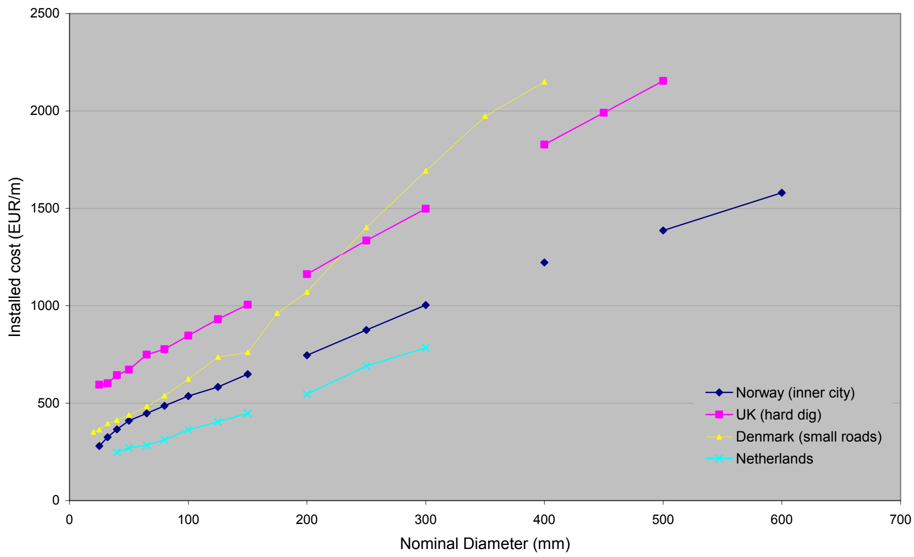

Figure 6-G Cost of DH mains (under roads, UK)

The results show the expected increase in costs as the loading on the network increases, caused by the requirement for larger diameter pipes. There is also an increase in average pipe cost per m with increasing network length for a given load, which is approximately linear and has been shown as such on Figure 6-F. This is caused because larger pipe diameters within the longer pipes are needed to avoid high pressure drops, increasing the overall average cost.

The peak heat load and land area of each postcode sector were used to derive values for load per node and unit branch length. These values were used to find an average cost per metre of pipe based on the relationships shown in Figure 6-F, interpolating as required. By multiplying this value by the total theoretical network length a capital cost for the network was produced.

As discussed above, the notional grid model does not make provision for the branches that will serve domestic consumers. A single dwelling branch has been sized by the following methodology:

- 50kW maximum peak instantaneous hot water demand
- 10m typical branch length (from street to dwelling)
- 95/65 DH flow/return temperature
- Pipe of nominal diameter 25mm supplies heat peak with flow velocity of 0.8ms^{-1}, pressure drop of 23mm/m.

For each postcode sector the cost for a single 10m long DN25 branch was multiplied by the number of dwellings in each category, with the following factors to account for multiple dwellings per connection for certain build types and for proximity to the street main, which are estimates based on typical UK experience:

- Detached houses 1.0
- Semi-detached houses 0.6
- Terraces 0.4

Communal housing was not included in this analysis as the typical connection size is larger and falls into the range already accounted for by the notional grid model. The dwelling connection costs were added to the notional grid costs resulting in a total cost for the Local mains for each postcode sector, which are displayed below.

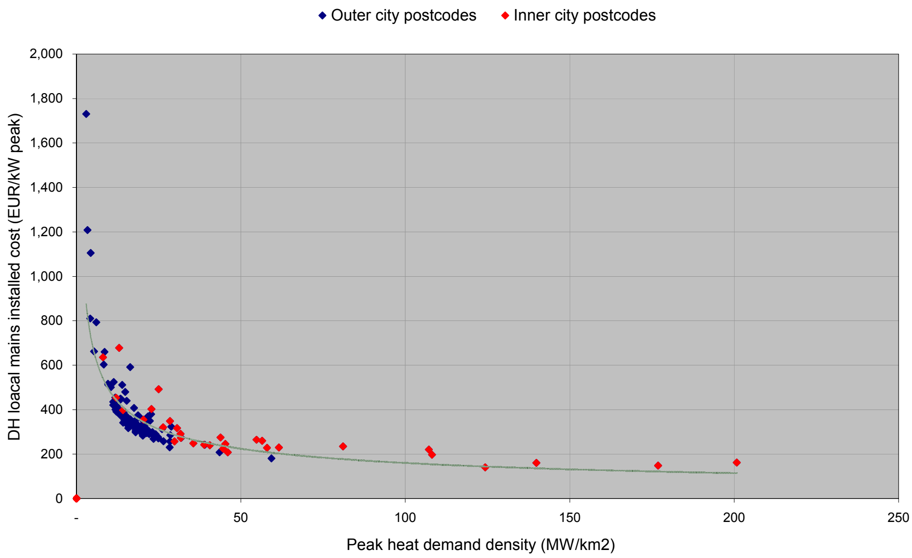

Figure 6-H Postcode sector Local DH mains specific cost versus heat density

District level heat mains design methodology
As shown in Figure 6-B, the District level mains specifically are the pipes that supply heat from the District level plant to pumping stations at the head of the Local networks, which under the Local CHP scenario would have contained the SIGE units.

From the size of the heat demand and the typical CHP plant sizes, it was determined that there would be a single District CCGT plant serving the inner city, and 7 plants in the outer city. The number of Local level heat networks was also known to be 31 in the inner city and 101 in the outer city. Using this data and the land area, the notional heat grid model as described above was used to assess the total required length of District level mains, assuming a uniform distribution of the Local supply points. The following design criteria were assumed:

- sized to deliver the maximum District CHP heat capacity, as peak boilers are located at the Local energy centres.
- a static head of 3bar.
- a factor of 1.1 on pressure drop through the network over and above pressure losses resulting from the roughness of pipes, to account for bends, branches and valves, based on a recommendation for typical DH networks.
- a 2bar differential pressure allowance at each Local energy centre connection to allow for the hydraulic interface heat exchangers and control valves.
- maximum system working pressure of 25bar based on typical good design practice and an analysis of the effect a range of working pressures on network design and cost implications.
- primary DH flow temperatures of 110ºC and an average return temperature of 70ºC, giving a 40ºC temperature difference across the network.

Transmission heat mains design methodology
The transmission mains were modelled as a ring serving the eight District pumping stations distributed throughout the city, as shown in Figure 6-A.

The total length of the mains is approximately 20.5km (using the Average City) including a branch of 500m length from the ring to the City-wide energy centre. The following design criteria are assumed:

- sized to deliver the maximum City-wide CHP heat capacity, as peak boilers are located at the Local energy centres.
- a static head of 3bar.
- a factor of 1.1 on pressure drop through the network over and above pressure losses resulting from the roughness of pipes, to account for bends, branches and valves, based on a recommendation for typical DH networks.
- a 0.5bar differential pressure allowance at each energy centre connection to allow for the hydraulic interface and control valves.
- maximum system working pressure of 25bar based on typical good design practice and an analysis of the effect a range of working pressures on network design and cost implications.
- primary DH flow temperatures of 110ºC and an average return temperature of 70ºC, giving a 40ºC temperature difference across the network.

7 Life Cycle Cost Evaluation

The method used to carry out an economic comparison of the schemes is a discounted cash flow over the whole life of the project.

The total capital cost is the summation of the costs for the CHP units, the DH network, and customer connections. Although capital costs can be considered to occur at year zero of a whole-life analysis, it is obvious that this would not reflect the way the CHP scenarios would develop in practice Thus, in addition to the operational period, a 7-year build-up period was modelled. It is assumed that construction commences at the start of this period, and 100% heat supply market penetration is achieved at the end (i.e. the whole city is then implementing the given energy supply scenario). By varying rates of capital cost input and heat connection rate during the lead in period, the anticipated differences in implementation of the different scenarios were simulated. The Building CHP scenario was considered a base case in which the rate of capital cost input and heat connection is linear. Figure 7-A and Figure 7-B illustrate the assumptions. Although idealised, this reflects the large number of small schemes, with short installation times and no requirement for a DH network, giving rise to rapid connections once a consumer has decided to install CHP. At the other extreme is the City-wide CHP/DH scheme, which requires the bulk of its capital cost in the initial stage of the lead-in period, as the large production facilities and DH networks are constructed. There is significant lag following this investment before customers are connected to the scheme once the infrastructure is in place although the connection rate is high. The intermediate CHP/DH scenarios have been allocated similar, though less-pronounced characteristics.

The level of heat connection affects the operating costs for the CHP options during the lead in period: consumers not connected to CHP are assumed to retain gas-fired boilers, and as such are modelled in the same way as the ‘supply of heat only’ option.

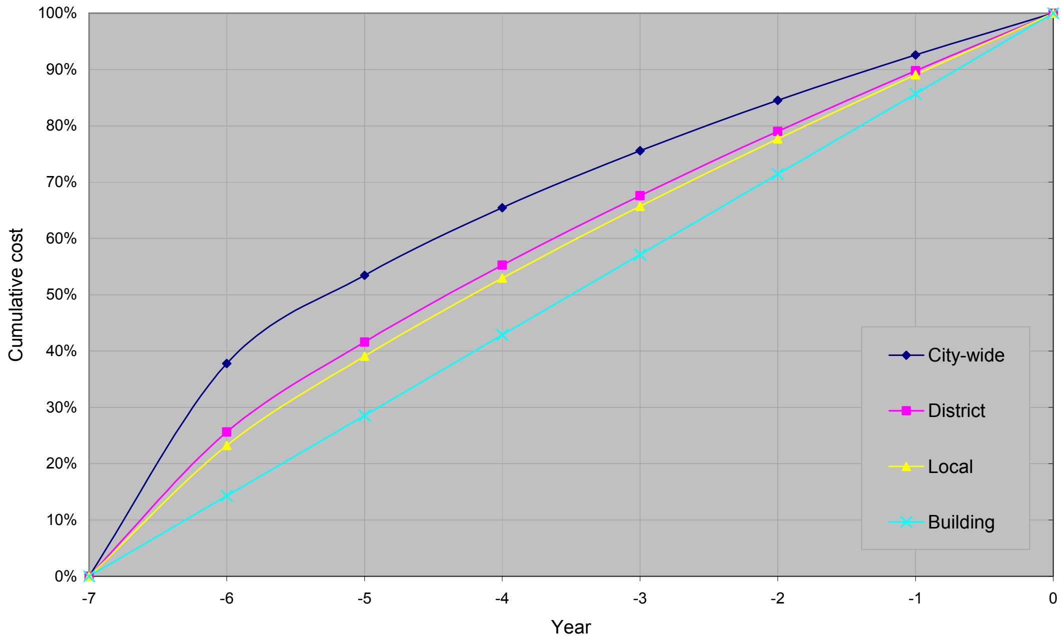

Figure 7-A Capital cost lead in

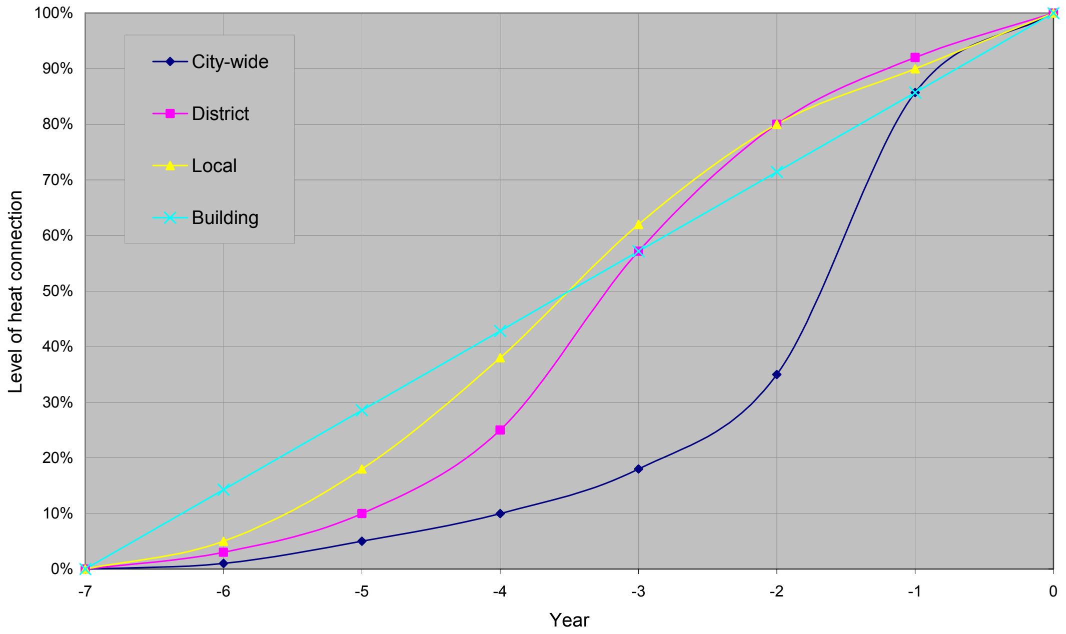

Figure 7-B Heat connection lead in

The operational period of the schemes is taken to be 25 years, during which time there is an annual cost incurred for fuel, electricity, maintenance and operation of the schemes. This annual operational cost is calculated separately for each of the schemes, and is assumed to be constant over the operational period.

The fuel costs, imported electricity costs and annual maintenance costs for CHP, DH mains and gas boilers were calculated using rates given in Appendix F. Allowances have been made for plant replacement in the CHP/DH options, based on typical plant lifecycles. These allowances have not been scaled to reflect the likely longer lifecycles of large SIGE and CCGT plant than the Buildings-CHP units. Further, it should also be noted that the lifecycle, maintenance and replacement requirements of domestic CHP units are currently largely unproven. It is however likely that these consumer units would be totally replaced when critical parts become worn, whereas a larger CHP unit could at such a stage be cost-effectively overhauled.

8 Economic Comparisons

The economic comparisons are based on calculating the lifetime cost of supplying energy to the city taking account of all capital, fuel, electricity import and export, operating, maintenance and lifecycle replacement costs over a 32-year period. This represents a 7-year lead in phase as schemes are implemented, followed by a 25 year operating period. A summary of the costs used may be found in Appendix F.

The costs are summated using a discounted cashflow analysis to provide a Net Present Value (NPV) for the city's energy needs (the NPV is negative as it represents a cost).

The NPV is calculated for the following assumptions:

- discount rates 3.5% in real terms
- lifetime 32 years
- no financial benefit from carbon savings
- constant energy prices

The results are shown in Figure 8-A below.

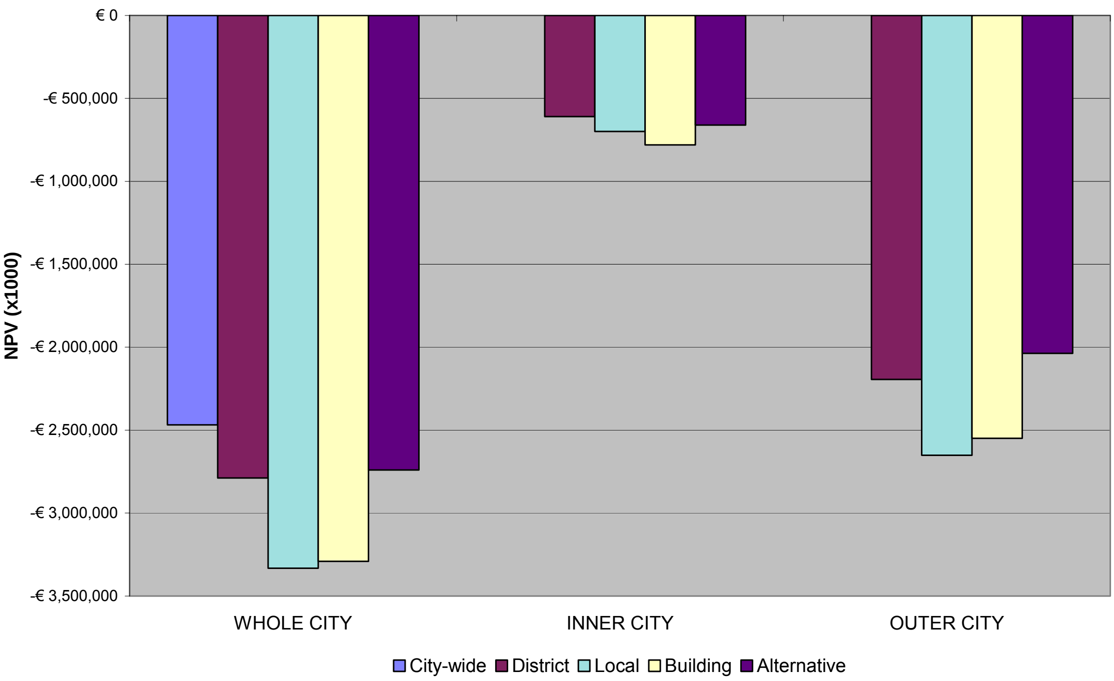

Figure 8-A Comparison of scenario Net Present Values

The comparison shows that in the whole city case the only economically viable CHP system (i.e. lower cost than the Alternative) is the City-wide scenario. In the inner city the District level CHP would be viable but in the outer city none of the CHP systems are economic. These conclusions apply even at the low discount rate used of 3.5% (UK public sector guidance discount rate). The City-wide CHP/DH system benefits from a high efficiency, low capital cost, CCGT power plant, which more than offsets the additional costs of city-wide heat distribution. The majority of the costs for heat distribution are at the local level, which is one of the reasons why the Local CHP/DH systems do not compete well particularly in the lower density outer city areas.

Electricity Network Costs
As discussed later in section 10, the cost of constructing and maintaining the electricity network will be similar for all systems. The cost of electricity is therefore based on the cost of importing power at the edge of the city and is constant for all scenarios. This is in contrast to a micro-

economic analysis, which would credit the Building CHP systems with a higher electricity price related to the market price at the building.

Gas network costs

The base case analysis has assumed that gas prices vary between the schemes with typical prices representative of that found in the market. Hence small customers at individual buildings pay more than the large CCGT at the edge of the city. The higher costs at the customers are needed to pay for the gas distribution system.

Whilst this seems reasonable, it is not necessarily correct as the gas distribution network is largely a fixed capital asset and hence the cost for its construction may still need to be paid for whether it is fully utilised or not. An alternative analysis assumes a constant gas price for all scales of scheme, representing the cost of gas at the city boundary. The results of this analysis are shown in Figure 8-B.

