Tyndall°Centre
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Fuel cells: providing heat and power in the urban environment

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Section 1: Overview of project work and outcomes

Abstract

Combined heat and power (CHP) plants, in which the heat produced as a consequence of electricity generation is used to provide local heating, offer significantly enhanced overall efficiencies, and therefore reduced CO_2 emissions, compared to conventional centralised generation. Fuel cell technology is ideal for CHP plants as it offers high fuel efficiency coupled with negligible impact on local air quality. In the context of climate change, perhaps its most important advantage is the ability to use low- or zero-carbon fuels, offering the potential for reduction of the current unsustainable growth in anthropogenic CO_2 emissions.

Although CHP using conventional generators is a well-established technology, fuel cell CHP is currently too expensive to be commercially viable. Although improvements in technology can be expected to reduce costs, the introduction of fuel cell CHP could be further facilitated by identifying and exploiting favourable ‘niche’ applications. This project has identified the costs and benefits of widespread implementation of small-scale (less than 1 MW_e) fuel cell CHP in urban environments, considering technical, environmental and socio-economic aspects, and has proposed possible implementation strategies.

The most significant results of the project were obtained in a life-cycle assessment of fuel cells, which included results for a potential fuel cell CHP solution for a community heating scheme.

Objectives

The overall aim of the project was “to identify barriers to widespread implementation of small-scale (less than 1 MW_e) fuel cell CHP in a range of urban environments, considering technical, environmental and socio-economic aspects. The project’s outputs will define the existing scope for fuel cell CHP, identify the conditions required for increased future penetration, and assess the associated social and environmental benefits.”

Work undertaken

The work was undertaken by researchers based at two centres, CCLRC Rutherford Appleton Laboratory, who were responsible for the technology review, system modelling, and case studies; and University of East Anglia, who were responsible for the social cost-benefit analysis, identification of barriers and solutions, and assessment of lifecycle emissions.

- The technical review considered the suitability of differing types of fuel cell, including consideration of the thermal/electrical power split and overall efficiency, sizing and siting considerations, and the matching of supply to local demand. An analysis procedure using several computer models was developed, to perform a comprehensive analysis of potential urban applications in which fuel cell CHP could be implemented.

- The environmental assessment considered the impact of fuel cell CHP on local, regional and global pollutants, including an external cost analysis.

- The socio-economic review included a social cost benefit analysis of energy generation and supply using conventional, CHP and fuel cell technologies. Using semi-structured interviews with stakeholders non-technical barriers to implementation were identified and possible means to their being overcome, including the use of economic instruments and demand-side management schemes.

- Modelling of fuel cell CHP systems was carried out by integrating the best features of two well-established CHP software simulation tools. Study of a specific case study enabled conclusions to be drawn about the relative merits of micro-CHP and community heating schemes, and the sensitivity of economics to variations in gas & electricity prices.

Results

This study has found that:
- Fuel cell CHP systems may be commercially available and in some cases economically viable by 2009.
- In high density developments (for example around 50 dwellings per hectare) community heating is likely to be economically viable and efficient, while in lower density developments (for example less than 25 dwellings per hectare) micro CHP is likely to be economically attractive.
- Conventional and fuel cell CHP economics are highly sensitive to the ‘spark spread’ of electricity and gas prices, defined as the difference between the price of electricity sold by a generator and the price of the fuel used to generate it. (Note : There are many other factors including specific negotiated tariffs, the electricity trading arrangements, the capital and running costs, Climate Change Levy Exemption certificates – LECs, as well as the Distribution Use of System Costs - DUoS[1]).
- Fuel cells are becoming available with high overall and electrical efficiencies, and when combined with CHP systems they can result in reduced CO_2 emissions.
- There may be significant environmental costs associated with the manufacture of the fuel cells, the magnitude varying with the type of fuel cell. It is therefore critically important to carry out a full lifecycle assessment of the different schemes in order to minimise overall environmental costs.

Relevance

In a broad, cross-cutting, multi-disciplinary, study, the project team has examined the technical opportunity of fuel cell CHP, considering the social, environmental and economic aspects as well as efficiency improvements. A key finding of the study using integrated assessment is that the results of the life-cycle assessment suggest that decision making at the policy level must consider all emissions, as well as the potential for efficiency improvements.

The UK Government has published an implementation strategy for CHP[2], including fiscal incentives and promotion of innovation, within a regulatory framework. The strategy is aimed at achieving the UK target for CHP capacity, and the resulting systems are likely to be based on the most economic solution, rather than consideration of levels of CO_2 or other emissions. The strategy does not target or encourage specific technologies. This project has highlighted the advantages and disadvantages of fuel cell CHP, and will therefore be a useful input to decision making for future policy and implementation strategies.

Potential for further work

It is suggested that further research is required to:
- Explore the application of fuel cells plus the use of renewable energy for hydrogen production, and the consequent change in lifecycle cost and emissions.
- Explore alternative fuel cell technologies (especially those which have lower emissions in the manufacturing stage).
- Determine the optimum scheduling of multiple fuel cell CHP systems, with modifications to the usual ‘heat led’ or ‘electric led’ control strategies.

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[1] Getting Best Value for Electricity Generated in Community Heating, Energy Savings Trust, CE75, 2004
[2] The Government’s strategy for Combined Heat and Power to 2010, DEFRA, April 2004

- Improve utilisation of CHP plant (including micro-CHP) by operating at full load for longer periods, achieved by the inclusion of heat or electricity storage to smooth the demand.
- Compare the benefits of micro-CHP in each dwelling, and community heating, for various housing densities. This would include investigation of the effect of heat loss in the distribution system.

Communication highlights

Posters were provided each year for the Tyndall Assembly, and two Tyndall Working Papers were produced during the course of the project:

- Fuel Cells for a sustainable future? A review of the opportunities and barriers to the development of fuel cell technology. Powell J.C., Peters M.D., Ruddell A., Halliday J., Tyndall Working Paper No. 50, March 2004.

- Fuel Cells for a sustainable future II. Stakeholder attitudes to the barriers and opportunities for stationary fuel cell technologies in the UK. Peters M.D., Powell J.C., Tyndall Working Paper No. 64, October 2004.

Two journal papers are currently being written on the results in the social cost-benefit analysis (Chapter 3) and the life-cycle assessment (Chapter 4).

Section 2: Technical report

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1. INTRODUCTION

Combined heat and power (CHP) is a well-established technology and is in widespread use. The UK Government target is to achieve 10GWe of ‘good quality’ CHP capacity by 2010, and has recently set out its strategy[3]. Government incentives include exemption from climate change levy (CCL) charges for electricity generated by a ‘good’ CHP system. Grants are available for Community Heating schemes, which could include the use of CHP systems. Promotion covers the full range of capacity, including the smallest systems known as micro-CHP (domestic CHP) of around 5kWe capacity.

The overall aim of this study was to review technical environmental and socio-economic factors determining the viability of fuel cell CHP in the urban environment. Fuel cell technology is under intensive development for mobile and stationary applications, including efficient electricity generation. The advantages of high electrical efficiency and clean and quiet operation are well known. Although the current high price of fuel cells currently limits commercial application in CHP systems, it is appropriate to investigate the future potential of fuel cells from the point of view of environmental benefits, in particular carbon dioxide savings. The multi-disciplinary study was wide-ranging, and the results are presented in chapters corresponding to the main factors and work packages. The chapters are self-contained and can be read in isolation; however the chapters also contain the linkages and cross-references to make the whole study cohesive.

The study basically covers:

- A review of the state of the art in CHP, fuel cells, and fuel cell CHP;
- Quantification of economic, social, and environmental costs and benefits;
- Analysis of fuel cell CHP system solution in target applications;
- Conclusions and implementation strategies.

Review of the state of the art in CHP, fuel cells, and fuel cell CHP

There is a wealth of information available on conventional CHP and fuel cells, and the state of the art of these two subjects is reviewed in **Chapter 2**. CHP systems are usually based on the use of reciprocating engine and gas turbine prime movers for electricity generators; while the use of fuel cells is in an early stage of development and demonstration. However the use of fuel cells in CHP systems under 1MW capacity is already being actively demonstrated, and therefore the state-of-the-art of development and demonstration of fuel cell CHP is also reviewed in **Chapter 2**.

Quantification of economic, social, and environmental costs and benefits

It is often assumed that fuel cells will become the technology of choice in many applications, including CHP, based on the optimistic promotion of this ‘clean’ technology. However the decision is not simple, and should be based on quantification of all economic and environmental costs and benefits. A cost-benefit analysis is described in **Chapter 3**, and further analysis of atmospheric emissions for the full lifecycle of fuel cell CHP systems, from manufacture, use, and disposal, is described in **Chapter 4**. The barriers and solutions relevant to fuel cell introduction, as perceived by the various stakeholders, are investigated in **Chapter 5**.

Analysis of fuel cell CHP system solution in target applications

Potential CHP system solutions, applied to target applications, have been analysed in detail in order to quantify their economic and environmental performance including fuel usage and associated emissions. The software tools and techniques used in this study for system modelling of CHP systems is described in **Chapter 6**. These tools can be used to investigate a range of target applications. A case study of a community heat and power system for a new development of mixed residential, business, retail, leisure, and school buildings is described in **Chapter 7**, and the performance of fuel cell CHP systems is compared with the use of conventional CHP.

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[3] The Government’s strategy for Combined Heat and Power to 2010, DEFRA, April 2004

Conclusions and implementation strategies

Chapter 8 draws conclusions resulting from integration of the study, and includes discussion of possible implementation strategies.

2. TECHNOLOGY REVIEW

2.1 Introduction

A technology review of fuel cells was undertaken early in the project, and the results are presented in three sections, i) Combined heat and power (CHP), also known as co-generation in continental Europe, ii) Fuel cell technology, and iii) CHP using fuel cell electricity generation.

The scope of the review is small-scale (i.e. $<1MW_e$) combined heat and power plant using natural gas, typically used for small residential or industrial developments. The results are presented in detail in Tyndall Working Paper 50 (Powell et al, 2004).

CHP is already well established as an efficient way of generating electricity where there is a heat demand. The installed capacity in the UK in 2003 was around $4.8GW_e$ ($11.2GW_{th}$), and the UK Government has set an installed capacity target of $10GW_e$ by 2010. Small-scale CHP ($<1MW_e$) represents 83% of the total number of installations, but only 3.9% of the current total installed CHP capacity in the UK (DTI, Digest of UK Energy Statistics, 2004). Power companies currently say that the new electricity trading rules (NETA) and high prices of natural gas will make the installed capacity target difficult to meet (Ofgem 2002). In the decade to 2000 CHP capacity more than doubled representing an average growth rate of 8% per annum; however since 2001 difficult market conditions have slowed the growth rate. Despite a decreasing number of CHP systems, the overall electrical capacity has still been increasing slowly.