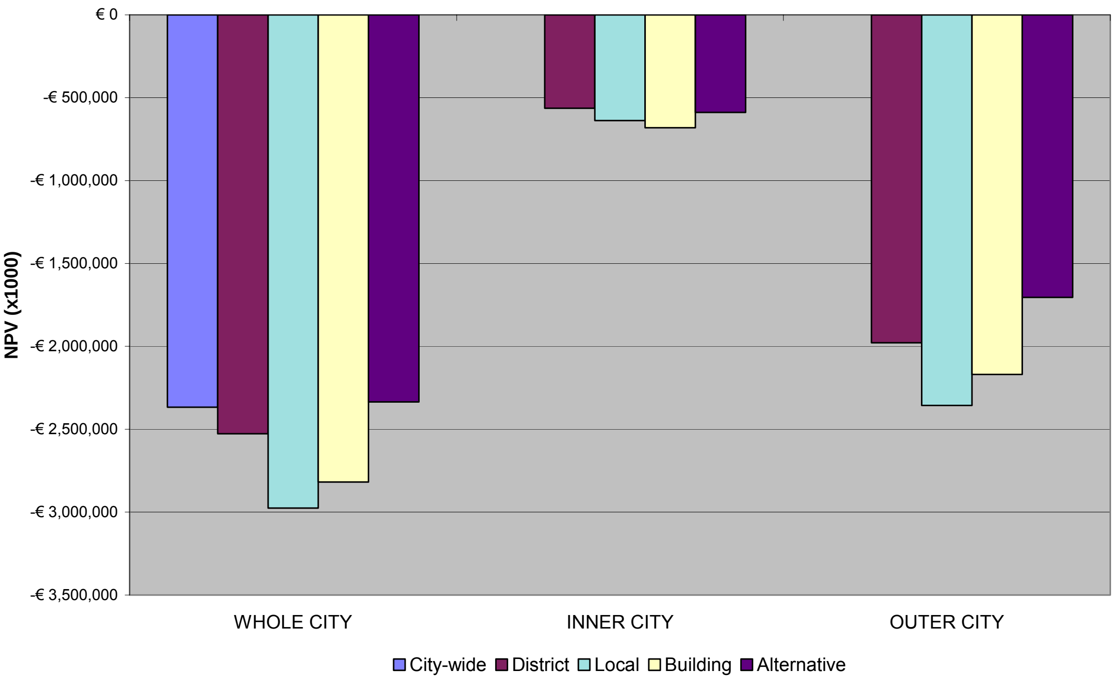

Figure 8-B Comparison of Net Present Values with constant gas price across scenarios

The main difference is that the Alternative and Buildings systems benefit significantly compared with the other schemes. However it is still the case that the City-wide and District CHP/DH schemes are preferred over the other CHP systems. Only the District CHP/DH in the inner city is economically viable under this assumption.

Both of the analyses can be considered valid depending on the circumstances.

If, for example, the gas grid has not yet been installed then the base case comparison gives an indication of the relative merits of the systems. This might be the case for new developments in the city or where there is a choice between renewing an old District Heating network or installing a new gas network. Another example where the base case analysis is appropriate would be where the gas infrastructure is ageing and any debt on the gas grid has been paid off; the cost difference seen in the market is then solely for ongoing maintenance work.

If, however, the gas grid is relatively recent and there are high fixed costs that will need to be recovered irrespective of the CHP/DH system, then the second analysis is more correct.

9 Environmental Comparisons

Comparison of CO_2 emissions
From the energy balance for each of the four CHP concepts it is possible to directly calculate the CO_2 emissions associated with each and compare this to the base case of separate heat and power production. The initial calculations assume natural gas is the only fuel used for heating boilers and CHP plant, with an emissions factor of 190gCO_2/kWh fuel supplied. There is also a need to specify an emissions factor for imported electricity to the city from the external grid. An emissions factor of 430gCO_2/kWh is used in the UK, which reflects an average of power sources approximately a third nuclear, a third gas and a third coal. For the Alternative case we have assumed a gas-fired CCGT plant at the boundary of the city, which for a GCV efficiency of 48% would result in an emissions factor of 390g/kWh slightly lower than the UK grid mix. It is this figure that is used for the Alternative case and for the import/export of electricity at the city boundary. This means that the environmental benefit calculated is solely the result of the use of CHP technology and not fuel switching to gas.

The results of this comparison are given in Figure 9-A. This shows that the large-scale CHP/DH system provides the greatest CO_2 saving over the base case of separate heat and power. Although there is additional energy needed to cover heat and electricity distribution losses and pumping energy, the higher efficiency of the central CCGT plant more than offsets this disadvantage.

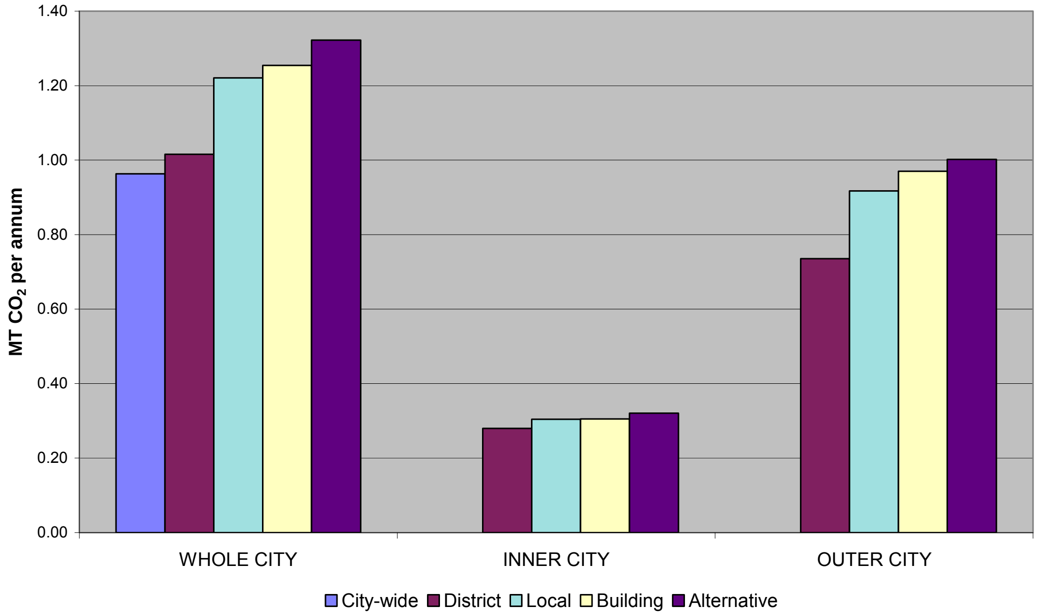

Figure 9-A Comparison of scenario Carbon Dioxide Emissions

Use of Alternative and Renewable fuels and heat sources
It is possible that other fuels could be used for the CHP plant with lower CO_2 emissions. The main fuels available would be municipal waste and biomass. Municipal waste may be processed first to manufacture a fuel in pelletised form. Biomass may be derived from local energy crops, surplus wood from industrial operations, sawmills, furniture manufacture, wood arising from tree prunings within the parks and gardens of the city or green waste from households.

Of the CHP technologies currently available within this field, the most proven is mass-incineration of municipal waste or combustion of biomass in a conventional boiler to raise steam for steam turbine power generation. Both of these processes are typically carried out at a relatively large-scale to achieve good economics and are most relevant to the City-wide and the District scale. The newer technologies such as anaerobic digestion and pyrolysis could be employed at the more local scale in the future. It is unlikely that any of these sources could contribute to CHP at the individual Building scale.

In order to assess the impact of municipal waste we have estimated the usable waste arising from the generic city as 105,000 tonnes p.a., resulting in a potential electrical generation capacity of at least 40GWh p.a. and useful heat generation of 80GWh if fully utilised, representing 2% and 3% of the total city demands for electricity and heat respectively.

Industrial waste heat sources

Heat from industrial activity can be utilised in DH schemes. As the industry is unlikely to be located close to centres of population this advantage is unlikely to be gained except at the District or City-wide scale.

It is therefore considered that the CO_2 emissions associated with the large-scale CHP/DH scheme would in practice be lower as other low-carbon fuels would be able to be used. Figure 9-B shows the CO_2 emissions predicted assuming the use of municipal waste for the City-wide and District CHP/DH schemes only.

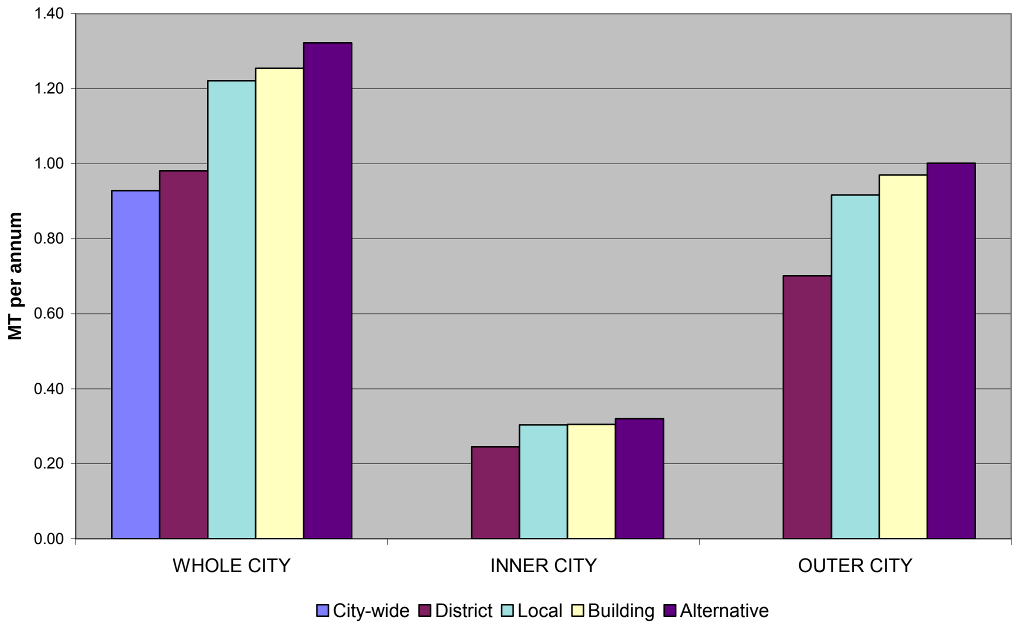

Figure 9-B Comparison of CO_2 emissions for city assuming waste incineration

Air Quality

Local Effect

One of the advantages of DH systems in the past has been the improvement in air quality. This is because centralised high efficiency boilers or CHP can control emissions to a higher level and are displacing localised small boiler systems. The change from fuel consumption in small boilers to heat supplied from a CHP plant can lead to local improvements in air quality. The main issue with gas-fired systems is NOx that is attributed to poor health and acidic damage to stone buildings.

The local air quality benefits therefore increase as the size of the CHP system increases as any pollutants although more concentrated can be dispersed at the edge of the city via a high stack. In addition, the larger-scale gas turbine systems burn the fuel continuously in external combustors rather than by means of an internal explosion. Hence NOx production from a modern large-scale gas turbine is significantly less than from gas-engines.

Global Effect

The 'acid rain' effect is well known: NOx production in one country, although dispersed above the city area, can be transported by the global air streams to other countries, creating acid rain. There is a clear benefit here from all of the CHP systems as less fuel will be burned and less NOx will be produced. However, although the large-scale CHP/DH systems will result in the lowest NOx emissions the dispersion may occur over a wider area.

Visual impact and disruption

Of the four CHP/DH options considered, the visual impact on a city is likely to be least for the individual Building CHP (located within existing boiler rooms in buildings) and the very large scale – located at the edge of the city in an industrial zone for example. The Local gas-engine CHP systems could also be integrated within the built environment with careful design, however stacks will be visible and cannot be easily concealed. The most difficult CHP/DH type is probably the District level where a large site area is needed and the height of the boilers and stack is also significant.

10 Other Comparisons

Referring back to Table 3-1, it can be seen that the quantitative modelling carried out does not take account of all of the factors that might influence the nature of CHP/DH developments. These other issues are therefore discussed below in a qualitative manner.

DH Technology
The smaller Local systems are more likely to be designed using low operating temperatures which can result in a higher efficiency CHP plant, or better use of heat from other sources e.g. industrial waste heat. In general though, the additional heat recovery from using lower temperatures is relatively small and there is unlikely to be a significant difference between Building CHP and the Local level CHP plant.

The use of direct connection could be easier to achieve with the Local CHP systems, however it would still be possible with the larger systems if hydraulic separation was used at a higher point within the network

DH Administration
The administration costs of operating a Local level DH network are likely to be high in proportion to the heat sold than the larger systems. Overall the impact is expected to be small however.

Impact on electricity networks
The large City-wide systems would have least impact on the development of the electricity network. In selecting sites for a new CCGT plant consideration would be given to a location closer to the city than would otherwise be the case. This may result in minor changes to the costs of connecting to the national grid. There would be no change to the design of the electrical distribution system within the city as the power flows would be the same as the non-CHP case. The morning peak heat demand is likely to occur before the electrical demand rises, and with a large extraction-turbine CHP the provision of the heat peak will result in a reduced electrical output at a time when prices are still low.

At the other extreme, a large number of Building CHP plants could have a significant impact on the electricity network as fault levels may be exceeded as a result of the additional generating capacity and this would mean that additional capital expenditure is required. A large amount of local generating capacity would however reduce the capacity required for importing and distributing power to the city potentially leading to avoided costs for upgrading for capacity reasons. At times when the amount generated would exceed the local demand there would be a need for power to be transferred up the network to be exported. This could occur for example in the early morning period when buildings are being pre-heated prior to occupation but when electrical demand has not risen to day time levels. This reverse power flow would cause problems in the networks. A recent study in the UK concluded that existing LV networks can, in most circumstances, accept up to 100% penetration of micro-generation, provided relatively low cost modifications were made to transformers [4]. However this solution would also require the adjustment of current system operating voltage parameters, which has raised concerns from the network operators regarding quality of supply.

Intermediate types of scheme, the Local CHP and the District CHP could have advantages to the electricity network in terms of capacity flows however the same issues of fault levels and potentially reverse power flows would occur. This study has not attempted to analyse these impacts in detail and as discussed in section 8, the broad assumption has been made that electricity network costs are constant for all CHP/DH types.

Impact on gas networks
For the City-wide scheme the gas network within the city would see a reduction in its load as buildings are transferred to the District Heating supply. A new high-pressure supply would be required at the CCGT plant. Local heat only boilers would still be needed for top-up and standby and the capacity in the network to supply these boilers would need to be retained. The overall effect would be that the price of gas rises as a similar network capacity is needed but with less volume being sold.

For the Building CHP system the load on the gas network will increase both in peak terms and volume terms as electricity as well as heat is being generated at the customers. The improved load factor would lead to lower gas prices. However the increased peak demand could lead to the need for additional investments in the gas network capacity and hence increases in the price of gas.

For the intermediate cases, gas volumes would increase at the level of the CHP plant but local gas distribution volumes would be displaced by the DH supply. Again the cost of gas is likely to increase as a result of lower volumes being sold over a relatively fixed asset. This study has not been able to evaluate changes to the gas network in detail and the economic evaluation in section 8 uses two contrasting assumption to evaluate the economics of the CHP/DH types.

Implementation and market issues
The straightforward economic implications of the implementation differences between the scenarios have been accounted for in the modelling (see section 7). In reality though, the initial high capital costs involved with the larger CHP/DH schemes are only likely to be committed if there is a guarantee of sufficient heat sales. Although some potential customers could be committed prior to the project commencing this is unlikely to be a significant proportion of the city demand. Either the marketing risk will need to be taken by the public sector, or there will need to be a regulatory regime that will require connection or make it very advantageous to do so via taxation of the alternatives.

The Building-CHP systems are different in that they can be implemented incrementally as individual building owners take decisions to install CHP. This does not necessarily mean that the systems will be implemented more easily or more quickly, as the building owners will have many calls on their money and the economic case for Building CHP is unlikely to be very strong except in niche markets. One possible scenario is the use of an energy services contract whereby the CHP supplier finances the CHP unit and recovers the cost by selling electricity and heat to the owner/occupier.

Overall market penetration could be higher with the District and City-wide schemes if the advantages of diversity of demand outweigh the additional costs. This means that low load factor buildings such as offices and schools could be economically connected to a large network even though a Building CHP system would not normally be economically viable.

Security of supply for electricity
Advocates of distributed generation point to the advantages of security of supply when compared to centralised power stations and an extensive electricity distribution network. This would appear to be valid in rural areas where storm damage is more frequent. In city areas, the reliability of the system within the city is usually relatively high and any weakness is a function of the national grid and the margin in capacity of the generators connected. Whereas an individual Building CHP system can be designed also to act as a standby on the public supply, including the incorporation of suitable demand side management equipment (i.e. load-shedding of non-essential loads) it is difficult to see how other embedded generators at Local or District level could improve security of supply as they would not necessarily be sized to meet the electrical demands of any given area, and load shedding would not be feasible. The CHP size will be dictated by the economics of supplying heat - which will normally result in a smaller capacity than that needed for standby electrical supply. Overall the enhancements to security of supply offered by any other types of CHP/DH proposed is likely to be very marginal with the Building CHP type offering a small and limited improvement in some buildings.

Security of supply for heat
For larger heat customers who are retaining their boilers for standby and peak use the security of heat supply would clearly improve with any of the DH options, as they introduce a second source of heat supply. For residential districts the security of heat supply is a function of the reliability of the DH networks and the heat sources that supply them. The larger-scale DH systems are likely to offer higher security levels as there would be multiple heat sources and possibly parts of the network would be a ring main. In addition, a larger DH organisation is likely to have more sophisticated monitoring and maintenance capabilities, with higher quality water treatment.

Whether DH networks are more reliable than individual heating systems is difficult to establish. The gas and electricity distribution systems have a high level of reliability, however breakdowns of individual boilers are more likely than with central plant where there will be additional reliability through standby boilers and pumps. The main difference is one of perception. A failure on a DH network will affect all customers at the same time, whereas failures of individual heating systems may occur much more often but with little overall impact as only one customer is affected at any one time. However another aspect is the difference in outage duration and local consumer impact in the event of a failure. If a domestic boiler or dCHP unit fails, the consumer is responsible for arranging repair, which is likely to be time-consuming and stressful, and may not be immediate. If failure occurs on a DH network the repair is administered by the organisation responsible and is likely to be attended to with high priority; the consumer may not even be aware that a problem has occurred.

The location of peak and standby boilers is probably the most important factor in determining security of supply. In this study we have assumed that major buildings retain their boilers and that the peak and standby boilers are located at the Local level.

Integration of alternative heat production technologies
A key advantage of larger DH networks is fuel flexibility. There are many options when additional heat production facilities are introduced to expanding networks. Once a large DH 'main' is established, it serves as a ready route to market for heat production facilities. This could stimulate the development of heat production plants using alternative fuels such as biomass, waste and hydrogen, and new technologies such as pyrolyisis, gasification or fuel cells, which may, on a small scale, not be efficient, economic or simply not viable. Larger scale biomass and waste-to energy heat production facilities are more likely to be positioned near to good transport facilities, to minimise environmental impact from fuel transportation.

11 Sensitivity Analysis

Sensitivities considered
The results presented above contain a large number of assumptions, most of which are considered typical estimates for Western European countries. It is recognised that significant differences exist between countries and the results should be interpreted with care. Similar studies are recommended in individual countries using similar methodologies and local cost and energy data.

To carry out a comprehensive sensitivity analysis on all of the parameters involved and combinations of these sensitivities would be a very arduous task. The analysis has therefore concentrated on four key issues, which are expected to influence the results significantly. These are:

The heat density

For cities with a low heat density the District Heating mains would be more expensive in the total cost and therefore the Building CHP systems would be more likely to be the best option

The cost of imported natural gas and imported power

If energy costs are high the more efficient energy systems i.e. large-scale CCGT and City-wide DH would be expected to improve their position compared to the smaller-scale systems

The cost of capital – discount rate

The economic comparisons have been carried out assuming a discount rate of 3.5% as recommended by the UK Treasury for public sector projects. Higher rates would be used for private sector projects and in this case, those options with a relatively high capital cost such as CHP/DH would become less attractive compared to Building CHP options.

The cost of District Heating networks

The network costs used in the comparisons are based on typical prices seen in the UK. If the cost of the network is lower then the District and City-wide DH schemes would be expected to become more competitive compared to the other options.

Heat density
Heat density can be considered to be a function of the built form i.e. detached houses, terraced (row) houses, apartment blocks etc, the standard of construction and the climate. To a certain extent the effect of heat density may be seen from the base case results, as the heat densities of the different areas of the city vary considerably, as shown in Figure 11-A.

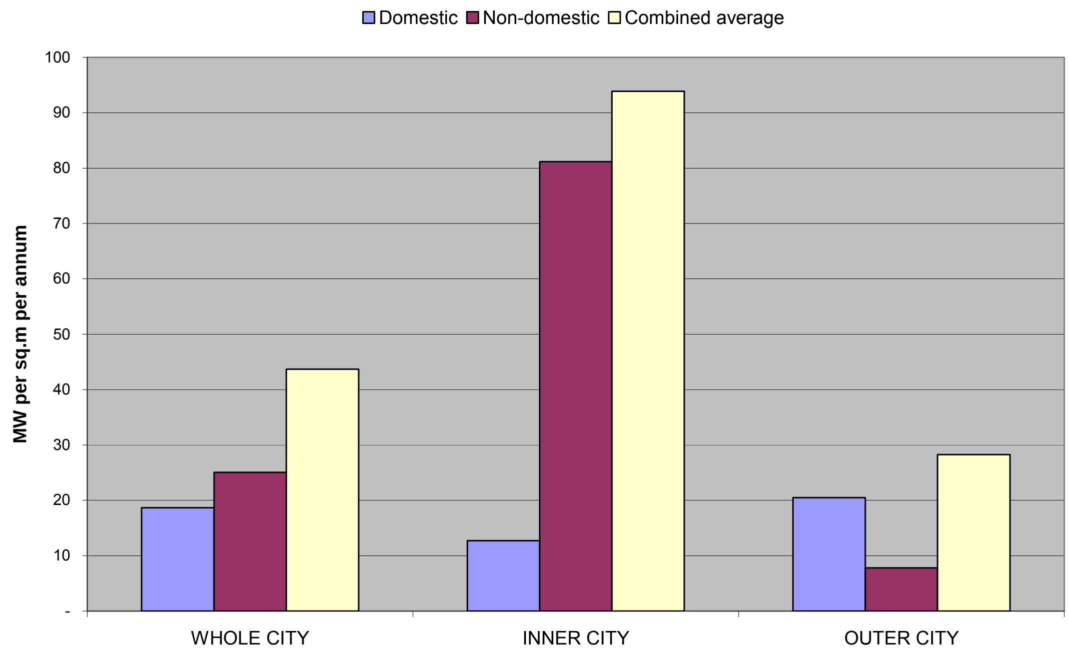

Figure 11-A Heat density of city sectors

It has been shown (in Figure 8-A), the Local CHP/DH is more economic than the Building CHP option in the inner city but not in the outer city.

The cost of imported natural gas and imported power
Figure 11-B and Figure 11-C present a sensitivity analysis of the price of gas and electricity respectively. The result of an increase in gas price is an increase in overall cost for all of the schemes. However the larger CHP/DH schemes can be seen to suffer slightly more. The result of an increase in electricity price is a cost increase for the Local, Building and Alternative schemes, the Building and Alternative schemes being hit particularly because they rely more heavily on electrical import. The larger CCGT based CHP/DH schemes actually benefit from an increase in electricity price because they are net exporters of electricity. If electricity prices fall then none of the CHP systems are viable compared to the alternative.

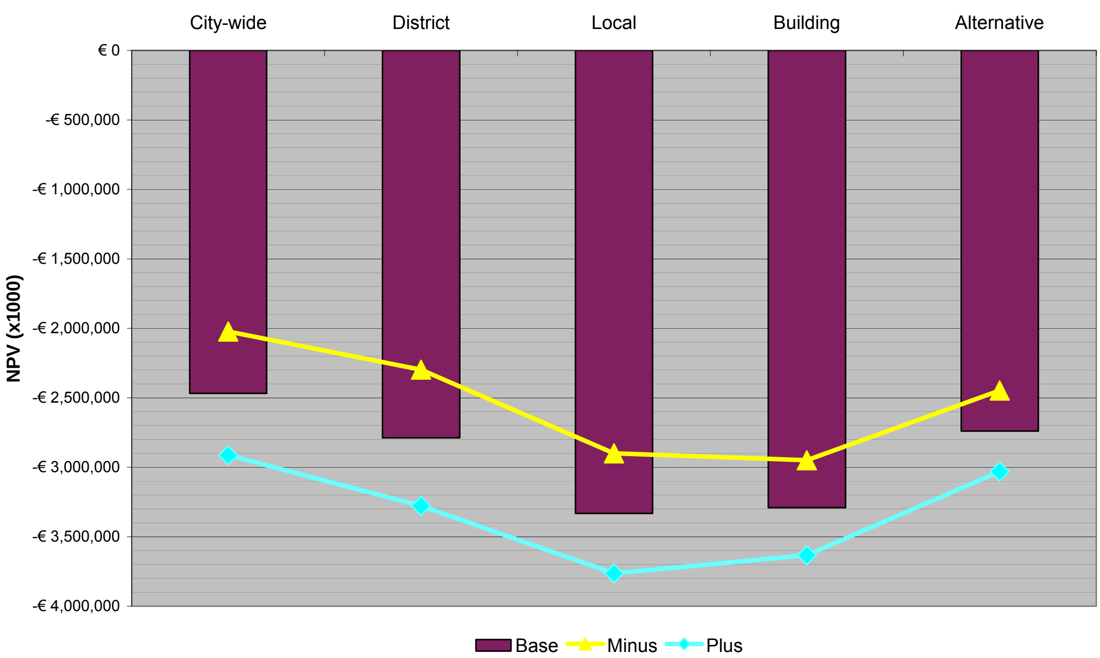

Figure 11-B NPV with gas price variation of 30% (Whole City)

Figure 11-C NPV with electricity price variation of 30% (Whole City)

The cost of capital – discount rate

Figure 11-D, presents the change in NPV for the CHP scenarios when using increased discount rates. It can be seen that the whole life costs of the larger CHP/DH schemes are less affected by changes in the discount rate used than the smaller schemes, because more of the capital is invested at an earlier stage, and subsequent annual running costs are less. This means that at higher discount rates, schemes with higher running costs and lower capital become more attractive. At a 9% discount rate the Building CHP option and the City-wide CHP/DH have similar NPVs.

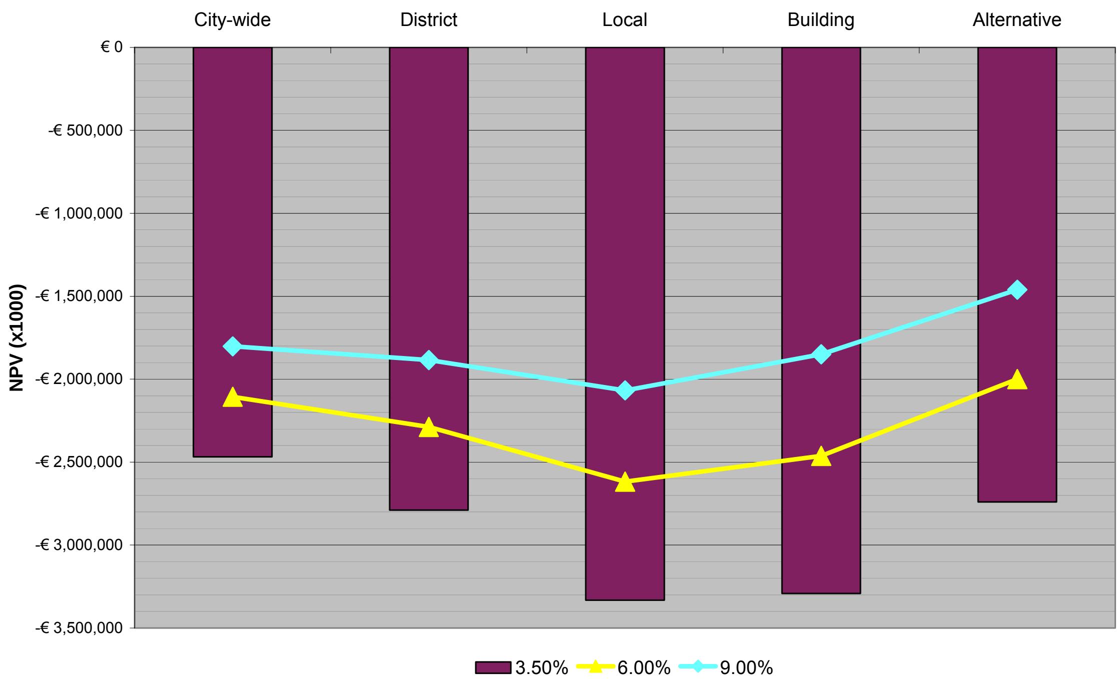

Figure 11-D NPV with variation in discount rate (Whole City)

The cost of District Heating networks

Figure 11-E present a sensitivity analysis of the capital cost of District Heating network infrastructure. As expected, the CHP/DH options exhibit some sensitivity to the capital cost of DH installations, whilst the non-DH options obviously do not show any at all. The fact that there is a

similar impact from this sensitivity between the Local, District and City-wide options reflects the fact that the District and transmission mains are a relatively small cost compared to the Local level mains.

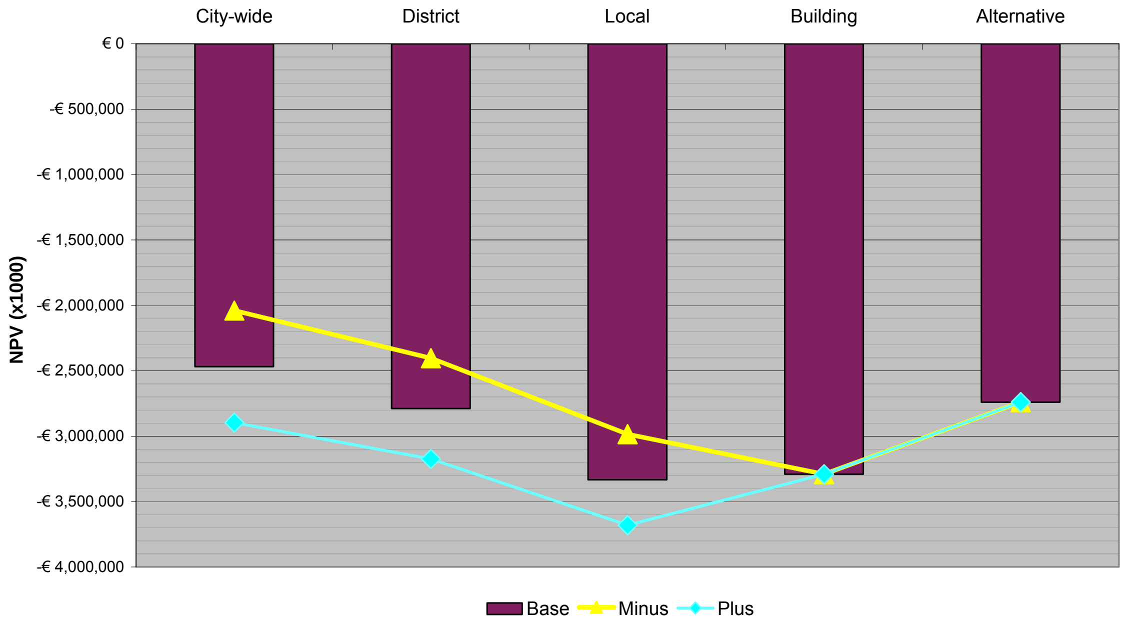

Figure 11-E NPV with variation in DH capital cost by 50% (Whole City)

12 Discussion of Results

A number of commentators have predicted that the traditional concept for large-scale power generation and an electricity distribution system that is designed to transfer power in one direction from the remote power station to the consumers is likely to change in the future to a more active network with large numbers of distributed generators.

Some of these predictions are related to the use of CHP but others are related to the development of renewable energy sources which, in many cases, are more suited to smaller-scale, distributed power generation such as photo-voltaics or bioenergy plants.

The change to a hydrogen economy and the development of fuel cells could also result in the historical economic drivers for ever larger power station developments and greater reliance on the national grid becoming superseded.

However, this study does not show, as far as CHP/DH systems are concerned, that the trend towards large numbers of small generators is necessarily the most likely forward scenario or the most advantageous one in environmental or economic terms. Whereas some of the renewable energy technologies use diffuse sources of energy and therefore need to be distributed this is not the case with CHP where there is still a case for large centralised plant. Although this results in energy losses in distribution of electricity and heat these are more than offset by the higher electrical efficiency obtained with large-scale power generation. Large power stations also benefit from lower capital costs, higher availability and lower operation and maintenance costs.

The Local gas engine CHP results in a self-sufficiency of power generation over the year. The CCGT options (District and City-wide) result in a net export of power, whereas the Building CHP options still require significant import of power from outside the city.

The study has only analysed one size of city (population circa 250,000). The results for the Building CHP and Local CHP/DH systems will be equally relevant to smaller cities. The larger CCGT option may be a valid solution for a smaller city but will need to be evaluated against the specific heat demands of the city.

13 Conclusions

This report has compared CHP/DH systems at four different scales and evaluated the whole life costs and environmental benefits of each. The conclusions for each system are:

City-wide CHP/DH

The study has shown that despite the potential offered by new distributed CHP technologies the most cost-effective and environmentally beneficial energy supply for any city will be the construction of a large-scale District Heating system supplied with heat extracted from a major power station. The higher energy efficiencies and lower capital costs of large-scale gas-fired power stations have been shown to more than offset the costs of developing the large-scale District Heating network. This solution also provides the biggest reduction in CO_2 emissions of all the options compared to separate generation of heat and power.

The large-scale heat networks also potentially allow the use of a wider range of heat sources not available to the smaller schemes e.g. waste heat from industry and waste incineration, giving further environmental benefits.

It can therefore be recommended that cities where large-scale CHP is not yet established prepare long term plans to develop City-wide heat networks. However if these are to be implemented without undue marketing risk, it is likely that a high degree of regulation will be required, both to oblige consumers in designated areas to take heat from the DH network, and to sanction the necessary infrastructure works.

District CHP/DH

CCGT CHP plants in the range 30MWe to 100MWe are now available however these appear to be too expensive to compete with the larger-scale City-wide scheme. Although DH transmission mains are required for the City-wide scheme, the cost of these is not very significant. The additional efficiency of the District CCGT appears to be sufficient to offset the additional costs for the more complex CHP plant and for the District mains when compared to the Local CHP/DH systems.

Local CHP/DH

The study has shown that small-scale Local CHP/DH schemes are not as cost-effective or as environmentally beneficial as either the City-wide schemes or the small CCGT schemes. The largest part of the DH cost is in the Local level mains. The gas engine CHP/DH is not as economic as the CCGT options due to lower electrical efficiency, lower availability and a lower proportion of CHP heat. In general, regulation will not be required to the same extent as larger schemes as only a few anchor customers need to commit to a long-term heat contract. Local environmental impact can be minimised with careful design and there is some additional economic and energy efficiency benefits from generating and using the electricity within the local area.

Building CHP

The new technologies of mini and micro CHP offer the cost advantage of avoiding the DH network investment, and the generation of electricity near to the point of use leads to lower electrical losses in the distribution system. As a result, the Buildings CHP option is more economic than the Local CH/DH in the outer city lower density areas. These advantages do not however outweigh the disadvantage of lower electrical efficiency and there may be costs associated with the electrical network if maximum market penetration is to be achieved. The new technology of fuel cells offers much higher electrical efficiency levels and as this technology is also being developed for vehicles this may lead to a reduction in capital costs. At present however the breakthrough in cost and lifetime appears 10-15 years away. Such fuel cell systems are most likely to be introduced initially in lower density housing areas where the additional capital cost is also less likely to be a major barrier. Consequently the development of CHP/DH schemes can be seen as complementary to future developments of fuel cell CHP. In addition, fuel cells can be constructed at a larger-scale as well and these may become more cost-effective so that they could be incorporated into the larger CHP/DH systems. Fuel cells are best operated continuously rather than intermittently which again indicates a benefit in using them in conjunction with larger DH systems where diversity of demand and thermal storage will lead to a smoother heat demand profile.

These conclusions are drawn using typical cost data for Western Europe and may not be directly transferable to other countries. The principles and methodologies discussed will however be of value to energy planners in all cities seeking cost-effective solutions to environmental concerns.

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[3] **Reuse of Excavated Materials (1999: T3.3)**, *IEA Programme of Research, Development and Demonstration on District Heating Annex V*, 1999, http://www.iea-dhc.org/dhcV_1.htm

[4] **System Integration of Additional Micro Generation (SIAM)**, *UK Department of Trade and Industry*, September 2004, www.dti.gov.uk

Appendix A Report on Experience in Finland

District heating in Finland
Large-scale District Heating (DH) was first started in cities in the 1950s and 1960s. Later in the 1970s after the first oil crisis DH developed in the smaller towns. There are now over 200 heat distribution utilities in Finland. Most District Heating utilities are owned by municipalities and they operate within the owners' area.

Approximately 32% of electricity used in Finland in 2002 (83.8TWh) was produced in Combined Heat and Power (CHP) plants and 75% of District Heating energy (31.8TWh) in 2002 was produced from CHP. The Finnish industrial sector consumed 53% of all electricity in 2002, and about 32% of electricity was generated in CHP plants. District heating covers 55% of the space heating demand of Finnish dwellings district heat power was 14,900MW and the length of the pipeline system was 9,100km. In total 37% of district heat and CHP electricity was produced by natural gas, coal accounted was 27%, peat 19%, oil 5.7% , wood 8.4% and other (industrial process heat, recycled fuels, biogas and other) 2.9%.

CHP production in Finland
At first, mainly oil fired CHP plants were built in the 1960's and large coal and peat fired CHP plants in 1970's. Building of CHP plants were based on large enough District Heating activities in towns, where CHP plants are located. CHP production has a high overall annual efficiency, which in Finland often reaches 85–92%. This is much higher than the efficiency of 40–45% with condensing power plant. Separate power and heating plants need about 40% more fuel than a corresponding CHP plant. Figure A-A presents the development of CHP plant in Finland from 1960 to the present time and some future trends.

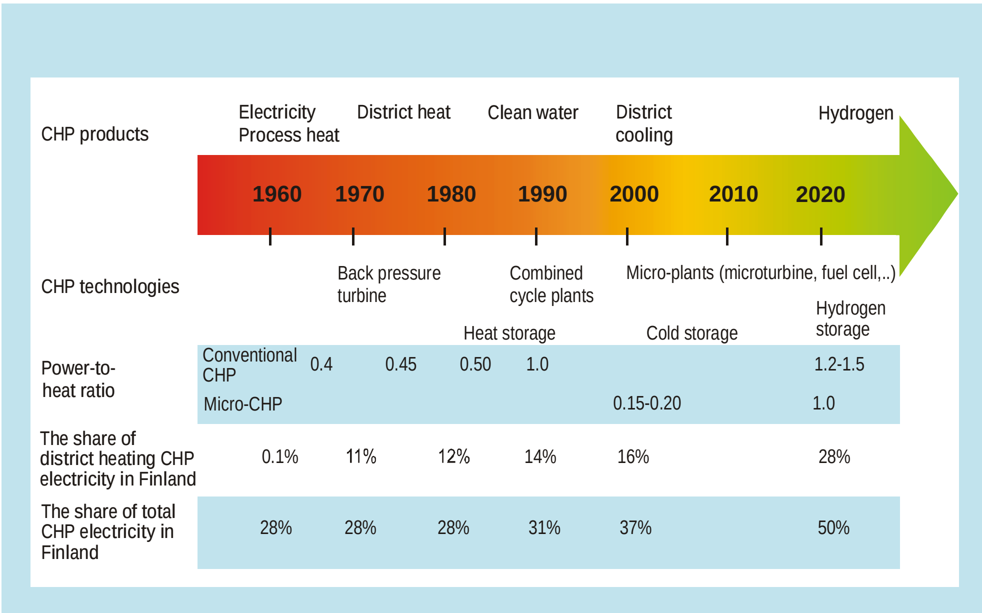

Figure A-A Past and anticipated future development of CHP technology

In 2002 there were 58 locations in Finland that have CHP production connected to a DH-network. The total capacity was 4,310MW electricity and 6,790MW heat. The capital Helsinki of Finland has the biggest CHP capacity of 1,017MW in electricity and 1300MW in heat.