The importance of CHP technology as a way of achieving emission reductions has also been recognised at the international level. For example, a two year study by Capros et al (2001) for the European Commission, 'Economic Evaluation of Sectoral Emission Reduction Objectives for Climate Change' had the objectives: (i) to identify the (least-cost) contribution of different sectors and gases for meeting the Community’s quantitative reduction for greenhouse gases under the Kyoto protocol; and (ii) to determine a package of cost-effective policies and measures for all sectors and gases towards meeting the goals. The study identified decarbonisation of energy supply as one of six ways for the EU to reach the Kyoto target in the most cost-effective manner. Within the energy supply sector the measures identified were further switching from coal to gas, more efficient generation of power including increasing the share of CHP, and increase in the use of renewable energy.

Fuel cell technology is ideally suited for CHP in the urban environment as it offers high efficiency, and negligible noise and emissions at the point of use. However assessment of full lifecycle costs shows that emissions during manufacture are significant and need to be taken into account. Fuel cells can operate from the existing natural gas distribution network, using a reformer to convert methane gas to hydrogen. While there are CO_2 emissions caused by reforming methane gas, the output of the fuel cell stack is H_2O with negligible levels of other emissions. The development and implementation of fuel cells using reformed natural gas is already justified in terms of efficiency improvements and emissions reduction. The development and deployment of fuel cells could lead into future development of a sustainable ‘hydrogen economy’, in which hydrogen gas is generated using renewable sources of energy, and which offers the possibility of negligible emissions overall (Dutton et al 2004, Dunn 2002, Conte et al 2001).

Fuel cells are under active development for many applications ranging from automotive to stationery power, including CHP. The phospheric acid fuel cell (PAFC) is already a reliable and commercial technology, however it does not offer much potential for further cost reduction and efficiency improvements. The fuel cell technologies which are attractive for CHP systems include Proton exchange membrane (PEMFC) and solid oxide (SOFC), however both require significant price reductions to be competitive with gas engines and gas turbines.

The UK's first commercial fuel cell CHP system was installed at Woking Park in 2001 to provide heat and power for a swimming pool and leisure centre. The 200kWe phosphoric acid fuel cell system (PAFC) complements two conventional systems, and provides an opportunity to make economic, operational, and environmental comparisons between technologies.

Deployment of fuel cell power plants in or near buildings will require careful attention to standards of construction, performance, installation, and operation. Pennycook (2001) provides a list together with details of codes and standards which are already available and under development.

2.2 Combined Heat and Power

2.2.1 CHP overview

The installation of a CHP plant on a site with simultaneous demand for electrical power and heat can make significant cost savings. The savings, which are achieved by higher overall thermal efficiency, and by exploitation of the spread of electricity and gas tariffs, can be further improved by exemption from the Climate Change Levy (CCL). The introduction of the CCL on imported electrical power and gas is having an impact on CHP system design. To achieve exemption from the CCL, a CHP scheme should be certified as achieving a Quality Index target, and an electrical efficiency of greater than 20% (Defra 2000). There were 1252 small-scale ($<1MW_e$) installations in 2003, which are typically in hotels, leisure centres, hospitals, universities, and community heating systems, applications which offer the best cost savings. Information is available from the Combined Heat and Power Association (CHPA) which is the industry association, and from the CHP Club (Carbon Trust) which is an initiative funded under the Carbon Trust’s Action Energy programme, aimed at assisting users and potential users in getting the maximum benefits from CHP.

Most small-scale CHP units use reciprocating internal combustion (IC) gas engines as the prime mover, which can achieve high levels of reliability, and a heat to power ratio of about 1.5:1. Heat can be recovered from the engine exhaust (at around 400ºC) and from the engine cooling system (at around 80ºC). Gas turbines are widely used in larger-scale CHP systems, and are now becoming available for small-scale systems. Although gas turbine systems have a lower electrical efficiency, they have a high temperature exhaust (up to 600ºC) which can be used for raising steam. Alternatively small-scale gas turbines can use a recuperator to improve the electrical efficiency, but with a lower exhaust temperature. Heat to power ratios of 1.5:1 up to 3:1 can be expected. Gas turbines offer benefits in certain applications as they require less frequent maintenance than gas engines.

Two basic control strategies can be used to manage heat and power production. The CHP system is usually operated to match heat generated to heat demand (heat led). When the CHP system reaches rated power, an auxiliary boiler is used to satisfy the full demand. Alternatively the system can be electric led, where the electrical power output follows the demand or is maintained at maximum. In this case surplus heat can be rejected via a radiator or heat dump. The process of controlling heat and power output is known as regulation or modulation.

Most small-scale CHP systems are operated in parallel with the utility supply, and are normally designed to meet only part of the site electrical load. It is not common practice to export power to the utility network because the cost of export metering and contracting may outweigh the export revenue. However systems can be designed to operate in Island Mode (in the event of a utility supply failure), and may be used together with conventional standby generators. The DTI (ETSU, 1999) have provided a technical guide to connection of embedded generators to the distribution network.

The NETA arrangements, introduced on 27th March 2001, did not encourage small embedded generators (such as CHP plant), and a review of the impact of NETA on smaller generators was included in a wider review of the first year of NETA (Ofgem 2002). Ofgem proposed a mechanism known as 'consolidation' to assist the competitiveness of small generators, however Ofgem's view that consolidation addressed the problems faced by small generators, including CHP, was not shared by the UK Combined Heat and Power Association (CHPA Press Release, 8-Feb-2002). High gas and low electricity tariffs continue to make a difficult economic climate for CHP.