There are some 40 small-scale CHP plants with electric powers less than $20MW_e$ connected to District Heating networks in Finland. Ten of these plants utilise oil or coal as fuel while the others use either natural gas, biomass or peat. During the last 10 years, no new coal or oil fired plants have been built while 10 new biomass plants and several gas fired units have started operation. Most of the small CHP plants using biomass also use peat as fuel. In some plants, peat is the main fuel and the share of biomass is less than 30%.

The potential for additional CHP capacity in Finland has been estimated to be 900MW of electricity and 1,600MW of heat with 6,000 hours annual peak load time based on district heat energy consumption in 2000. The size of CHP plants would be mostly in the scale 1–$20MW_e$.

CHP plants in Finland

Vuosaari natural gas fired combined CHP plant in Helsinki

Vuosaari B combined CHP plant was started in 1998. The plant consists of two gas turbines, two exhaust gas boilers and one steam turbine with two pressure levels. The total power is $463MW_e$ (2x159 MW + 145MW) and 416MW district heat (heat exchanger 1 @ 176MW + heat exchanger @ 170MW + heat exchangers 3 and 4 @ 35MW each). The scheme of the CHP plant is presented in Figure A-B. The total thermal efficiency is 92 % (NCV) and power to heat ratio is 1:1. The gas turbines have low NOx burners and the average annual emission limit 80mg/MJ can be reached. The gas flow to exhaust boiler is 520kg/s in temperature of 540°C. The temperature of exhaust gas after the boiler is 52°C. Steam turbine can generate $145MW_e$ in back-pressure used when temperature of 510°C, pressure of 75bar and steam mass flow of 136kg/s exist. The investment cost of the Vuosaari B combined CHP plant is about €460/ kW_e.

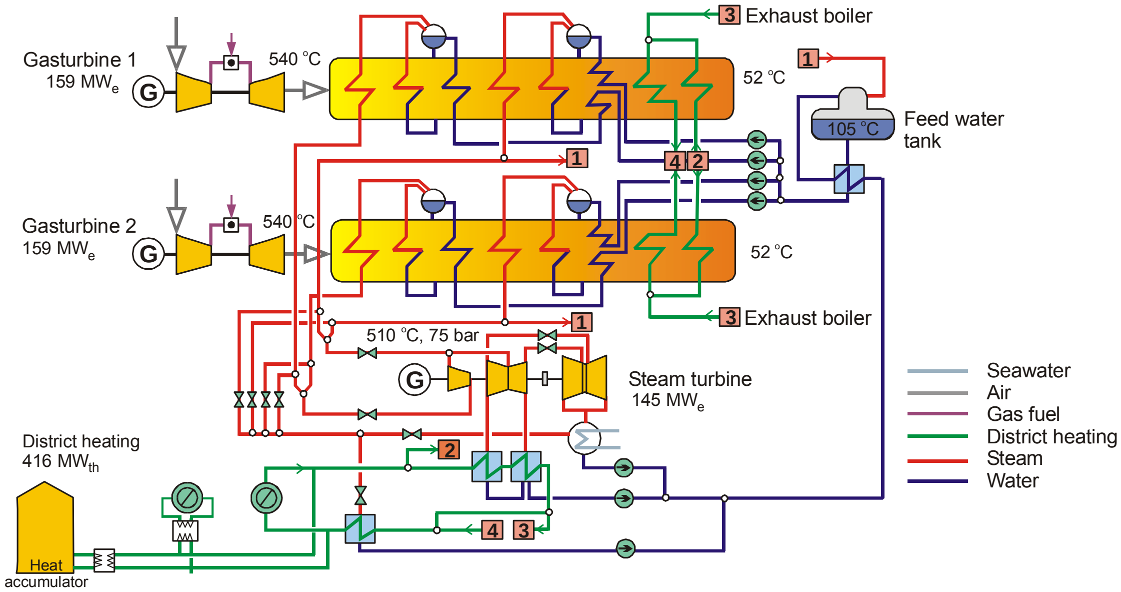

Figure A-B Helsinki, Vuosaari B natural gas fired 463MWe/416MWth combined CHP plant

A cylindrical heat store with the volume of 26,000m^3 (42m height and 29m diameter) is connected to the power plant. The maximum temperature in the unpressurized steel tank is 98°C. Thermal capacity is 130MW with temperature difference of 48°C. The heat storage can be used to compensate the variation of District Heating consumption.

Forssa biofuel CHP plant with BFB boiler

Forssa bubbling fluidised bed (BFB) boiler CHP plant is fuelled by wood biomass. It is started in 1996. The main fuel (54%) is sawdust and bark from wood processing industry and forest chips (34%). Wood building wastes and other wood-containing material are also used as well as recycled fuels (4%) from the neighbouring waste treatment plant [A1]. Total use of solid fuel is about 720TJ (200GWh) when annual operation is 7,500 hours. Hot corrosion, possibly due to chlorine from green chips, has resulted in the need for annual replacement of a part of the pipes in the super-heater.

A schematic of Forssa biopower CHP plant is presented in Figure A-C. The power is 17.2MW$_e$ and District Heating output 48MW$_{dh}$, when boiler output is 66MW$_{th}$ and fuel input 71.7MW$_{th}$. The total efficiency is 92% while the electrical efficiency is 24%. The boiler is fluidised bed type with the height of 20m and the cross-section area of 25m^2. The fuel ignites and burns when supplied to the glowing fluidised sand layer. Additional air is blown above the fluidised bed. The burning temperature is 800–850°C that gives low nitrous oxide emissions. When wood is used no sulphur dioxide is emitted. The live steam flow 22.8kg/s in temperature of 510°C and pressure of 62bar is led to back-pressure steam turbine. The turbine is equipped with two extractions, one for feed water heating and one for a 2nd district heat exchanger. After the turbine the steam is condensed in the 1st district heat exchanger for District Heating. The investment cost was about €17.1M, which equates to around €1000/kW$_e$.

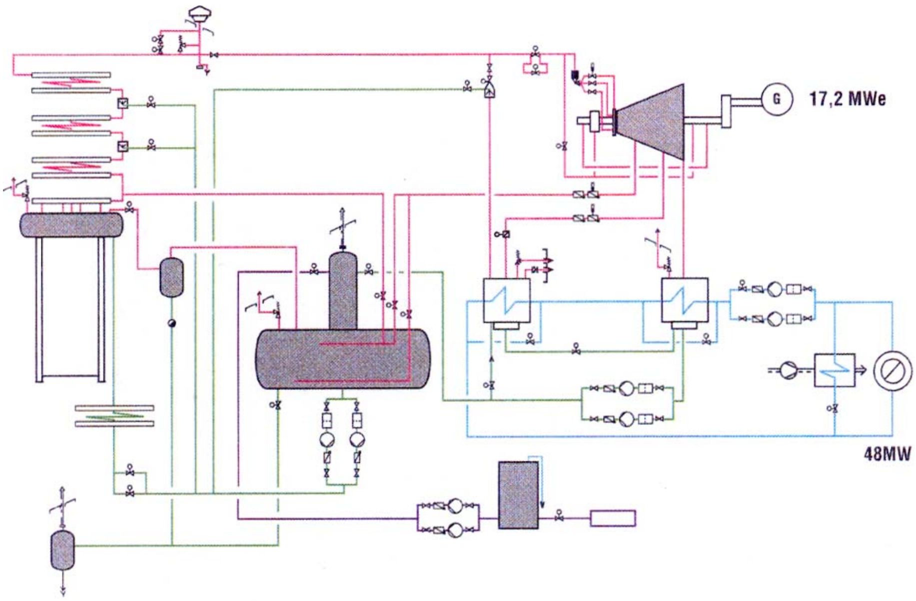

Figure A-C Forssa 17MWe/48MWth biomass CHP plant

Alholmens Kraft multifuel CHP with CFB boiler in Pietarsaari

Alholmens Kraft power plant in Pietarsaari is started in 2001 and is one of the largest biofuel circulating fluidised bed (CFB) boiler CHP plant in the world. The schematic of the CHP plant is presented in Figure A-D. The CHP plant produces in addition of electricity district heat to Pietarsaari town and process steam to UPM-Kymmene pulp and paper mill. The main fuels of the boiler are wood (40 %), peat (45 %) and coal (15 %). The total annual need for fuel is 12,600TJ (3 500 GWh). The plant is designed for flexible fuel utilisation from 100% biomass to 100% coal.

The CHP plant generates 240MW of electricity, 100MW process steam and 60MW district heat. The boiler produces steam 550MW$_{th}$ with 580MW fuel input. The steam temperature is 545/545°C (super heated / intermediate super heated) in pressure 165/40bar and steam flow of 194 /179kg/s.

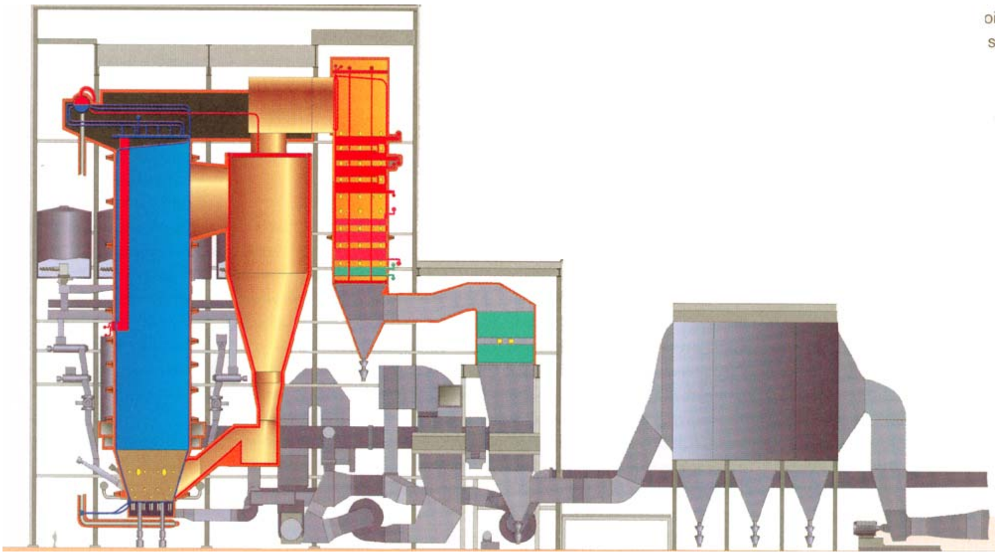

Figure A-D Pietarsaari biofuel CFB boiler CHP plant with 240MWe/100MWsteam/60MWdh

Iisalmi small-scale bio fuel CHP plant

The CHP plant with a BFB boiler has a fuel power of 48 MW, electric power of 14,7 MW and district heat power of 30 MW. Annual operating time is about 5,000 hours, annual power production 60-70 GWh_e and district heat production 150-185 GWh_{dh}. The plant started commercial operation in October 2002. A picture of the Iisalmi CHP plant is presented in Figure A-E and the process scheme of the plant in Figure A-F.

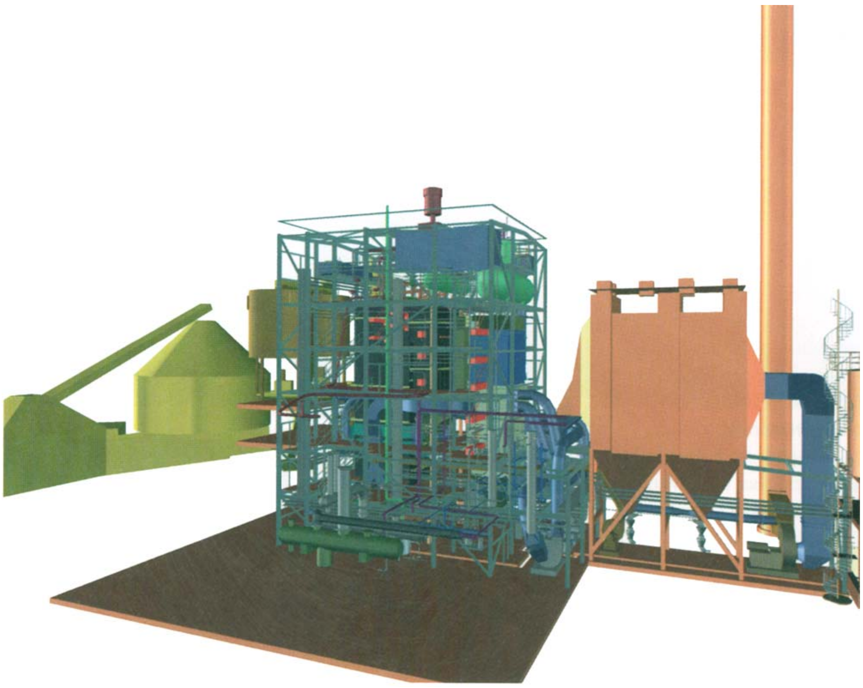

Figure A-E Small scale bio fuel CHP plant with BFB boiler at Iisalmi

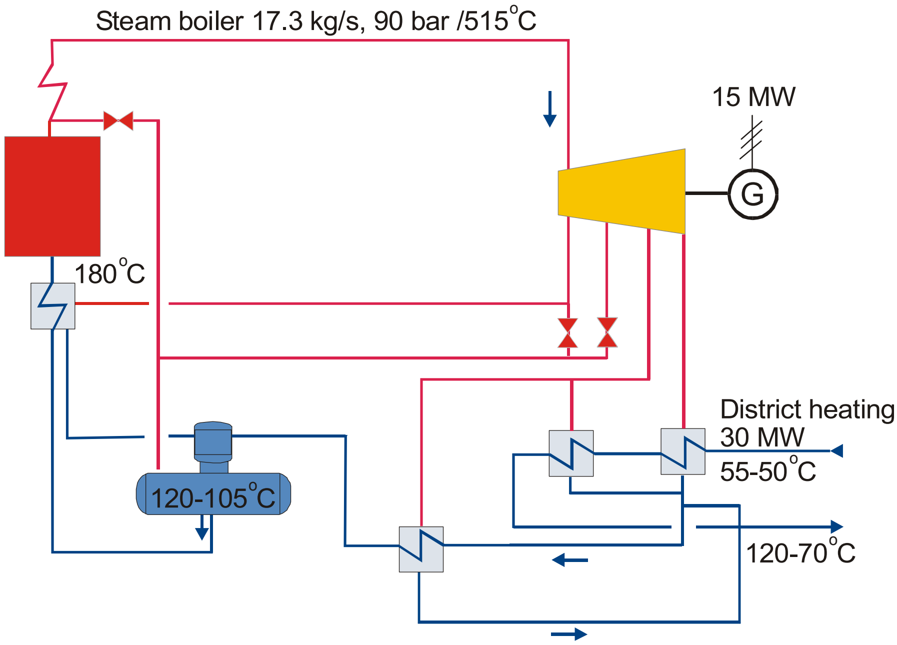

Figure A-F Schematic of Iisalmi 14.7MWe/30MWdh CHP plant

The total investment in the power plant was €21M, which gives €1430 /kW$_e$ specific investment for electric power.

The plant uses milled peat (70-100%), wood based fuels like wood chips, sawdust and bark (0 - 27%) and (0-3%) as fuels [A2]. Light fuel oil is used as start-up and backup fuel. The share of wood based fuels could be increased up to 70% without modifications in the future, availability permitting.

The fuel is burned in a bubbling fluidised bed boiler. The live steam flow is 17.5kg/s, steam temperature 515°C and pressure 93bar. The steam turbine is a new single casing 2-stage model with double flow District Heating tail, where the steam flow is distributed to separate turbine flow sections so that the steam is evenly distributed between both heat exchangers at higher DH-water exhaust temperatures and also at partial loads. It means that the additional co-generation power achieved by 2-stage DH water preheating is not lost during winter. The 1MW additional power capacity is available in winter compared to the conventional construction. This construction results in power to heat ratio of 0.49 which is considerably higher than usual in this size class.

Particles are removed with an electrostatic precipitator. The particle emissions will be 25mg/MJ, SO_2 emissions 140mg/MJ, NO_x emissions 150mgNO_2/MJ and CO_2 emissions 80-113g/MJ, depending on the fuel mix.

CHP future development trends

Until recent times CHP plants in Finland have been built primarily on a large scale. Almost all the large District Heating systems are connected to CHP plant. In future smaller CHP plants could be built to supply the smaller DH-systems. The emerging small-scale power plant technologies for distributed generation offer new possibilities. The technological development in fuel cells, micro turbine, ORC-process power plants and Stirling engines may allow smaller unit installations in DH-systems and even in buildings.

Another trend is to increase the efficiency of CHP plants and the amount of electricity so as to obtain a higher power-to-heat ratio as shown in Figure A-A. Also boiler plants with the steam process parameter in super critical values have given very promising results for increasing the plant's efficiency. Very promising results have also been found when developing bio fuel boilers for wood chips, logging residues, industrial wood residues, recycled fuels [A3] and bio gases.

Solid fuel gasification (pyrolysis) has an important role in the development of the combined cycle CHP technology (gas turbine or diesel engine together with steam turbine or fuel cell).

A separate heat store connected to a CHP plant can be utilised to compensate different temporal variations in heat and power demands. An efficient heat storage system can increase electricity production when charging the heat store and can increase the possibility for electricity regulation and decrease the use of additional condensers, thus cutting waste heat and thermal pollution. Also peak boiler starts can be decreased when discharging the heat storage. The heat store is also a good instrument for regulated energy production in the liberalised electric market. The District Heating pipeline system can also serve as a short-term heat store.

The utilisation of CHP production can be enlarged to tri-generation, if District Cooling or/and fresh water production is increased in the system. They can be called as CHP/DHC and CHP/DHCW.

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Appendix B Report on Experience in Denmark

Introduction

The history of CHP in Denmark is closely connected to the development of District Heating. In the early years the heat was regarded as a by-product of the electricity generation, but over the last decades the combined production of heat and power has become much more sophisticated.

Today, a close cooperation between the power sector and the District Heating companies has made it possible to optimise the combined energy production. In the larger cities the heat is produced in CHP plants based on coal, gas, biomass or waste incineration with oil or gas fired back-up boilers. In smaller towns CHP has also become quite common with production based on gas turbines or gas engines. Biomass is considered an option for future plants or refurbishments.

To understand the background for this development, a closer look at Danish energy policy is essential.

History

In Denmark the history of District Heating and CHP goes back to 1903, when the first supply of heat from a new waste incineration plant to a nearby hospital was established. The heat was produced in combination with electricity so this was also the first CHP plant.

Until the 1960's there were only a limited number of buildings supplied from District Heating networks and CHP production was still very limited. The breakthrough came when a number of Danish companies began to develop pre-insulated district pipes. Initially poor quality of the pipes was a real obstacle, but the quality was gradually improved and it became possible to supply new District Heating schemes with high quality pipes at temperatures up to 120ºC. The cost of a network with pre-insulated pipes was much lower than the previous systems with concrete ducts.

It is remarkable that District Heating in Denmark went through the same development as in other European countries before the beginning of the fuel crisis in 1973/74. Before the crisis this development was based on cost-effective heat from CHP plants near the larger cities and the difference in price between light oil and heavy fuel oil for District Heating schemes in smaller towns.

The fuel crisis in 1973/74 and again in 1979 changed the picture. The new situation called for the implementation of alternatives to oil and it made the introduction of new energy saving measures absolutely essential, not least for space heating. Denmark relied almost 100% on imported oil for the generation of heat, and heat budgets multiplied within few months.