Technical and tariff issues were addressed by the DTI embedded generation working group on network access issues for embedded generation [Ofgem/DETR/DTI, 2001a). The report calls for:

- a fundamental change in regulation to provide new opportunities for small generators and network operators alike to encourage the growth of local generation;
- transparent and fair access for smaller generators to the electricity network;
- rewarding the competitive benefits that local generation brings to consumers and the environment.

Following a consultation in Sept 2001 (Ofgem 2001b), Ofgem reported progress on measures to remove barriers and provide a fair regime for distributed generation (Ofgem 2004).

2.2.2 CHP feasibility

Determination of the feasibility of installing a CHP plant in a particular site involves a number of logical steps, which may be repeatedly considered in order to optimise the selection of particular plant. A clear procedure is detailed in The Manager’s Guide to CHP (CHP Club, 2002), with the basic steps as follows:

- determine the site heat and power demands;
- select CHP plant of an appropriate rating and type;
- assess operating costs/savings when using CHP plant;
- determine where/how CHP unit will be installed and connected to fuel, heat and power systems
- assess capital costs of installation;
- assess the economic, energy and environmental benefits of installation;
- assess the nature of other relevant issues (e.g. permits or consents).

Other tools are available for both feasibility and full engineering design studies. These are further described in Chapter 6 (System Modelling) of this report.

2.2.3 CHP applications

There are many applications of small scale CHP applications in the UK (1252 installations < 1MWe in 2003). Descriptions of selected CHP applications can be viewed on the CHPA website.

Guides for designers and managers are available from several sources, for example, Good practice guides (Carbon Trust), Applications Manual CIBSE (1999), The CHP QA standard (CHP QA, 2000).

There is considerable interest in installing CHP systems in domestic properties, called micro-CHP or dCHP (domestic CHP). A domestic CHP system is a replacement for conventional domestic heating boilers, providing electrical output while operating in a heat-led mode. A report by Harrison and Redford (2001) concludes that micro-CHP may ultimately provide an installed generating capacity of 15-20GW in the UK, contributing to annual reduction of 16 million tonnes of carbon. Field trials have been held in the UK, and full availability to the general market by 2007 is expected from companies including Microgen, Powergen, and Baxi.

2.3 Fuel cells

2.3.1 Fuel cell principles

A fuel cell is an electrochemical engine that converts the energy of a chemical reaction directly to electricity. Hydrogen and oxygen are combined over a catalyst to produce electricity and water.

Several types of fuel cell are under active development. A useful factfile describing the fuel cell principles of operation, types and applications is available from the Institution of Electrical Engineers (IEE, 2003).

Fuel cells are clean enough for power to be generated at the point of use utilising a variety of fuels. When run on hydrogen, the fuel cell is a true ‘zero emissions’ source of power, emitting only pure water. They produce no particulates, are extremely quiet and can operate in the same room as people with almost no detrimental impact on the local environment. Fuel cells are thus ideally suited for use in micro Combined Heat and Power (CHP) applications in the home. In these applications 3 to 10kW electricity can be generated by a fuel cell, and the heat produced can be used to heat, or even to air-condition the building. The ability to utilise the heat greatly increases the efficiency of the fuel cell system and provides many benefits over electricity generated by central power stations and transmitted over long power lines.

The basic principles of fuel cells are essentially simple, and are best described for the Polymer Electrolyte Membrane (PEM), see Fig. 2.1. Fuel cells have no moving parts. At their heart are two catalysed electrodes separated by a sheet of polymer. The catalyst is coated onto a sheet of special carbon fibre paper that acts as a gas diffusion layer. The catalyst layer is in contact with the polymer membrane. Hydrogen is supplied to one side of the cell (the anode) and oxygen to the other (the cathode).The membrane prevents the two gases from mixing but it also has the unique ability to conduct protons. The catalyst on the anode ionises the hydrogen gas and protons can then pass through the membrane and react with the oxygen in the presence of the catalyst on the cathode to form water. The reaction is completed by the hydrogen electron rejoining the proton via a wire, thus creating an electrical current. The membrane and the two gas diffusion and catalyst layers are laminated together to create a Membrane Electrode Assembly (MEA). This is placed between two gas flow plates that distribute hydrogen and air to either side of the MEA.Together these five components form a single cell. Each cell generates about 0.7 volts so they are stacked together to add up to a usable 200 to 300 volts. This is called a Fuel Cell Stack.

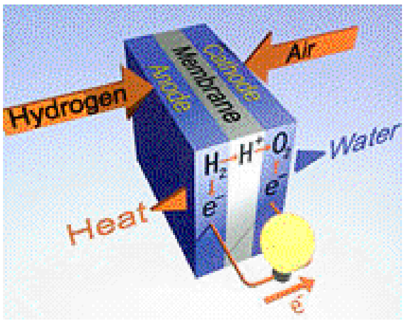


Fig 2.1. Fuel cell - basic principle (reproduced from DTI)

A fuel cell system using natural gas is typically grouped into three main functions, the gas processor to reform natural gas (methane) to hydrogen, the fuel cell stack producing useful heat and d.c. electricity, and the power conditioner to convert d.c. to a.c. power compatible with the electricity distribution network. In some fuel cell technologies which operate at high temperatures, such as the MCFC and SOFC, reforming can take place within the fuel cell itself. The fuel cell technologies are well described in many texts, see for example Larminie and Dicks (2000), Acres (2001), and Cacciola (2001). The US Department of Defense Fuel Cell Demonstration Program website contains a particularly useful description (US DOD FuelCELL).

2.3.2 Fuel cell technologies

The four primary fuel cell technologies are summarised in Table 2.1.

The Phosphoric Acid Fuel Cell (PAFC) is the most mature fuel cell technology in terms of system development and commercialisation activities. It has been under development for more than 20 years and has received a total worldwide investment in the development and demonstration of the technology in excess of $500 million. The PAFC was selected for substantial development a number of years ago because of the belief that, among the low temperature fuel cells, it was the only technology which showed relative tolerance for reformed hydrocarbon fuels and thus could have widespread applicability in the near term. Almost 400 pre-commercial systems have been sold worldwide (total capacity ~44MW). Demonstrated in buses, it has been pursued as a candidate for CHP and distributed power applications. Increasingly it is being marketed as a technology for uninterruptible power supplies (UPS) and premium power applications.

	PAFC Phospheric acid fuel cell	**MCFC** Molten carbonate fuel cell	**SOFC** Solid oxide fuel cell	**PEMFC** Proton exchange membrane fuel cell or **SPFC** Solid polymer fuel cell
ELECTROLYTE	Phosphoric Acid	Molten Carbonate Salt	Ceramic	Polymer
OPERATING TEMPERATURE	190°C	650°C	1000°C	80°C
FUELS	Hydrogen(H_2) Reformate	H_2/CO/ Reformate	H_2/CO_2/CH4 Reformate	H_2 Reformate
REFORMING	External	External/Internal	External/Internal	External
OXIDANT	O_2/Air	CO_2/O_2/Air	O_2/Air	O_2/Air
ELECTRICAL EFFICIENCY (% HHV)	40-50%	50-60%	45-55%	40-50%

Table 2.1. Features of the four main fuel cell technologies
(reproduced from: US DOD FuelCELL Demonstration Program)

The Molten Carbonate Fuel Cell (MCFC) evolved from work in the 1960's aimed at producing a fuel cell which would operate directly on coal. While direct operation on coal seems less likely today, operation on coal-derived fuel gases or natural gas is viable. The MCFC is a candidate for stationary power and CHP applications and has been demonstrated at 2MW scale.

The Solid Oxide Fuel Cell (SOFC) uses a ceramic, solid-phase electrolyte, which reduces corrosion considerations and eliminates the electrolyte management problems associated with the liquid electrolyte fuel cells. To achieve adequate ionic conductivity in such a ceramic, however, the system must operate at about 1000°C. At that temperature, internal reforming of carbonaceous fuels should be possible, and the waste heat from such a device would be easily utilized by conventional thermal electricity generating plants to yield excellent fuel efficiency.

The Proton Exchange Membrane Fuel Cell, Polymer Electrolyte Membrane (PEMFC), Solid Polymer Fuel Cell (SPFC) offer an order of magnitude higher power density than any other fuel cell system, with the exception of the advanced aerospace Alkaline Fuel Cell (AFC), which has comparable performance. The PEMFC can operate on reformed hydrocarbon fuels, with pre-treatment, and on air. The use of a solid polymer electrolyte eliminates the corrosion and safety concerns associated with liquid electrolyte fuel cells. Its low operating temperature of 80ºC provides instant start-up and requires no thermal shielding to protect personnel. Recent advances in performance and design offer the possibility of lower cost than any other fuel cell system. The PEMFC has a high power density, and is very promising for mass market applications such as automotive and stationary small scale CHP applications. There is a massive global effort to develop commercial systems. PEMFCs are now being demonstrated in a range of commercial applications including buses, cars, small-scale CHP and distributed power.

2.3.3 Environmental benefits

The potential environmental benefits of using fuel cells in cars, buses and stationary combined heat and power (CHP) plants of different sizes has been investigated by Hart (1997, 1998). The environmental analysis was conducted for the UK on a 'full fuel cycle' basis, encompassing all greenhouse gas and regulated pollutant emissions for the supply chain and end-use technology under consideration. Solid polymer fuel cells (SPFCs) with methanol or natural gas reformers were analysed for cars, SPFCs and phosphoric acid fuel cells (PAFCs) with on-board hydrogen for buses. CHP plants were PAFCs or solid oxide fuel cells (SOFCs). Each option was compared with one or more conventional technologies. In all cases the analysis showed that fuel cell technologies can substantially reduce emissions in comparison with conventional technologies. Regulated emissions (CO, hydrocarbons, NO_X) are lowest, by up to two orders of magnitude. Fuel cell technologies were found to be more efficient in all cases, with carbon dioxide (CO_2) emissions reduced broadly in line with energy savings. The investigation concluded that from an overall emissions perspective the use of fuel cells in transport and power generation is highly beneficial.

Bauen and Hart (2000) presented results which built on the earlier work by Hart (1997) and provided a detailed analysis of a wider range of systems. The paper provides a comprehensive comparison of fuel cells and competing systems, and points out strengths and weaknesses of the different fuel cell systems, suggesting areas for improvement. The analysis compared system emissions (global, regional and local pollutants) and energy consumption on a full fuel cycle basis. It considers a variety of primary energy sources, intermediate fuel supply steps and fuel cell systems for transport and stationary end-uses. These are compared with alternative systems for transport and stationary applications. Energy and pollutant emission reductions of fuel cell systems compared to alternative vehicle technology vary considerably, though all fuel cell technologies show reductions in energy use and CO_2 emissions of at least 20%, as well as reductions of several orders of magnitude in regulated pollutants compared to the base-case vehicle. The energy, CO_2 and regulated emissions advantages of fuel cell systems for distributed generation of electricity were found to be more consistent than for transport applications, with regulated pollutants (CO, hydrocarbons, NO_X) reduced to less than 10%, and CO_2 and energy use reduced to around 70% compared to the use of electricity generation using a combined-cycle gas-turbine (CCGT). For CHP applications around 200kWe, the analysis concluded that fuel cell systems show reductions of CO and NO_X to less than 10%, CO_2 to 81%, and energy use to 78% compared with the use of grid electricity and a conventional heating boiler.