The Danish government introduced a number of initiatives to support the saving of energy and to reduce energy costs:

- Systematic planning of the heat supply in all cities and towns
- Highest possible percentage of heat produced as CHP
- Additional insulation of all buildings
- Support to the development of highly efficient pre-insulated District Heating pipe systems with low installation costs.

Through a firm energy policy with a close co-operation between central and local authorities, public or private heat supply companies and industry it was possible to reduce the energy demand for space heating per capita by 50% from 1973 to 2003.

Today District Heating supplies almost 60% of the heated floor area and the share is increasing. The total number of dwellings connected to District Heating is close to 1.5 million.

CHP plants based on coal, gas, waste and biomass produce the most of the heat. When looking at the last 3-4 years, 75% of the total heat production was generated at CHP plants. The other 25% was generated with heat-only boilers.

When comparing Denmark with other European countries and regions and countries worldwide, District Heating and the use of CHP has been developed to a very advanced state. The potential for further expansion is limited and focus is now on the optimisation of the District Heating systems that exist already. The main concern of the business is therefore not connected with the support for new schemes, but how to safeguard the investments that have been made over the last decades. The use of CHP in combination with the liberalisation of the electricity market will necessarily have an influence on heat prices and the payback of investments in the District Heating sector.

Energy policy

The development of CHP in Denmark is closely connected to the national Danish energy policy.

In 1979 a new heat supply law was implemented. The law meant that a heat planning process was launched in the Danish municipalities in order to establish a completely new infrastructure. The target was to cover 15% of the space heating with a supply of natural gas from the Danish part of the North Sea and to increase the District Heating coverage to 60% of the heat demand by year 2000. The main part of the District Heating was to be produced as CHP.

The most important result of the planning was a least cost zoning of natural gas networks and District Heating networks to substitute individual oil fired boiler installations. Another result was the zoning of new integrated District Heating transmission systems to supply local distribution systems with heat from large CHP plants and existing waste incineration plants.

A political objection to zoning was that it would eliminate the market forces, the opposite point of view being that the introduction of District Heating would open the heat market to different fuels, which would not be possible in individual boiler installations. An important condition of the heat law was that District Heating companies had to be non-profit organisations. This is still the case today, even if a private investor is the owner of the network.

On the national level energy taxes or levies were used as a tool to encourage estate owners and individuals to connect to District Heating.

An increase in CHP capacity was part of the planning, so that the increase in District Heating load could be covered. All new CHP units were designed and located in order to allow the utilisation of the heat from the plants most efficiently. In Copenhagen two new large-scale CHP units were established in the 1980s and a third was commissioned in the late 1990s to supply additional heat to a City-wide scheme with transmission networks linking four CHP plants, four waste incineration plants and more than 50 heat plants with back-up boilers. Similar transmission networks were established in other cities with large CHP plants.

In a drive to support the CHP concept in smaller communities the heat supply law was revised twice in the 1990s. Gas fired CHP was introduced in smaller towns and villages as “Decentralised CHP”, sometimes serving villages with only a few hundred inhabitants.

Following the liberalisation of the power generation, the Danish energy policy has gone through various changes. In recent years the planning procedures have become less rigid, but the least cost principles are still followed. The non-profit obligation is also in force.

Appendix C Report on Experience in Netherlands

Introduction

After the oil crises of the seventies and eighties Combined Heat and Power (CHP) production for use in industry and District Heating was one way to reduce energy costs. Later, protection of the environment became the incentive for further development. Instead of a high level of electricity efficiency, overall efficiency became the most important criterion. By designing the CHP to meet the heat demand, overall efficiency can be increased to 80 to 90% and valuable energy can be saved. In the case of District Heating, such installations would have to be as close to the city as possible.

Government Policy

In 1988 the Dutch government encouraged the introduction of Combined Heat and Power by the Cogeneration Incentive Programme. Important elements of this programme were investment grants, favourable gas tariffs (especially attractive for smaller CHP units) and the establishment of a CHP promotion agency, the "Projektbureau Warmte/ Kracht". At the same time changes were introduced in the electricity sector. A new Electricity directive gave CHP a special status. Utilities were obliged to accept electricity produced by CHP. A minimum tariff was introduced for electricity supplied to the public grid.

In the third Energy Memorandum (1996) the Dutch government aimed to create an active policy on energy conservation and CO_2 abatement. This policy is based on co-operation with energy users and on voluntary measures to improve energy efficiency. Since CHP was the most cost-effective way of reducing CO_2 emissions, it became the most important method of reaching the targets in long-term agreements on energy conservation between the government and industry. In the Environmental Action Plan, voluntarily drawn up by the energy distribution sector, CHP had to account for 40% of the targeted CO_2 reduction. The targets of CO_2 reduction taken on by the Dutch government after the Kyoto conference (1997) aims at a 6% CO_2 reduction in the period 2008-2012.

Results

About 40 % of Dutch electricity is generated by CHP. Compared with the European average of l0%, this is high. Due to CHP the abatement of CO_2 amounts about 11 million tons per annum.

CHP has grown in the Netherlands from 3,000MWe in 1990 to 7,400MWe in 2000 [C1]. This includes 2,000MWe for District Heating (DH), 3,900MWe of gas turbine based CHP, most of which is found in industry, and 1,500MWe of gas engine CHP units. The use of gas engines is mainly found in greenhouses, hospitals, hotels, swimming pools and small local District Heating schemes. District heating increased from 100,000 households in 1981 up to 400,000 households in 2000.

Large scale versus small scale CHP

The larger CHP schemes, some District Heating schemes and some very large industrial projects have been carried out by the electricity generation sector. Co-operation between end users and electricity companies, organised in joint-ventures, offers opportunities to supply the electricity surplus to the public grid: the value of electricity rises when they are able to control its generation and use CHP at the high tariff hours. The smaller CHP units, often consisting of gas engines combined with boilers, are mostly in private hands. The distribution utilities have invested and completed the largest number of CHP projects.

The value of the heat generated by CHP is very important in economic terms: the extra income generated by the heat leads to lower electricity generation costs. Generating and using electricity on the same site reduces the cost of networks for transmission and distribution of electricity. The advantages of energy efficient production processes from a high number of smaller installations compensate the economies of scale of large power plants and there are also savings in energy distribution costs. In industry, a high overall efficiency and a high utilisation add considerably to the economic value of a project. Some years ago, these factors resulted in much interest in small scale CHP, for sites such as greenhouses, hospitals and large buildings. High prices for electrical power and government stimulation were other keys to the growth of small scale CHP. However, other more negative factors concerning small scale CHP are connected with the environmental benefits. Although they reduced CO_2 output, they were not free of other pollutants and also, in many cases, efficiencies were not that good, hence there was only a limited reduction of CO_2 output. The great speed with which projects have been realized has led to poor process design and very adverse operating conditions (start/stop for a large part of the season). This has led to high maintenance and operating costs.

Developments

In 1998 the Government in the Netherlands introduced a new law on electricity. This law enabled the liberalisation of the energy market. As a result, the import of cheap foreign electricity increased to up to 50% of the total electricity demand in 2000. Therefore, one of the main problems faced by CHP is the overcapacity in the existing electricity supply industry. Due to liberalisation the cost-effectiveness of CHP showed a downward tendency which led to stagnation in the growth of CHP. Investments in new production capacity are not likely and even several existing CHP projects, which could not remain profitable anymore, were closed down.

Slowly, the government has acknowledged the stagnation in the CHP market and, in order to meet the Kyoto agreements, is starting to stimulate the operation and growth of CHP again. The government has taken some measures in favour of CHP. Investments in CHP can, until a certain %, be deducted from company taxes (EIA), the gas used in the CHP is free of energy tax, and there is a fund to support CO_2 abatement projects (CO_2 reduction funds).

CHP, with production and consumption of energy close together, makes less use of the electrical network, which originally was built to bring large quantities of electricity from large central power stations to the customers. In order to look for instruments to favour CHP the minister has now asked the distribution companies to reduce the tariffs for using the public grid for CHP providers. Currently, the government is searching for ways to stimulate CHP on a general basis related to the CO_2 abatement. The government is still relying on the increase of CHP capacity to 17,000MW in 2010 to achieve its CO_2 objectives.

District Heating

Large-scale District Heating implies extensive networks for heat transport and distribution, with heat produced by electricity generation plants. The advantages of large-scale District Heating are clear: large plants, high efficiency, low energy costs and great flexibility. One of the major drawbacks is the major investment required for the distribution of the long-distance heat network. Such investments are particularly a problem in newly developed areas. There were no initiatives for District Heating with CHP in existing areas. Although nowadays most successful DH projects in the Netherlands are found in large-scale District Heating projects, it must be noted that the government, to reorganise the sector, has had to invest millions of euros in DH projects, in order to reduce the debts made during construction.

On smaller scale CHP, Dutch power companies are running local District Heating quite successfully at several locations. Small, relatively cheap installations based on gas engines and local heating mains have been constructed. The local District Heating schemes are expanded as the building development proceeds, and step by step these small units, which are located as close as possible to homes or buildings, meet the total heating demand. This way the major investments at the start of the project are replaced by smaller investments spread out over the development of an area. Since it may take up to ten years before an area with new buildings is completed, the financial advantages are considerable. Flexibility also increases, reducing the risk of having to change the plans.

However, when building near to housing areas these projects tend to be very expensive, due to strict environmental regulations (low sound emissions, tight restrictions on odours) and architectural requirements. The total CHP project might cost 3.5 to 4 times as much per kWe as the CHP-package (gas engine, generator, exhaust boiler) itself. Also management costs (to administer and operate) tend to be more than for large-scale projects, because much the same organisation is needed for a smaller project.

Different examples show the conditions for a successful DH project:

- the heat source is within an acceptable distance, or the location is suitable for a small scale heat source
- the building density is sufficient
- the total heat demand of the project is sufficient

There might be an optimal scale for CHP/DH, but there is a lack of research concerning the influence of scale on projects. Projects advised and realised by our own organisation show that in projects where 10 to 50 households are connected to local CHP heat distribution, the cost for investments and maintenance are too high. This is compared to the reference situation where all houses have an individual gas boiler for heat and hot water. Projects where the heat distribution can deliver to over 500 to 1,000 houses however seem to become interesting for the distribution utilities. Part of this eagerness finds its origin in the fact that DH consumers, in a liberated energy market, can also become customers for other services.

New technologies are being developed even including solutions at household level, combinations of Micro Combined Heated Power (single-household sized) and heat pumps together. Solar energy, producing heat and electricity from the roof of individual houses will be elements in systems for local energy production. Fuel cells, Stirling engines, are both emerging from the research room to test in practice, and a large variety of gas turbines will be the prime movers in the new localised electricity production.

Other CHP Applications

Hospitals

Hospitals require a large amount of energy in many forms, such as heat, electricity, cooling and steam. The CHP can cover most of the hospital's electricity demands. The heat, which is produced simultaneously, can be used in three different ways. First the exhaust gases are used to generate steam. The remaining heat is used for heating and hot water supply. And in the summer, the heat is used in an absorption chiller to achieve cooling. This threefold use of heat is an excellent example of how optimal use can be made of what is normally considered a waste product. Another important advantage for the hospital is the higher level of reliability. Together with an existing standby unit and its connection to the grid, the CHP unit furnishes high reliability at low cost.

Horticulture

The Netherlands is an important producer of flowers and vegetables. Dutch growers have overcome the disadvantages of the Dutch climate by building greenhouses and making sure that the energy required for horticulture is produced efficiently. Horticulture makes use of numerous gas engine-driven CHP installations to meet the heat demand of the greenhouses. Many CHP-units generate electricity for assimilation illumination, to enhance the growth of flowers. The CHP exhaust gases have even been used to stimulate the growth of plants by means of photosynthesis. The process itself is of course almost as old as creation, but Dutch growers recognised that by cleaning the exhaust gases of a CHP unit, a cheap source of CO_2 became available. The gases have to be cleaned to ensure that no damaging components will affect the plants. Another waste product of energy production is then made useful.

Industry

Many Dutch industries depend on CHP; in particular the chemical and petrochemical industries, steel plants, paper production mills and the food industry. Typically, the demand in these sectors for steam or process heat is higher than the demand for electricity therefore CHP projects are scaled to meet the heat demand and generate a surplus of electricity.

This surplus of electricity is one of the reasons why power companies are interested in these projects. By co-operating with industry in joint ventures, the advantages of CHP are made available to both industry and the energy sector. For industry, these joint ventures provide an outlet for surplus electricity and furnish price guarantees. The supply of natural gas for CHP and top-up and back-up contracts for electricity are often included in the joint-venture contracts.

But perhaps the most important aspect of such joint ventures is that they offer a method of obtaining off- balance sheet financing. The relatively high investment is one of the main obstacles to CHP. Many companies prefer not to commit their own resources to non- core business. The joint venture, a single purpose company, takes over the investment and the supply of heat and electricity are "out- sourced".

References

[C1] **Marktmonitoring warmtekrachtkoppeling in Nederland**, F.A.M Rijkers, ECN, Petten

Appendix D Report on Experience in UK

Early Developments
District heating was established in the UK in the 1950s with the Pimlico housing scheme in London an early example. This was supplied with heat from Battersea power station but was of limited scale with about 4,000 dwellings connected. Other District Heating schemes were built to supply heat to new housing in the 1960s and 1970s. The initial rationale for choosing District Heating was to enable heavy fuel oil to be used in place of light oil and to provide cleaner heating from centralised facilities in an era before natural gas became established.

When natural gas became available heating was normally provided by individual boilers where feasible and electric heating was also used.

The District Heating schemes continued in operation and some were upgraded to improve their controls and heat mains as some of the early designs were not satisfactory. Most were then converted to gas and benefited from the price difference between bulk gas supply and domestic tariffs. The main advantage of District Heating being able to use non-premium fuels or CHP waste heat has not been widely employed however.

City-wide CHP/DH
The Government sponsored a number of investigations into the viability of City-wide CHP/DH systems in the 1970s, culminating in Energy Paper 35 in 1979. This recommended that CHP/DH be implemented in one major city and to identify the preferred lead city a number of studies were carried out and reported in 1982 in Energy Paper 53. Further Government support was provided to consortia hoping to develop such schemes. The only city that was able to take the concept to reality was Sheffield which based the heat supply on waste heat from an existing incinerator.

Small-scale CHP
From the mid-eighties, small-scale CHP units were introduced in the UK and significant numbers have been installed in hotels, leisure centres and hospitals. The economics are not favourable where these have been installed to supply small District Heating networks as the price obtained for the electricity generated on the market is much less than the imported price of electricity to a building, with the exception of private wire. Consequently the use of CHP to supply DH remains limited; exceptions include the Southampton, Citigen, Barkentine schemes. Other CHP installations were developed at industrial sites however the CHP capacity remains low, delivering about 6% of annual electricity generation.

Community Energy Programme (CEP)
The Community Energy Programme, a UK programme sponsored by the Carbon Trust and the Energy Savings Trust, was introduced in 2001. The programme, with a budget of £50m, has subsequently awarded development grant and capital funding to public sector projects incorporating District Heating, cooling and/or Combined Heat and Power. At the time of publishing this report, the programme had awarded £42M of capital and development funding for projects with a cumulative anticipated annual carbon saving of 22,000 tonnes. The success of the programme to date has been vindicated with a further £10M of funding recently being allocated for a continuation of the programme until March 2008.

Environmental Drivers
Previous arguments for CHP/DH have been mainly driven by economic factors. In recent years the risks of climate change have become more widely known and there has been a focus on CO_2 savings from CHP. This has resulted in a renewed interest in District Heating but also research into domestic scale CHP units. The UK is also planning to construct a large number of new homes to meet growing demand. Some of these will be built at a relatively high density especially in the east London area and this could become a new application for District Heating.

Appendix E Report on small-scale CHP systems

Available CHP Technologies

This section of the report is an introduction to the main technologies that are considered to be the prime movers of small-scale and micro CHP. Some of the technologies discussed are commonly used today, some are in the early stages of commercialisation, while others are expected to be available within the next few years.

Internal Combustion (IC) Engines

Of all the CHP technologies it is the IC engine that is the most common and technically mature, with a number of small-scale CHP units commercially available. Available in sizes as small as $5kW_e$ and up to sizes as large as $10MW_e$, IC engine units cross the size boundaries of CHP.

An IC engine works by converting fuel energy into mechanical power by way of a combustion process, which in turn is used to turn a shaft in the engine. Electrical power is obtained by attaching an alternator/generator to the rotating shaft. Thermal power is obtained by passing the hot exhaust gases through a heat exchanger in order to heat water. Cooling jacket water is also used to pre-heat water before exhaust heating.

A typical IC engine can be adapted and set to run on a variety of fuels including: gasoline, natural gas, diesel, landfill gas and digester gas, with natural gas the preferred choice for CHP applications. In general, diesel powered IC engines operate with a higher efficiency than their gas counterparts because they operate at higher compression ratios. However, this is an area that is expected to be addressed in the future and it is anticipated that gas powered IC engines will soon operate with efficiencies comparable to diesel IC engines. Current IC CHP units, running on natural gas, operate with electrical efficiencies in the region of 25 – 40% and overall efficiencies (electrical and thermal) in the region of 70-80%. There are natural gas diesel technologies emerging for both transportation and stationary power applications.

Due to their mature technological status, IC engines are widely available and are manufactured inexpensively in large quantities (35 million units annually in North America alone) [E1]. IC engines formed the basis of the majority of the initial CHP units.

IC engines are generally less expensive than other CHP technologies and can offer very fast start up times - as low as 10 seconds. In addition to this, IC engines can comfortably cope with interrupted operation, which is essential when carrying out maintenance or repairs and meeting a variable energy demand. Other strengths of IC engines include: relatively low investment cost, they can be maintained and overhauled onsite by trained operators and they can operate on low-pressure gas.

The main weaknesses of IC engines are that they are noisy and produce relatively high emission levels of NO_x and particulates, when compared to other CHP technologies (see later sections). However, these weaknesses can be overcome, to an extent, by the incorporation of acoustic attenuators and catalytic converters. On-highway emissions control technology will continue to advance with spin off to CHP applications.

Table E-1 lists the main strengths and weaknesses of IC engine CHP units.

Table E-1 Strengths and weaknesses of the IC engine

Strengths	Weaknesses
Low capital cost	Atmospheric emissions
Good overall efficiencies (up to 80%)	Noisy
Quick start up time	Requires fairly regular maintenance intervals
Fuel flexibility	

High reliability and proven technology	
Low natural gas pressure required	

Stirling Engines

A Stirling engine is essentially a sealed system with an inert working fluid, usually helium or hydrogen and is classed as an external combustion engine. As a concept, Stirling engines have been around for a very long time, first being patented in 1816 by Robert Stirling, but have never really found a mass-market application. Recent interest in small scale CHP has identified Stirling engines as a suitable technology due to its very low pollutant emissions and high combustion efficiency. There are now a small number of commercially available units with several more due to launch within the next 12 months. Stirling engines operate without any valves or potentially complex ignition system, thus permitting long service intervals and low running costs. The free piston Stirling engines offer particular advantages by avoiding some of the complex mechanical components needed by kinematic forms of the engine.