2.3.4 Efficiencies

The comparison of operational efficiencies of conventional generation and fuel cells is not straightforward. The theoretical maximum efficiency of the basic technologies can be calculated, and the actual efficiency of a fuel cell system operating at rated power can be measured. However evaluation or measurement of the efficiency of specific complete systems while operating dynamically is not straightforward, and therefore published efficiency claims need to be carefully interpreted.

A fuel cell power system will normally comprise a fuel processor (unless the fuel is pure hydrogen), a fuel cell stack, and an electrical power conditioner to convert the fuel cell d.c. output to a.c.

The choice of fuel processor will depend on the input fuel and the type of fuel cell. For example, a natural gas fed proton exchange membrane and phosphoric acid fuel cell could use an external steam reformer. The composition of methane in natural gas from the North Sea is around 95%. For reforming methane gas to hydrogen, the basic reactions are:

$$CH_4 + H_2O \rightarrow CO + 3H_2 \quad (\Delta\mathrm{H} = 206\mathrm{kJ/mole})$$

$$CO + H_2O \rightarrow CO_2 + H_2 \quad (\Delta\mathrm{H} = -41\mathrm{kJ/mole})$$

The overall enthalpy of formation is 165kJ/mole (i.e. 10g methane reformed into 8g hydrogen). The reformer is normally multi-stage for desulphurisation, steam reformation to hydrogen and carbon monoxide, and conversion of carbon monoxide. There are a number of temperature changes in the process, resulting in further losses.

The efficiency of a fuel cell is usually defined as the ratio of electrical energy produced to the calorific value of the fuel, in this case hydrogen. The lower heating value (LHV) for combustion of hydrogen is –241.83kJ/mole (2g hydrogen), while if the water produced is condensed back to liquid, the higher heating value (HHV) is –285.84kJ/mole, where the negative values mean that the reaction is exothermic, i.e. energy is released. Efficiency claims may be based on either the LHV or the HHV.

The maximum electrical energy produced is equal to the 'Gibbs free energy' for the reaction:

$$H_2 + ½O_2 \rightarrow H_2O$$

This is a function of temperature; for example the Gibbs free energy is –228.2 kJ/mole at 80°C, and –177.4kJ/mole at 1000°C. Using the above definition, the maximum electrical efficiency possible ranges from 80% at 80°C, to 62% at 1000°C, relative to HHV. In practice the cell voltage of a fuel cell is less than the theoretical open circuit voltage, and achievable efficiencies are considerably lower than the theoretical maximum.

When the energy needed for methane gas reformation is taken into account, the theoretical maximum electrical efficiency of a fuel cell system operating at 80°C is reduced to around 65%, based on the HHV of methane gas. Higher temperature fuel cells (for example the SOFC) operate at higher temperatures and the cell efficiencies are lower, however reformation of methane is possible within the fuel cell, which is more efficient than an external reformer.

The rejected heat, i.e. heat not utilised in the fuel processing and fuel cell sub-systems, can be used to generate hot water, steam, or additional electricity, depending on the needs of the end-user. The higher temperature fuel cells (i.e. MCFC and SOFC) are capable of generating significant quantities of high-pressure superheated steam because of the high temperature of the rejected heat. In a large fuel cell power system (>100MW) production of electricity can be maximised using a steam turbine.

In the case of a heat engine (e.g. a steam or gas turbine), the maximum (Carnot) efficiency limit is defined as $\eta = (T_1 - T_2)/ T_1$, where T_1 is the maximum temperature of the heat engine, and the exhaust temperature is T_2 (temperatures in degrees Kelvin). This means that for a steam turbine operating at 500°C (773K), with water exhausted through a condenser at 50°C (323K), the Carnot efficiency limit is 58%. The best combined-cycle gas turbines have electrical efficiencies up to 60%. Such systems are optimised for electrical power generation, and thus have low grade waste heat which may not be useable.

2.3.5 Status of demonstrations

The PAFC PC25 fuel cell power plant was first manufactured by ONSI (now UTC Fuel cells) in 1991, and by 2004 more than 250 systems had been delivered to customers in 19 countries, accumulating more than six million hours of operational experience. The overall efficiency in a CHP application is 87% (electrical efficiency 37%, thermal efficiency is 50%.

A SOFC design has been developed by Westinghouse Siemens and Mitsubishi, currently targeting generating systems in the multi-MW range. The high cost of production is a drawback. Cell efficiencies are in excess of 40%, and the high temperature output can be fed into a turbine to increase the electrical efficiency, or used in a heating application.

The published efficiencies of commercial and pilot systems are significantly lower than the theoretical values. Examples of available published data include the phosphoric acid fuel cell 200kW model

PC25 manufactured by UTC (ref: UTC PC25 Performance data). The LHV efficiency quoted is 87% total (37% electrical, 50% thermal).