A Stirling engine differs from a conventional IC engine in that the gases used never leave the engine, there are no exhaust and inlet valves and there are no intermittent "combustion events". In its most simple form a Stirling engine consists of a *regenerator*, *cylinder*, *piston* and a *displacer*. Fuel is burned continuously outside the engine to maintain one end of the cylinder at high temperature while the opposite end is cooled by circulating water around it. Power is obtained from the pressure fluctuations acting on the working piston, as a fixed volume of gas (sealed within the engine) is alternatively heated and cooled, forcing it back and forth between the two temperature zones via the regenerator. The working gas is moved by the displacer. One key difference between a Stirling engine and an IC engine is that, in an IC engine, it is possible to adjust power virtually instantaneously by controlling the fuel supply. This makes an IC engine ideal for automotive applications where rapid variations in power are required. However, there is a significant time delay between fuel input and power output in a Stirling engine, as there is usually a substantial amount of heat stored in the hot end, which continues to transfer energy to the working gas after the fuel supply to the burner is cut. Although this is not a concern in stationary applications, which do not require instantaneous power variation, it is a consideration for control that there is a delay of the order of minutes between a thermostat calling for heat, the availability of heat and finally the output of power.[E2]

Due to the simple combustion needs of a Stirling engine, they can be adapted to run on a variety of fuels including: gasoline, natural gas, diesel, landfill gas and digester gas, with natural gas the preferred choice for CHP applications. It is anticipated that future Stirling engines will be more easily adaptable to biofuels, when compared to IC engines.

Stirling engine based CHP units have electrical efficiencies falling within the range of 15-25% and 60-75% for the overall efficiency.

Very low production numbers result in relatively high capital costs for Stirling engines which at present make them uncompetitive with other CHP technologies. However, due to the recognised application of Stirling engines for CHP, together with a number of other specialised applications i.e. solar dish applications, space, refrigeration and aircraft, developers are working to lower these costs through a combination of design refinements, material substitution and mass production techniques. Stirling engine based micro CHP units are seen as an ideal intermediate technology before the eventual widespread introduction of fuel cell based systems.

Table E-2 Strengths and weaknesses of the Stirling engine

Strengths	Weaknesses
Low noise and near vibration free operation	High costs
Low emissions	Low efficiencies
Low maintenance, and high reliability	Slow start up times
Relatively few moving parts – mechanically simple	
Multi-fuel capability, including solar power	
Long life cycle	

Microturbines

Microturbines are small combustion turbines that have been derived from turbocharger technologies found in large trucks or the turbines in aircraft auxiliary power units. Most microturbines are single stage, radial flow (also known as centrifugal flow) devices with very high rotating speeds of 90,000 to 300,000 revolutions per minute. In a microturbine, air enters the compressor where it is compressed. The air is then preheated in a recuperator using some of the heat from the hot turbine exhaust. Next, the heated air from the recuperator mixes with fuel in the combustor and the hot combustion gas expands through the turbine. In its most common format, the turbine is attached to the compressor and a generator by a simple shaft. Finally the remaining hot exhaust gases are fed into a heat exchanger typically connected to a water system.

Microturbines can be designed to run on a variety of fuels including: natural gas, gasoline, kerosene, propane and diesel. When running on natural gas, low inlet temperatures and high fuel-to-air ratios results in low NO_x emissions.

Microturbines are technologically mature because they have benefited from many years of research and development into larger turbines and systems. The first commercially available microturbine CHP units were introduced in the year 2000 and there are currently a number available for use with more expected in the near future.

An important aspect of microturbines is their ability to be connected together in parallel in order to serve larger buildings or small clusters of smaller buildings.

Microturbines based micro CHP units are typically positioned at the upper end of the scale with sizes in the range of 25–100kW_e. Microturbines can achieve overall operating efficiencies as high as 85% and electrical efficiencies in the range of 20-30%. A typical microturbine contains relatively few moving parts and so manufacturers expect the units to provide higher reliability than IC engine technologies. The associated capital costs of a microturbine are slightly above those of an IC engine but still lower than those for a Stirling engine.

Table E-3 lists the main strengths and weaknesses of microturbine CHP units.

Table E-3 Strengths and weaknesses of the Microturbine

Strengths	Weaknesses
Small number of moving parts	Low fuel to electricity efficiencies
Compact size	Loss of power output and efficiency with higher ambient temperatures and elevation
Light weight	
High efficiencies	
Low emissions	
Can utilize waste fuels	
Long maintenance intervals	

Fuel Cells

Of all the CHP technologies discussed in this section it is those based on fuel cells that are creating the strongest level of interest, due to their potential for clean, quiet, near zero emissions and high operating efficiencies. Fuel cells use an electrochemical process to convert the chemical energy of a fuel and oxidant directly into combustion products, producing electricity and heat in the process. The required fuel (hydrogen in the case of the Proton Exchange Membrane) is typically generated from a hydrocarbon fuel such as natural gas or LPG, and the oxygen is obtained from ambient air.

A fuel cell can be said to be similar to a battery in that an electromechanical reaction is used to create an electric current. The charge carriers can be released through an external circuit via wire connections to anode and cathode plates of the battery or fuel cell. The major difference between fuel cells and batteries is that batteries carry a limited supply of fuel internally as an electrolytic solution and solid materials (such as the lead acid battery that contains sulphuric acid and lead plates) or as solid dry reactants (such as zinc carbon powders found in a typical battery). Fuel cells have similar reactions; however, the reactants are gases (hydrogen and oxygen) that are combined in a catalytic process. Since the gas reactants can be fed into the fuel cell and constantly replenished, the unit is never discharged [E3].

Fuel cells are named based on the type of electrolyte and materials used. The fuel cell electrolyte is sandwiched between a positive and a negative electrode. Fuel cells generally fall into one of the following 5 categories:

1. Phosphoric acid (PAFC)
2. Proton exchange membrane (PEMFC)
3. Molten carbonate (MCFC)
4. Solid oxide (SOFC)
5. Alkaline (AFC)

PAFC – are most common because they were the first fuel cell types to become commercially available. They have an acid electrolyte and operate at relatively low temperatures of around 370–410ºF (190–210ºC). *ONSI*, the only commercial manufacturer of fuel cells using this technology, produces units sized at 200kW_e with 205kW_{th} energy recoverable in the form of hot water. (ONSI is a subsidiary of United Technologies Inc).

PEMFC – operate at low temperatures in the range of 150–180ºF (65–85ºC). Manufacturers are targeting CHP units in the range of 7–250kW_e. Their very low thermal and noise signatures might make them especially useful for replacing military generator sets. Their low operating temperature leads to bulky system designs.

MCFC – are relatively high temperature units, operating at temperatures in the range of 1200–1300ºF (650–700ºC). MCFC's are currently designed for large-scale CHP applications in the order of 50–100MW_e.

SOFC – also operate at high temperature, in the range of 1350–1850ºF (750–1000ºC). At these temperatures, a natural gas powered fuel cell does not require a reformer. A variety of 20–25kW_e SOFC CHP units are under development and being tested.

AFC – are the arguably the simplest type of fuel cell but also return the lowest electrical and overall efficiencies and operate at temperatures in the range 190–500ºF (90–260ºC). The alkaline fuel cell must use an oxidant that is free of carbon dioxide. This leads to complexity in practical systems that must include a carbon dioxide scrubber unit [E4].

The PEMFC, PAFC and MCFC groups of fuel cells are the three that are showing the greatest promise for CHP applications, especially PEMFC. PEMFC technology development has been driven in large part by the automotive sector, where PEMFC's have a compelling advantage over other fuel cell categories in terms of their size and start up time (a PEMFC takes less than 0.1

hours to start up compared to PAFC which can take 1–4 hours, MCFC 10+ hours and SOFC 5–10 hours).

Table E-4 Characteristics of various Fuel Cells (source Energy Nexus Group)

	PEMFC	AFC	PAFC	MCFC	SOFC
Type of electrolyte	H^+ ions (with anions bound in polymer membrane)	OH^- ions (typically aqueous KOH solution)	H^+ ions (H_3PO_4 solutions)	CO_3^{2-} ions (typically, molten $LiKaCO_3$ eutectics)	O^{2-} ions (stabilized ceramic matrix with free oxide ions)
Typical construction	Plastic, metal or carbon	Plastic or metal	Carbon or porous ceramics	High temp. metals or porous ceramics	Ceramics or high temp. metals
Internal reforming	No	No	No	Yes, good temp. match	Yes, good temp. match
Oxidant	Air to O_2	Purified air to O_2	Air to enriched air	Air	Air
Operational temperature	150 – 180ºF (65 – 85ºC)	190 – 500ºF (90 – 260ºC)	370 – 410ºF (190 – 210ºC)	1200 – 1300ºF (650 – 700ºC)	1350 – 1850ºF (750 – 1000ºC)

Because individual fuel cells produce low voltages, fuel cells are stacked together to generate the desired output suitable for micro CHP. The fuel cell stack is then integrated into a fuel cell system with other components including:

1. a fuel processor (consisting of a reformer and post processing of the gas) which extracts the hydrogen from the fuel,
2. a power conditioner (or inverter) that processes the electric energy into either AC or DC current.

A big advantage of fuel cell based CHP systems is that because each cell can be made to generate anything from $100W_e$ to $2kW_e$ each, they can be stacked into a range of configurations in order to produce a wide range of electrical outputs, and so could easily be configured for specific individual uses/requirements.

Due to the early development level of fuel cell systems, current manufacturers are faced with very low volume production runs, very high capital costs, lack of support infrastructure and technical risks. However, the huge potential benefits of a fuel cell based CHP system mean that they are currently the subject of extensive research activity and as more units are installed and new players join the market prices will eventually fall.

There are currently a small number of fuel cell based CHP systems undergoing a series of field trials but is not for another 5 years until they are expected to be available on a competitive scale.

It is anticipated that fuel cell based CHP systems will operate with electric efficiencies in the range of 30-50% and overall efficiencies of 65-85%.

Fuel cell systems produce very few emissions since the primary power generation process does not involve combustion. In fact, the fuel processing subsystem is the only significant source of emissions [E5]. Fuel cell systems should also be virtually silent.

Table E-5 Strengths and weaknesses of fuel cell CHP units

Strengths	Weaknesses
High efficiencies	Very high costs
Low emissions	Need to demonstrate long term dependability
Nearly silent	

Hybrid Systems

Many developers and manufacturers of CHP equipment are looking for ways to combine technologies in order to improve performance and efficiency. Several examples of hybrid systems include:

- SOFC's combined with a microturbine
- Stirling engine combined with a solar dish
- Wind turbines with battery storage and diesel backup generators
- Engines (and other prime movers) combined with energy storage devices such as flywheels

The SOFC/microturbine hybrid system is hoped to achieve electrical efficiencies of 60-70%. SOFC/microturbine concepts rely on the principle that fuel cell efficiency and reaction speed will improve when the fuel cell stack operates above atmospheric pressure. By operating the fuel cell stack at 4 atmospheres or higher, it is possible to integrate the fuel cell with a microturbine. In this hybrid arrangement, the microturbine compressor is used to pressurize the fuel cell, then the hot exhaust from the fuel cell stack, which still contains 50% of the fuel's energy (as unreacted fuel and waste heat), is fed back into the microturbine, combusted and expanded to extract more energy. Energy recovered from a recuperator is used to help heat inlet air for the fuel cell stack and the compressor.

Several companies are working to develop Stirling engine/solar dish hybrid systems. These kinds of hybrid systems will be small, with typical electrical outputs of 5 – 25kW. This size makes such hybrid systems ideal for stand-alone applications.

Wind turbines can be used in combination with energy storage and some type of backup generation (i.e. reciprocating engine, microturbine or fuel cell) to provide a steady power to remote locations not connected to the grid.

Energy storage devices such as flywheels are being combined with IC engines and microturbines to provide a reliable backup power supply. The energy storage device provides ride-through capability to enable the backup power to get started. In this way, electricity users can have an interruption free backup power supply [E3].

Benchmarking of Technologies

The following section of this report sets out to compare important cost and performance characteristics of the various CHP technologies that were introduced in the previous section.

Capital cost

Capital expenditure (Capex) is the term given to the costs encountered in order to purchase and install a CHP technology. A Capex figure refers to the total equipment cost of a CHP technology to the end user. Capex costs of CHP technologies can vary significantly even within one technology category, depending on size, power output, performance and fuel type etc.

Table E-6 shows typical Capex cost ranges for the identified CHP technologies.

Table E-6 Typical capital costs for the various CHP technologies (source Energy Nexus Group*)*

CHP Technology	Capex (US$/kW)
IC Engines	300 – 800
Stirling Engines	2,000 – 50,000
Microturbines	700 – 1,100
Fuel Cells	3,500 – 10,000
Hybrid	1,000 – 1,500 (estimated)

When interpreting the data shown in Table E-6 a few points are worth noting:

- IC engines are a mature technology with a high production volume, therefore costs are relatively low
- Stirling engine manufacturers target lower costs (~US$2,000) if higher production volumes were to be achieved. The high costs shown refer to very low production and prototype engines, primarily for space programs
- Microturbine costs represent early commercial production costs and will likely decrease as production levels increase
- Fuel cells are in varying stages of development and production, as represented by the large range of Capex costs

Operating cost

Operating expenditure (Opex) can be said to consist of both fixed and variable components. Fixed Opex costs consist primarily of plant operating labour. Variable Opex costs consist of variable maintenance and are estimated from an algorithm incorporating a CHP technology unit's expected capacity factor. The variable Opex costs includes periodic inspection, replacement and repair of system components (i.e. filters etc), as well as consumables (i.e. water, limestone etc) computed directly from the CHP plant material balance [E3]

Table E-7 lists sample maintenance intervals and Opex costs for the identified CHP technologies.

Table E-7 Typical Opex Costs of CHP Technologies (source Energy Nexus Group*)*

CHP Technology	Maintenance interval	Average Opex (US$/kWhr)
IC Engines	750 – 1,000: change oil and oil filter 8,000: rebuild engine head 16,000: rebuild engine block	0.7 – 1.5 (natural gas) 0.5 – 1.0 (diesel)
Stirling Engines	5,000 – 8,000	1.4 – 2
Microturbines	5,000 – 8,000	0.5 – 1.6 (estimated)
Fuel Cells	40,000: replace fuel cell stack Yearly: fuel supply system and reformer system check	0.5 – 1.0 (estimated)

Performance

The main performance criterion of any CHP technology is its efficiency. There are many different definitions of efficiency and many methods of calculating each of them, but for the purpose of this report only *overall efficiency* and *electrical efficiency* will be considered. The overall efficiency is calculated from the sum of net electrical power and net useful thermal output divided by the total fuel energy consumed. The electrical efficiency is calculated from dividing the electrical output by the total fuel energy consumed. Also of some interest is the power to heat ratio of the CHP technology. Table E-8 lists typical values for the above described efficiencies and power to heat ratios. (N.B: The fuel cell system electrical efficiencies include the reformer).

Table E-8 Typical Efficiencies of CHP Technologies (source Energy Nexus Group)

CHP Technology		Electrical Efficiency	Overall Efficiency	Power to Heat Ratio
IC Engines		25 – 45%	70 – 80%	~0.6
Stirling Engines		15 – 25%	60 – 75%	~0.4
Microturbines		20 – 30% (recuperated)	Up to 85%	~0.5
Fuel Cells	PEMFC	~35%	~68%	~0.75
	AFC	~30%	~60%	~0.8
	PAFC	~36%	~75%	~0.9
	MCFC	~40%	~65%	~1.95
	SOFC	~45%	~70%	~1.8

Emissions

In addition to cost savings, CHP technologies offer significantly lower emissions compared to separate heat and power systems. The promise of lower emissions could well result in a more enthusiastic acceptance and take up of CHP technologies.

Exhaust emissions are probably the greatest concern with IC engines. The primary pollutants from IC engines are NO_x (nitrogen oxide), CO (carbon monoxide) and VOC's (volatile organic compounds – unburned, non-methane hydrocarbons). Other pollutants such as SO_x (sulphur oxide) and PM (particulate matter) are primarily dependent on the fuel used. The sulphur content of the fuel determines emissions of sulphur compounds, primarily SO_2 (sulphur dioxide). The use of an oxidation catalyst or a three way conversion process (non- selective catalytic reductions) could help lower the emissions of NO_x, CO and VOC's by 80–90%. Lean burn engines also achieve lower emissions rates than rich burn engines [E1]

Since Stirling engines are external combustion engines, which allow continuous, controlled combustion, they result in very low pollutant emission levels – potentially far superior to IC engines and microturbines.

Microturbines have the potential for low emissions. All microturbines operating on gaseous fuels feature lean premixed (dry low NO_x, or DLN) combustor technology. The primary pollutants from microturbines include NO_x, CO and unburned hydrocarbons. They also produce a negligible amount of SO_2. Microturbines are designed to produce low emissions at full load and emissions are often higher at part load [E6]

Fuel cell systems have low emissions profiles because the primary power generation process does not involve combustion in the cell itself. The fuel processing subsystem is the only significant source of emissions as it converts fuel into hydrogen and low energy hydrogen exhaust stream [E7]

Table E-9 lists estimated figures for various emissions levels for the identified CHP technologies. N.B: The data shown in Table E-9 is based on actual CHP systems available and so only units of similar sizes are compared, as shown in first data row (electrical output). Table E-10 presents a summary comparison of CHP technologies.

Table E-9 Typical Emissions Levels of CHP Technologies (source Energy Nexus Group*)*

	IC Engines	Microturbines	Fuel Cell (PEMFC)	Fuel Cell (SOFC)
Electrical Output (kW)	100	100	100	100
NO_x (g/kWhr)	20.09	0.36	0.027	0.023
CO (g/kWhr)	16.07	0.22	0.03	0.018
THC (g/kWhr)	-	<0.09	-	-
CO_2 (g/kWhr)	606.9	773.82	566.92	412.77
Carbon (g/kWhr)	165.56	210.92	158.76	111.13
VOC (g/kWhr)	0.94	-	0.005	0.005

Table E-10 summary Comparison of CHP Technologies

	IC Engines	Stirling Engines	Microturbines	Fuel Cells
Size range	>5kW$_e$	>5kW$_e$	25 – 100kW$_e$	>0.5kW$_e$
Commercial availability	Yes	Limited	Yes	2004 onwards?
Fuel	Natural gas Gasoline Diesel Land fill gas Digester gas	Natural gas Gasoline Diesel Land fill gas Digester gas	Natural gas Propane Kerosene Diesel Gasoline	Hydrogen Natural gas Propane
Electrical efficiency	25 – 40%	15 – 25%	20 – 30%	50 – 70%
Overall efficiency	70 – 80%	60 – 75%	Up to 85%	60 – 75%
Environmental	Poor	Good	Fair	Excellent
Power to heat ratio	~0.6	~0.4	~0.5	~0.75 (PEMFC) rising to ~1.95 (MCFC)
Capex (US$/kW)	300-800	2,000 – 5,000	700 – 1,100	3,500 – 10,000
Opex (US$/kWhr)	0.5 – 1.5	1.4-2	0.5 – 1.6	0.5 – 1.0
Maintenance intervals (hours)	16,000	Unconfirmed	5,000 – 8,000	40,000
Start up time	<1 minute	5 – 60 minutes	<1 minute	<0.1 hours (PEMFC) 1 – 4 hours (PAFC) 5 – 10 hours (SOFC) 10+ hours (MCFC)
Noise	Poor	Good	Good	Excellent

Technology Potentials

The CHP technologies which were identified in the Available CHP Technologies section of this report, all have various research and development programs which are currently active. Most programmes are led by the U.S. Some of the US Department of Energy (DOE) programmes are specifically concerned with CHP whilst others are concerned with the individual technologies. Of most relevance to this report however are those concerned with each of the technologies as they give an indication of the future direction and performance levels being sought.

Advanced Reciprocating Engines System Program

The *Advanced Reciprocating Engines System Program (ARES)* is a current program being run by the DOE (Department of Energy) in the U.S. The general aim of the program is to develop advanced natural gas fired IC engine systems for distributed energy resources (DER) applications in industry, commercial buildings and utility settings. The mission of the program is stated as being:

"to lead a national effort to design, develop, test and demonstrate a new generation of reciprocating engines for DER applications that are cleaner, more affordable, reliable and efficient than products that are commercially available today"[E7]

Backed with over US$40 million and involving industry experts from, amongst others, *Caterpillar*, *Cummins* and *Waukesha Engine* the program has a number of clear activities and goals, these are summarized below [E7]:

Higher Efficiency – The target for electrical efficiency is 50% by the year 2010 (an approximate rise of 25% from existing products).

Environment – Engine improvements in efficiency, combustion strategy and emissions reduction will substantially reduce overall emission to the environment. The NO_x target for future engines is 1.11g/kWhr, a 95% decrease from today's NO_x emissions rate with no deterioration of other criteria or HAPS emission.

Fuel Flexibility – Natural gas fired engines are to be adapted to future firing with dual fuel capabilities. Dual fuel capabilities may be considered in the design.

The Cost of Power – The target for bus-bar energy costs, including operating and maintenance costs, is 10% less than the current state-of-the-art engine systems while meeting new projected environmental requirements.

Availability, Reliability and Maintainability – The goal is to maintain levels equivalent to current state-of-the-art systems.

Advanced Microturbine Program

The *Advanced Microturbine Program* is a six-year DOE program running between 2000 and 2006 and is supported with a budget of US$60 million. Industry partners in the program include *Capstone*, *General Electric*, *Honeywell Power Systems* and

NASA. The program is making use of synergies with other industries and microturbine applications including: back up power, remote power, mechanical drive systems and resource recovery of waste fuels.

The mission of the program is stated as being:

"to lead a national effort to design, develop, test and demonstrate a new generation of microturbines for suitable technology applications" [E7]

The advanced microturbine program focuses on the following performance targets for the next generation of microturbine products [E7]:

High Efficiency – The target for electrical efficiency is at least 40%, which would push the overall efficiencies up to above 90%.

Environment – The NO_x target for emissions is less than 7ppmv in practical operating ranges.

Durability – The goal is 11,000 hours of operation between major overhauls and a service life of at least 45,000 hours.

Cost of Power – The target is achieving installed costs lower than US$500 per kW, a cost competitive with current technologies.

Fuel Cells for Buildings Program

Run by the *Energy Efficiency Department* within the DOE, the *Fuel Cells for Buildings Program* is developing the PEMFC as a cost effective and efficient technology suitable for CHP. Performance targets of the program include [E7]:

- Target overall efficiencies of 75–80%
- Target electrical efficiencies of 35–50%

- Achieve operating temperatures of 120-150°C
- Market clearing price of US$1,500/kW or less
- Operating life greater than 40,000 hours

The programs near term goals are to install a full laboratory prototype PEMFC system in a building in 2004, and develop a commercial product based on the first generation PEMFC by 2005. Another goal is to improve the efficiency of reformers that extract hydrogen from a variety of fuels, including natural gas, propane and clean oil.

The Environmentally Preferred Advanced Generation Program

The *Environmentally Preferred Advanced Generation (EPAG)* unit of the Public Investment Energy Research (PIER) program is run by the US DOE and is aimed at facilitating the widespread use of non-renewable distributed generation through the advancement of CHP technologies. In the short term this means reducing the emissions of IC engines. In the medium term it means reducing the emissions and costs of microturbines whilst at the same time improving their performance characteristics. In the long term the aim is to develop cost competitive, highly efficient and innovative technologies such as fuel cells and hybrids. Some of the targets of the program are summarized in the tables below [E8]:

Table E-11 Future IC Engine targets

Parameter	2003	2005	2007	2010
Electrical Efficiency	≥ 38%	≥ 40%	≥ 43%	≥ 50%
Overall Efficiency	≥ 85%	≥ 85%	≥ 86%	≥ 88%
NO_x (g/kWhr)	≤ 0.23	≤ 0.23	≤ 0.023	≤ 0.014
CO (g/kWhr)	≤ 2.75	≤ 2.72	≤ 0.036	≤ 0.036
VOC (g/kWhr)	≤ 0.45	≤ 0.45	≤ 0.01	≤ 0.01
Capex (US$/kWhr)	≤ 500	≤ 300	≤ 250	≤ 200
Opex (US$/kWhr)	≤ 0.006	≤ 0.005	≤ 0.005	≤ 0.004
Mean Time Between Major Overhauls (hrs)	≥ 35,000	≥ 40,000	≥ 45,000	≥ 50,000

Table E-12 Future Microturbine targets

Parameter	Target	Stretch Goal
Electrical Efficiency	35%	40%
Overall Efficiency	88%	≥ 90%
NO_x (g/kWhr)	≤ 0.173	≤ 0.15
CO (g/kWhr)	≤ 0.154	≤ 0.12
THC	≤ 20 ppm	≤ 10 ppm
Mean Time Between Major Overhauls (hrs)	12,000	16,000

Table E-13 Future Fuel Cell targets

	Parameter	Target	Stretch Goal
PEMFC	Capex (US$/kWhr)	1,200	700
	Electrical Efficiency	65%	70%

	Power Degradation (% per 1,000 hrs)	<0.6	<0.4
SOFC	Capex (US$/kWhr)	800	400
	Electrical Efficiency	70%	75%
	Power Degradation (% per 1,000 hrs)	<1.0	<0.5
MCFC	Capex (US$/kWhr)	1,500	700
	Electrical Efficiency	65%	70%
	Power Degradation (% per 1,000 hrs)	<0.6	<0.4

In addition to the specific future fuel cell targets shown in Table 6.m. the following general goals are also being sought:

PEMFC – Transfer of advances made for vehicular applications to stationary applications. System demonstrations for operation on natural gas and/or propane that are designed to rigorously test robustness, maintainability, stack lifetime and flexibility in operation.

SOFC – Develop innovative stack concepts, materials and fabrication methods for CHP systems 10 – 100kW in size. Demonstration of stack integrity over time and develop multi fuel capability.

MCFC – Develop system demonstrations that are designed to rigorously test robustness, maintainability, stack lifetime, thermal cycling and flexibility in operation.

Non US Research Activity

As mentioned previously microturbines are currently situated at the upper end of the micro CHP scale with sizes in the range of 30 – 100kW$_e$. However, there are a number of current research and development programs in progress which are looking at producing microturbines capable of producing an electrical output as low as 1 – 5kW. One of the most advanced examples of such a program is one being run by *Tohoku University, Japan* in conjunction with *Ishikawajima-Harima Heavy Industries Co. Ltd. (IHI), Japan*. In a paper presented at the *ASME Turbo Expo 2003: Power for Land, Sea and Ai* [5] the partners lay out details of a small microturbine they currently have under development that produces an electrical output of just 0.3kW. The technology involved is a huge leap forward for microturbines with compressor and turbine diameters as low as 10 mm, shaft diameters as small as 4 mm and rotational speeds of 870,000rpm, significantly higher than existing speeds of 50,000 – 100,000rpm.

A search of the *Cordis (Community Research and Development Information Service)*[6] web site gives an indication of current research activities within the EU. Listed below is a summary of the most relevant micro CHP programs (for more information please see the contact details listed in Appendix 5).

Hybrid Solar/CHP System – Recently completed (May 2003) this program aimed to investigate a novel hybrid solar collector/CHP system intended for use in buildings to provide heating and electricity generation. The proposed system will be driven by both solar energy and natural gas and make use of innovative heat pipe and turbine technologies combined with an "environmentally friendly" working fluid. Published results are expected in the near future.

Small Scale CHP Plant Based on a Hermetic Four-Cylinder Stirling Engine for Biomass Fuels – The main objective of this program was to develop a small scale biomass fired CHP plant based on a 70–100kW$_e$ hermetic Stirling engine and to erect a pilot plant where comprehensive

[5] *Development of Micro-Turbo Charger and Micro-Combustor as Feasibility Studies of Three-Dimensional Gas Turbine at Micro Scale* by Kousuke Isomura et al.
[6] www.cordis.lu

test runs could be performed with solid biomass fuels. Published results are expected in the near future.

Small Scale Combined Heat and Power using Renewable Fuels – The objective of this program was to develop technically and commercially viable small (5 – 400kW$_e$) CHP plants involving a gas turbine fired directly by a pressurized biomass fuelled cyclone combustor. This program was completed in 2002 and results are expected in the near future.

Optimised Microturbine Energy Systems – Currently in progress, this program aims to obtain energy savings and reduced emissions through the use of microturbines in different CHP applications; validate data on performance, energy efficiency, availability and emissions etc. during practical operation for the only European made microturbine. This project is due to end in September 2003.

System-Development, Build, Field Installation and European Demonstration of a Virtual Fuel Cell Power Plant, Consisting of Residential Micro-CHP's – A forty month program due to end in March 2005, this is a fuel cell based research and development program. The aim of the program is to develop, install, test and demonstrate a virtual power plant consisting of 54 decentralised residential fuel cells.

Figure E-A indicates the current and expected future electrical efficiencies of the identified CHP technologies, while Figure E-B. does the same for the overall efficiencies. (N.B: The fuel cell efficiency figures are based on a PEMFC system as identified in the *Fuel Cells for Building Program*, discussed previously).

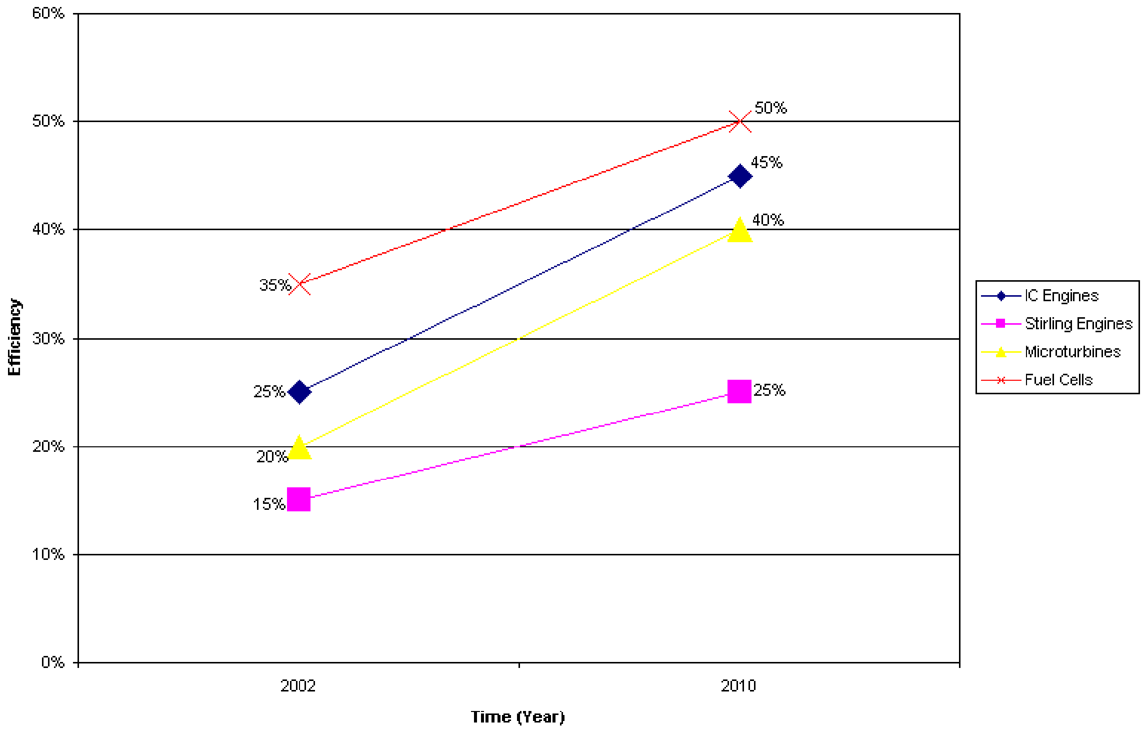

Figure E-A Current and Expected Future Electrical Efficiencies

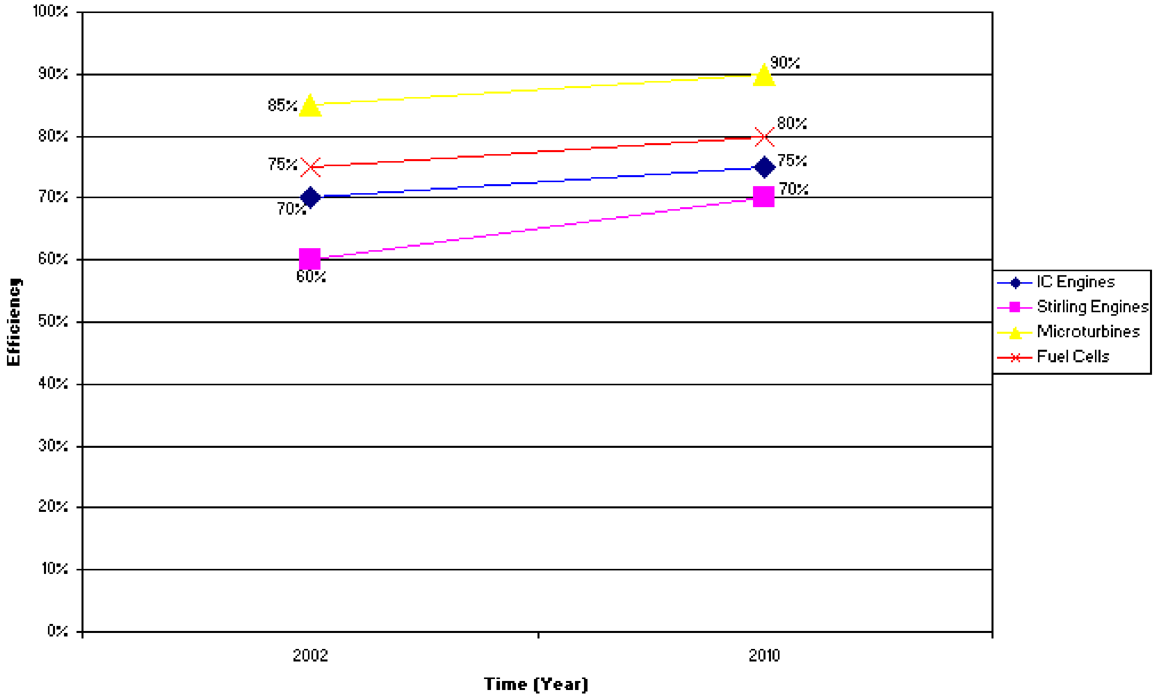

Figure E-B Current and Expected Future Overall Efficiencies

Sub-appendix E1 IC Engine Based Products

Company	**Electrical Output (kW_e)**	**Thermal Output (kW_t)**	**Available**	Company web address	**Notes**
Polar Power INC.	2.5-5	8.8	Now	www.polarpowerinc.com	2-cylinder US$9,985
ecopower	2.0 – 4.7	6.0 – 13.8	Now	www.ecopower.ch	1-cylinder
Senertec	5.0 –5.5	10.4 – 12.5	Now	www.senertec.de	1-cylinder
EC Power	15	35	Diesel version now, gas version 2004	www.xrgi.dk/index-uk.php	4-cylinder

Sub-appendix E2 Stirling Engine Based Products

Company	Electrical Output (kWe)	Thermal Output (kWt)	Available	Company web address	Notes
Microgen	1.1	15-36	2004	www.microgen.com	Claim 90%+ efficiency
Whisper Tech Ltd.	0.75	5	Now	www.whispergen.com	Multi fuel capability “High” efficiency
ENATEC	1	6-24	2004	www.enatec.com	
Tamin	1	Unconfirmed	In R+D	www.tamin.com	Very limited details
Sigma Elektroteknisk AS	3	9	In field trials, launch winter 2004?	www.sigma-el.com	

Sub-appendix E3 Microturbine Based Systems

Company	Electrical Output (kW_e)	Thermal Output (kW_t)	Available	Company web address	Notes
Bowman Power	80	136	Now	www.bowmanpower.com	
Capstone	30	60	Now	www.microturbine.com	Many units in use
Kohler Power Systems	80	Unconfirmed	Now	www.kohlerpowersystems.com	
Ingersoll Rand	70	Unconfirmed	Now	www.irco.com	
Turbec	105	167	Now	www.turbec.com	

Sub-appendix E4 Fuel Cell Based Systems

Company	Electrical Output (kWe)	Thermal Output (kWt)	Available	Type	Company web address	Notes
Vaillant	1 – 4.6	1.5-7	Extensive European trials	PEMFC	www.vaillant.de	Building on their successful installation of 3 prototypes (close partnership with Plugpower)
Ballard Power Systems	1	Unconfirmed	In R+D (a 250kW version is in field trials)	Unconfirmed	www.ballard.com	Aimed at Japanese market
Plugpower	2.5-5	3 -9	2004?	PEMFC	www.plugpower.com	
Ida Tech	3	Unconfirmed	In R+D	PEMFC	www.idatech.com	
Nuvera Fuel Cells	3.7	5.7	In R+D	PEMFC	www.nuvera.com	
Sulzer Hexis	1	2.5	Final testing, launch 2004?	SOFC	www.hexis.com	

Sub-appendix E5 Cordis Project Contact Details

Listed below are specific contact details for the micro CHP programs detailed above.