The US Department of Defence (DOD) Fuel Cell Demonstration Program has operated PAFC systems on 29 sites in the US, with start dates from early 1995 to late 1997. By early 2002 these systems had operated for a total of 794,621 hours, and generated 134,312 MWh at an average 31.6% electrical efficiency. The heat recovery efficiency in these applications is rather low overall, presumably because of low utilisation of heat. The electrical efficiency calculation includes fuel cell idle time, reducing the calculated efficiency. ONSI PC25 fuel cells (now manufactured by UTC) passed the US DOD Fuel Cell Program electrical efficiency criteria during unit acceptance tests (range = 33.5% to 37.2%, based on Higher Heating Value).

2.3.6 Research and development

The International Energy Agency (IEA) organised a programme on Advanced Fuel Cells (1999-2003), comprising three technology annexes and two application areas (IEA 2002). The UK was well represented in the technology annexes, including the Universities of Loughborough, Surrey, Southampton and Newcastle, Imperial College and Keele. However there has been little UK involvement in the systems annexes, or in stationary and transportation application areas.

The DTI has funded an Advanced Fuel Cells Programme since 1992, initially focussing on SOFCs and SPFCs, and has published a Technology Route Map for key technological milestones for the period up to 2020 (DTI 2002). Recently the programme has widened to allow other fuel cell types to be included in projects that contribute towards an assessment of the technologies. By the end of February 2000 the programme had supported 127 projects with a value of £66.7m (see Appendix II for DTI’s New and Renewable Actions and Targets time-scale). The DTI has published a fuel cell vision for the UK (DTI, 2003) and a review of fuel cell commercial potential DTI, 2003b). Fuel Cells UK has been established with initial funding from the DTI, to raise the profile and improve the positioning of the UK fuel cell industry, and to act as a liaison point to improve contacts and partnering opportunities, and has published a Guide to the UK Fuel Cell Industry, and a fuel Cell Vision for the UK (Fuel Cells UK, 2003). The Fuel Cells Forum (Fuel Cells Forum) is an initiative sponsored by DTI and other partners to bring together the views of fuel cells stakeholders in UK industry, academia, venture capitalists, and Government.

The ESPRC supports an academic research consortium for fuel cell development through its Supergen programme.

The EU Research programmes have recognised the potential of fuel cells as a key technology for meeting the challenge of sustainable energy, providing an essential bridge between today's fossil-fuel based energy economy and a future economy based on greater use of renewable energy sources. There has been strong growth in EU support for fuel cell R&D, rising from 8M€ in the 2nd Framework Programme (1988-92) to 54M€ in the 4th Framework Programme (1994-98). In the 5th Framework Programme, the first Call alone resulted in European Union support totalling 27.8M€. The present fuel cell strategy in the context of CHP includes recommendations for research and demonstration of low temperature fuel cells which have the potential for low specific cost and small-scale applications, and currently expensive high temperature fuel cells which have potential for industrial and large-scale systems (EC, 2000). The EU 6th Framework work programme in the area of Sustainable Energy Systems has identified fuel cells as one of five research activities having an impact in the medium and longer term. The breakdown of funding for fuel cells is unknown, however the area of Sustainable Energy Systems has a total indicative budget of 810M€, of which 198M€ was allocated to the first Call for Proposals (EC, FP6). Research is needed to reduce the cost and improve the performance and durability of fuel cell systems for stationary, transport, and portable applications, to enable them to compete with conventional combustion technologies. This will include the optimisation and simplification of fuel cell subsystems and components as well as testing and characterisation protocols. The research areas and topics for fuel cells in the first Call in the FP6 programme (EC, FP6) are:

a) Development of low cost, competitive high temperature fuel cell systems for clean, safe, durable and cost-effective decentralised power generation, combined heat/cold and power and mobile applications, covering power ranges from a few kW up to a few MW. The main targets are to provide solutions for future commercial Fuel Cell systems with a cost of less than 1000 €/kW (150€/kW for automotive Auxiliary Power Units) and with a durability of more than 40000 h.

b) Development of cost-competitive solid polymer fuel cell systems and components for stationary and transport applications. The main targets are to provide solutions for future commercial Fuel Cell systems with a cost of less than 100 €/kW for stationary and 50 €/kW for transport applications (for series production), and with a durability of more than 30000 h for stationary and 5000 h for transport applications.

c) Generation of new knowledge in key fundamentals for low cost sustainable materials, processes, components and systems for Proton Exchange Membrane (PEM) and Direct Methanol (DM) Fuel Cells.

d) Development of advanced, safe and clean fuel cell systems for small portable applications

e) Development and validation of the "next generation" of advanced computational models and simulation tools for fuel cell systems analysis

The EC has set up a European Technology Platform (EC European Hydrogen and Fuel Cell Technology Platform) which aims to accelerate the development and deployment of hydrogen and fuel cell based energy systems and component technologies.

In the USA, fuel cell development programs include the US Department of Energy Hydrogen, Fuel Cells & Infrastructure Program (US DOE, US DOE 2000), the Stationary Power Fuel Cell Program, and the Fuel Cells for Buildings Program. As phosphoric acid technology matured in the 1990s, the DOE's fuel cell research emphasis has shifted to higher efficiency systems, including molten carbonate and solid oxide fuel cells and fuel cell / microturbine hybrids. The US Department of Defense has an active Fuel Cell Demonstration Programme.

2.4 Fuel cell CHP

2.4.1 Overview

The literature contains several good technical papers on the application of fuel cells in CHP systems, and these are reviewed in this section.