Hybrid Solar/CHP System

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Small Scale CHP Plant Based on a Hermetic Four-Cylinder Stirling Engine for Biomass Fuels

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Small Scale Combined Heat and Power using Renewable Fuels

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Optimised Microturbine Energy Systems
Hans Joergen Rasmusen
Dong A/S (Dansk Olie og Naturgas A/S)
Agern Alle 24-26
Horsholm, 2970
Denmark
E-mail: hjr@dong.dk
Tel: +45-45171561

System-Development, Build, Field Installation and European Demonstration of a Virtual Fuel Cell Power Plant, Consisting of Residential Micro-CHP's
Michel Brosset
Vailant GmbH
Berghauser Strasse 40
Remscheid, 42859
Germany
Tel: +45-219-1183660

References

[E1] **Technology Characterization: Reciprocating Engines**, *Environmental Protection Agency Climate Protection Partnership Division*, 2002, Washington DC, USA, Prepared by: Energy Nexus Group

[E2] **Domestic Micro Combined Heat and Power**, *Jeremy Harrison, EA Technology*, 2002,UK

[E3] **www.energy.ca.gov**

[E4] **Combined Heat & Power: A Federal Manager's Resource Guide**, *US Department of Energy Federal Energy Management Division*, 2000, Washington DC, USA, Prepared by: Aspen Systems Corporation Applied Management Sciences Group

[E5] **Technology Characterization: Fuel Cells**, *Environmental Protection Agency Climate Protection Partnership Division*, 2002, Washington DC, USA, Prepared by: Energy Nexus Group

[E6] **Technology Characterization: Microturbines**, *Environmental Protection Agency Climate Protection Partnership Division*, 2002, Washington DC, USA, Prepared by: Energy Nexus Group

[E7] **www.eren.doe.gov/der**

[E8] **www.energy.ca.gov/pier/epag/index.html**

Appendix F Assumptions used in the modelling

Example of area boundaries defined for cities

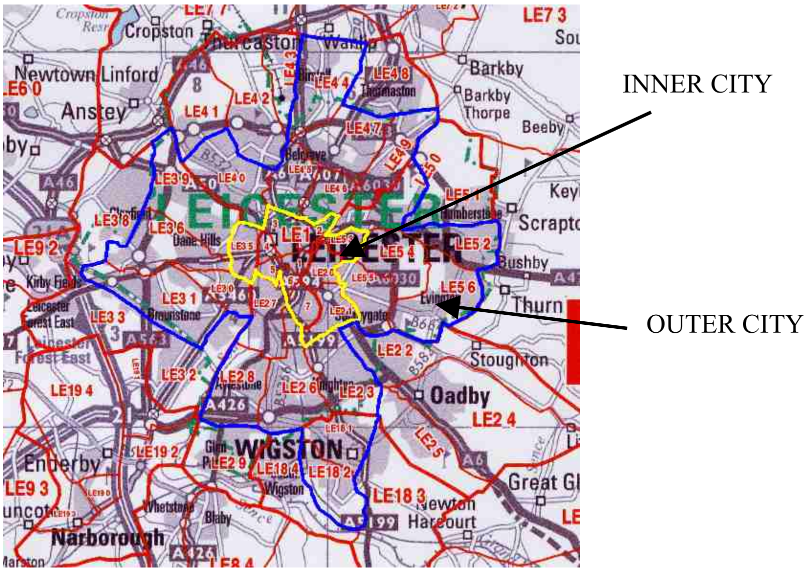


Figure F-A Example of the area boundaries defined for cities

Load factors used when generating demand profiles

Table F-1 Load factors used when generating demand profiles

	OVERALL	SPACE HEAT	HOT WATER	ELECTRICITY
One - Residential	20%	19%	25%	N/A
Two - Hospitals	35%	35%	N/A	N/A
Three - Universities	23%	23%	N/A	N/A
Four - Prisons	23%	23%	N/A	N/A
Five - Local gov offives	19%	19%	N/A	N/A
Six - Industrial	30%	30%	N/A	N/A
Seven - Commercial	15%	15%	N/A	N/A
Eight - Retail	15%	15%	N/A	N/A
Nine - Warehouses	19%	19%	N/A	N/A
Ten - Secondary Schools	23%	23%	N/A	N/A
Eleven - F.E. Colleges	23%	23%	N/A	N/A
Twelve - Overall Electricity	N/A	N/A	25%	71%

Estimating DH mains costs

Top-level methodology

- All loads are connected to the DH mains.
- DH mains modelled on three levels corresponding to system:

Table F-2 Top-level DH methodology

SCHEME	Local mains	District mains	Transmission main
City-wide	Included	Included	Included
District	Included	Included	Not included
Local	Included	Not included	Not included
Building	Not included	Not included	Not included

Local mains

A single notional grid is modelled for each postcode sector. The grids differ in size, but the geometry of every grid is the same:

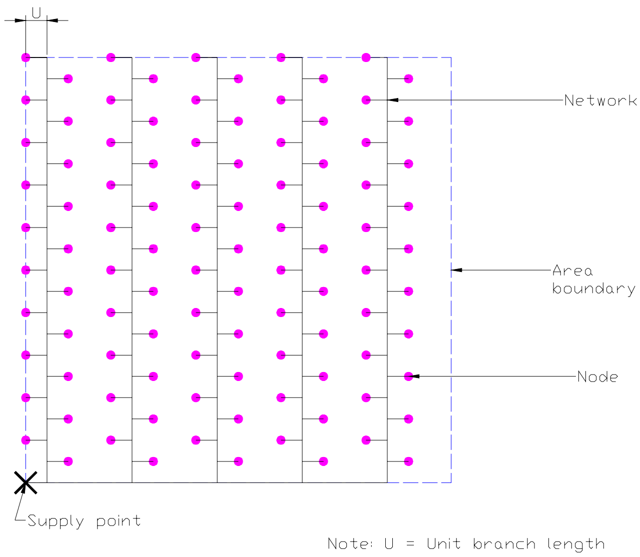


Figure F-B Schematic diagram of DH Local mains grid

- There are 100 nodes in every grid.
- The size of the grid varies to cover the postcode sector area ***A*** (m^2); equivalent to the area within the blue dotted line.
- The arbitrary unit used to measure the size of the grid is unit branch length ***u*** = (√***A***)/20
- Total length of pipe ***L*** in an grid = 217 ***u***
- The average load on each node ***p*** equals the peak combined heat load divided by 100

- The average pipe cost per metre ***x*** for a grid is a function of ***p*** and ***u***
- The total capital cost for the grid = ***xL***

Hydraulic analysis was carried of a range of network sizes and loading conditions (i.e. varying ***u*** and ***p*** respectively), the results of which are shown below. Linear interpolation within the resulting range of average pipe costs was used to estimate a value of ***x*** each network given its values of ***p***, ***u***. This was multiplied by ***L*** to obtain a capital cost estimate for the grid in each sector.

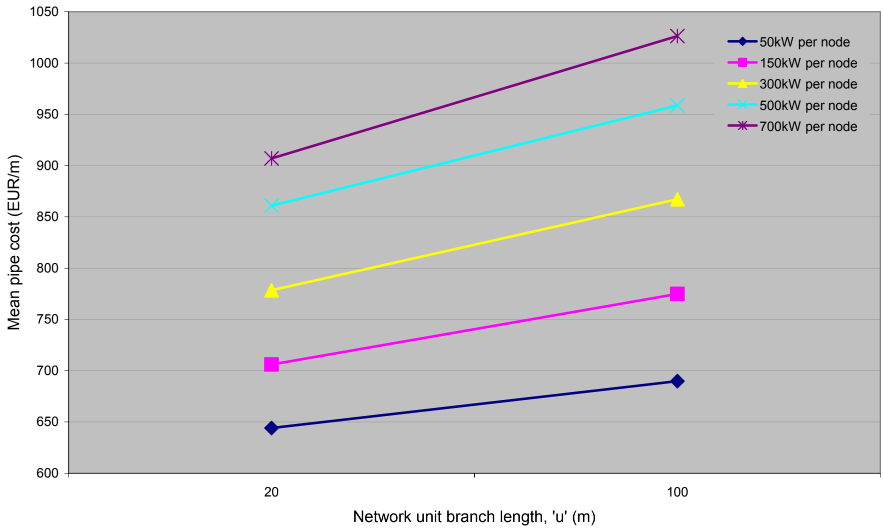


Figure F-C DH pipe average cost versus grid size for various loading conditions

The hydraulic analysis and optimisation of the notional grids was performed using a suite of hydraulic analysis software called System RØRNET. Given a set of parameters defining the network geometry and operational constraints, the software can calculate the optimum sizes of the pipes. For the Local level grids, the following design criteria are assumed:

Table F-3 Local DH design criteria

Static head	3 bar
Factor on pressure drop to account for bends, valves etc.	1.1
Minimum differential pressure at connection	1 bar
Maximum working pressure	10 bar
Nominal flow/return temperatures	95°C/65°C
ΔT	30°C

A ‘complexity weighting’ was then applied to each grid capital cost relating to the heat density of the sector.

Table F-4 Local DH complexity weighting factor

Heat density (MW/km2)	Factor on capital cost
<8	0.95
8 to 12	1
>12	1.3

For each DH scenario, the total cost of the Local DH mains is estimated the sum cost of all postcode sector grids relating to that scenario. This sum is then multiplied by a factor to account for the reduction in cost due to diversity on the network with that particular scenario.

An analysis was undertaken using a specific network on the effect of a reduction in the peak loads on the capital cost, shown on the plot below. The resulting factors used on DH mains capex are given in the table below.

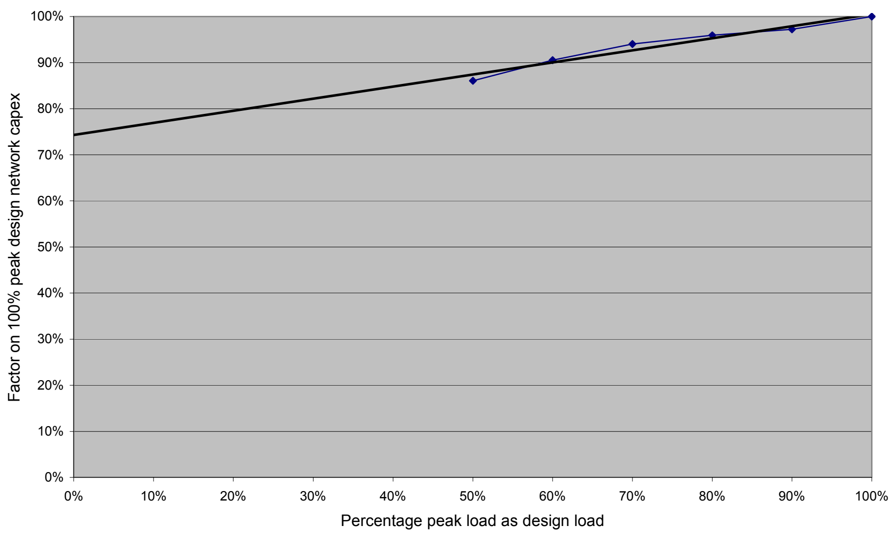


Figure F-D DH mains capex variation due to load diversity

Table F-5 Diversity factors assumed in CHP scenarios modelled

		Diversity factor on total heat peak	Factor on Local mains peak capex
WHOLE CITY	City-wide	63%	91%
	District	68%	92%
	Local	78%	95%
	Building	N/A	N/A
	Alternative	N/A	N/A
INNER CITY	City-wide	N/A	N/A
	District	68%	92%
	Local	77%	94%
	Building	N/A	N/A
	Alternative	N/A	N/A
OUTER CITY	City-wide	N/A	N/A
	District	67%	92%
	Local	78%	95%
	Building	N/A	N/A
	Alternative	N/A	N/A

Connection branches

The notional grid model does not make provision for the branches that will serve domestic consumers. A single dwelling branch was sized by the following methodology:

- 50kW maximum peak instantaneous heat demand
- 10m typical branch length (from street to dwelling)
- 95/65 DH flow/return temperature

DN25 pipe (nominal diameter 28.5mm) supplies peak with flow velocity of $0.8ms^{-1}$, pressure drop of 23mm/m.

For each postcode sector the cost for a single 10m long DN25 branch was multiplied by the number of dwellings in each category, with the following factors to account for multiple consumers.

Detached houses	1.0
Semi-detached houses	0.6
Terraces	0.4

District level mains

Notional heat grid model was used to assess the total required length of District level mains, assuming a uniform distribution of the Local supply points.

The District mains are sized to deliver the peak District CHP capacity, i.e. peak boilers are distributed at the Local energy centres. The following design criteria are assumed:

Table F-6 District DH design criteria

Static head	3 bar
Factor on pressure drop to account for bends, valves etc.	1.1
Minimum differential pressure at connection	2 bar
Maximum working pressure	25 bar
Nominal flow/return temperatures	110°C/70°C
ΔT	40°C

Transmission ring main

The total length of the mains is approximately 20.5km (using the Average City) including a branch of 500m length from the ring to the Energy Centre. Sized to deliver the peak City-wide CHP capacity i.e. peak boilers are distributed at the Local energy centres. The following design criteria are assumed:

Table F-7 Transmission main design criteria

Static head	3 bar
Factor on pressure drop to account for bends, valves etc.	1.1
Minimum differential pressure at connection	2 bar
Maximum working pressure	25 bar
Nominal flow/return temperatures	110°C/70°C
ΔT	40°C

All DH models were priced using the following schedule of inclusive installed costs given in EUR/m trench length:

Table F-8 DH pipe cost schedule

Pipe nominal diameter (mm)	Installed cost (EUR/metre)
25	595
32	602
40	644
50	672
65	749
80	777
100	847
125	931
150	1005
200	1162
250	1334
300	1498
400	1827
450	1991
500	2155

CHP model assumptions

Table F-9 CHP prime mover performance characteristics

SCHEME		DISTRICT	DISTRICT	CITY-WIDE	LOCAL	LOCAL	BUILDING	BUILDING	BUILDING	BUILDING	BUILDING	BUILDING
Description		CCGT	CCGT	CCGT	SIGE	SIGE	Micro	SIGE	SIGE	SIGE	SIGE	SIGE
Capacity	kWe	49300	70000	400000	5993	5100	0.85	122	305	625	836	2188
CHP Installed cost	Euro k	25,200	33,992	168,000	2,310	2,240	2.1	120	280	560	665	1,275
Standby boilers	Euro k	7,000	9,442	42,000	578	560	0.0	0	0	0	0	0
Balance of Mechanical Plant	Euro k	2,800	3,777	7,000	549	532	0.4	23	53	106	126	242
Energy Centre Electrical Works	Euro k	1,400	1,888	11,359	350	350	0.0	7	42	70	84	140
Energy Centre Control & Instrumentation Works	Euro k	1,400	1,888	11,359	350	350	0.0	7	42	70	84	140
Energy Centre Civil Works	Euro k	1,400	1,888	11,359	350	350	0.0	7	42	70	84	140
TOTAL CHP CAPEX	Euro k	39,200	52,876	251,077	4,486	4,382	2.5	164	459	876	1,043	1,938
Euro/kW installed	Euro k/kW	795	755	628	749	859	2,940	1,347	1,506	1,402	1,248	886
Combined efficiency		88%	88%	89%	80%	84%	96%	89%	84%	88%	88%	87%
Electrical efficiency (NCV)		53%	53%	54%	42%	46%	11%	34%	35%	40%	40%	42%
Thermal efficiency (NCV)		35%	35%	35%	38%	38%	85%	55%	49%	48%	48%	45%
Z-factor		6.27	6.15	n/a	n/a	6.27	n/a	n/a	n/a	n/a	n/a	n/a

Table F-10 CHP model operational inputs

		City-wide	District	Local	Building	Alternative
Energy prices						
Fuel for CHP (Natural Gas)	Eurocent/kWh	0.98	1.12	1.26	1.68	0
Fuel for boilers	Eurocent/kWh	0.98	1.12	1.26	1.68	1.68
Net electricity import price	Eurocent/kWh	3.5	3.5	3.5	3.5	3.5
Transmission losses on CHP energy						
DH pumping energy as % heat demand		3%	2%	1%	0%	0%
DH energy heat loss as % heat demand		10%	9%	7%	0%	0%
Electricity HV transmission losses		3%	3%	0%	2%	3%
Electricity LV transmission losses		6%	6%	6%	3%	6%
Non-fuel operating costs						
CHP unit availability		98%	97%	96%	100%	100%
CHP maintenance	Eurocent /kWh e	0.28	0.42	0.56	1.4	0
CHP staffing	Eurocent /kWh e	0.14	0.14	0.21	0.7	0
Boiler maintenance	Eurocent /kWh th	0.14	0.14	0.14	0.28	0.28
Boiler staffing	Eurocent /kWh th	0.05	0.05	0.07	0.00	0.00
DH maintenance (annual)	% of DH capital	1%	1%	1%	0%	0%
DH staffing (annual)	% of DH capital	0.3%	0.4%	0.5%	0.0%	0.0%
Combined administration (annual)	% of total capex	0.50%	0.50%	0.70%	0.50%	0.50%
Emissions factors (CO2) on imported fuel (boundary of city)						
Electricity	g/kWh	390	390	390	390	390
Gas	g/kWh	190	190	190	190	190

Table F-11 Scenario capex schedule for Whole City

		City-wide	District	Local	Building	Alternative
1. Energy Centre						
CHP Unit	Euro k	168,000	210,392	114,800	413,189	0
Standby boilers	Euro k	42,000	58,442	28,700	0	0
Balance of Mechanical Plant	Euro k	7,000	23,377	27,265	78,506	0
Energy Centre Electrical Works	Euro k	11,359	11,688	17,500	21,783	0
Energy Centre Control & Intrumentation Works	Euro k	11,359	11,688	17,500	21,783	0
Energy Centre Civil Works	Euro k	11,359	11,688	17,500	21,783	0
TOTAL	Euro k	251,077	327,276	223,265	557,044	0
2. District Heating Network						
Transmission heat mains	Euro k	93,848	0	0	0	0
District heat mains	Euro k	105,840	105,840	0	0	0
Local heat mains	Euro k	778,898	789,026	811,532	0	0
TOTAL	Euro k	978,586	894,866	811,532	0	0
3. Building connections						
Residential	Euro k	90,103	90,103	90,103	0	0
Hospitals	Euro k	442	442	442	0	0
Education	Euro k	1,600	1,600	1,600	0	0
Prison	Euro k	8	8	8	0	0
Commercial	Euro k	1,918	1,918	1,918	0	0
Retail	Euro k	3,103	3,103	3,103	0	0
Warehouse/Industrial	Euro k	2,453	2,453	2,453	0	0
TOTAL	Euro k	99,627	99,627	99,627	0	0
4. Electrical network costs	Euro k	4,200	4,760	3,500	0	0
5. Gas network costs	Euro k	2,800	3,500	2,450	0	0
TOTAL CAPEX	**Euro k**	**1,336,291**	**1,330,029**	**1,140,374**	**557,044**	**0**

Table F-12 Scenario opex schedule for Whole City

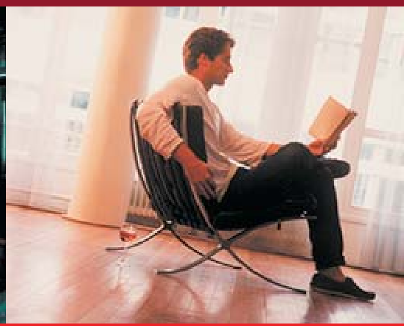
		City-wide	District	Local	Building	Alternative
Fuel for CHP	Euro k	75,359	80,642	66,718	38,852	0
Fuel for Boilers	Euro k	10,009	12,421	13,326	21,728	50,127
Net grid electricity imported to city	Euro k	-74,504	-60,648	1,527	61,302	88,660
CHP maintenance	Euro k	11,087	15,141	11,463	13,170	0
boiler maintenance	Euro k	1,144	1,242	1,185	1,449	3,501
boiler staffing	Euro k	477	518	740	0	0
DH maintenance	Euro k	9,786	8,949	8,115	0	0
DH staffing	Euro k	2,936	3,579	4,058	0	0
Administration	Euro k	6,681	6,650	7,983	2,785	0
TOTAL ANNUAL OPEX	**Euro k**	**42,975**	**68,495**	**115,115**	**139,285**	**142,288**

Appendix G Energy Demand Benchmarks

Table G-1 Energy demand benchmarks

DOMESTIC	Fossil fuel use due to space heating and domestic hot water	heat demand for space heating and domestic hot water	Electricity Use1	HEAT Load Factor	ELEC Load Factor
	(kWh/dwelling per annum)	(kWh/dwelling per annum)	(kWh/dwelling per annum)		
Detached	25,875	19,406	3,910	20%	35%
Semi-detached	19,210	14,408	3,145	20%	35%
Terraced	16,929	12,697	2,916	20%	35%
Purpose Built Flats	9,086	6,815	1,947	20%	35%
Converted Flats	10,140	7,605	2,340	20%	35%
Not Self Contained 2	5,070	3,803	1,170	20%	35%
Other Household Spaces Not self contained 2	5,070	3,803	1,170	20%	35%

NON-DOMESTIC	Fossil fuel use due to space heating and domestic hot water	heat demand for space heating and domestic hot water	Electricity Use	HEAT Load Factor	ELEC Load Factor
	(kWh/unit per annum)	(kWh/unit per annum)	(kWh/unit per annum)		
Hospitals (kWh/bed)	25,740	19,305	7,000	35%	65%
Universities (kWh/full time student)	4,200	3,150	1,710	23%	50%
Prisons	430	323	135	23%	40%
Factories (kWh/sq.m.)	245	184	471	30%	50%
Local Government Offices (kWh/sq.m.)	95	71	39	19%	35%
Commercial Offices (kWh/sq.m.)	147	110	95	15%	35%
Retail (kWh/sq.m.)	185	139	275	15%	40%
Warehouses (kWh/sq.m.)	64	48	81	19%	40%
Schools / Further Education (kWh/pupil)	2,583	1,937	372	23%	50%



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