The potential of fuel cell CHP was realised at least ten years ago by Gibbs (1992). The small-scale CHP sector is a likely early market for fuel cell plant, with the market for utility scale fuel cell plants expected to develop later. Issues which have caused the power industry in Europe to re-think its methods of generation include: concern over increasing carbon dioxide emissions and their contribution to the greenhouse effect; increasing SOx and NOx emissions and the damage cause by acid rain; the possibility of adverse effects on health caused by high voltage transmission lines; environmental restrictions to the expansion of hydroelectric schemes; public disenchantment with nuclear power following the Chernobyl accident; avoidance of dependence on imported oil following the Gulf crisis and a desire for fuel flexibility. All these factors are hastening the search for clean, efficient, modular power generators which can be easily sited close to the electricity consumer.

Doelman (1992) also realised that the most attractive application for fuel cells seemed to be in decentralised combined heat and power generation (CHP). The attractiveness of fuel cell powered CHPs for gas utilities depends firstly on the economy and reliability of CHP in general in the markets considered and secondly on the competitiveness of fuel cells versus, for example, the gas engine and gas turbine based CHP. Important possible activities for a gas utility in relation to fuel cell commercialisation are helping develop the market for CHP, defining the requirements for fuel cells in CHP and helping the fuel cell manufacturers to build up practical experience by participating in demonstration projects.

The experience of Packer (1992) as a designer, builder, and operator of small-scale combined heat and power systems (i.e. < 1 MW), suggests that CHP is an ideal application for the fuel cell. Packer describes conventional CHP together with typical applications, and also discusses the perceived advantages of fuel cells together with the potential for fuel cells opening up currently unapproachable markets. Various matters relevant to the application of fuel cells are also described including: initial and life costs for fuel cells CHP systems; maintenance requirements, security of supply requirements. In addition to these commercial aspects, technical issues including interfacing to building systems, control, protection, monitoring, operating procedures and performance are also discussed.

Sammes and Boersma (2000) investigated the market and technical requirements for small-scale fuel cells in residential applications, focusing on the 1 to 10 kW range. In particular, the peculiar features of the New Zealand situation are explored, with its specific energy resources and demands. It is shown that various technologies could be applied, with PEM, SOFC, PAFC and AFC competing on almost equal terms, with cost targets of 500 to 700 EUR/kW. The attributes and disadvantages are discussed, with a number of technology gaps being identified, and some solutions proposed. Two new developments in the PEM and SOFC systems are compared in relation to their use in domestic applications. The obvious premium application of fuel cells in New Zealand exists where grid connection in remote areas is expensive.

Siemens Westinghouse is in the final stage of its tubular solid oxide fuel cell (SOFC) development program, and the program emphasis has shifted from basic technology development to cost reduction, scale-up and demonstration of pre-commercial power systems at customer sites. George (2000) describes the field unit demonstration program including the EDB/ELSAM 100kWe combined heat and power (CHP) system, the Southern California Edison (SCE) 220kWe pressurized SOFC/gas turbine (PSOFC/GT) power system, and the planned demonstrations of commercial prototype power systems. In the Spring of 1999, the EDB/ELSAM 100kWe SOFC-CHP system produced 109 kWe net AC to the utility grid at 46% electrical efficiency and 65 kWth to the hot water district heating system, verifying the analytical predictions.

Hassmann and Rippel (1998) described fuel cell activities at Siemens, which concentrate on solid oxide fuel cell (SOFC) and polymer-electrolyte-membrane fuel cell (PEM FC) development, and direct methanol fuel cell (DMFC) research. Commercial application has, to date, been achieved in the field of PEM FCs for air-independent propulsion. A specific development project is being conducted aimed at the verification of an innovative cell concept to match the competitive cost of PEM FCs. SOFC development aims at decentralized power and combined heat and power (CHP) plants. Following the success achieved in the 10-kW class, a first prototype system with a power rating of 100 kW was scheduled for the year 2001. Achieving a cost advantage over competitive technologies is to be seen as the driving force behind all efforts.

As part of ECN's in-house R&D programme on molten carbonate fuel cells (MCFC), assessment studies for small systems in decentralised applications, e.g. commercial and industrial combined heat and power (CHP) and for large systems in centralised power generation applications, have been performed (Jansen and Mozaffarian, 1997). For a 500 kW internal reforming MCFC CHP plant, different system designs were evaluated with respect to the possibilities for production of process heat at different temperature levels. This included the calculations of the electrical and thermal efficiencies and estimations of the investment costs. System designs are characterised by the operating pressure and method of steam handling (anode gas recycling or separated steam injection). To determine the future market potential of coal-fuelled MCFC power plants, the promise of this fuel cell technology was assessed against the performance and development of the competing technologies normally used for these applications. Coal-fuelled fuel cell power plants will have to face severe competition from advanced pulverised coal and integrated gasification combined cycle (IGCC) power plants, despite their higher electrical efficiency.

After 25 years of effort, the phosphoric acid fuel cell (PAFC) is approaching commercialization as cell stack assemblies show convincingly low degradation and the balance-of-plant (BOP) achieves mature reliability (Appleby, 1996). A high present capital cost resulting from limited cumulative production remains an issue. The primary PAFC developer in the USA (International Fuel Cells, UTC) had manufactured 40MW of PAFC components by 1996, the equivalent of a single large gas turbine aero-engine or 500 compact car engines. The system is therefore still not far up the production learning curve. Even so, the next generation on-site 40% electrical efficiency (Lower Heating Value, LHV) combined heat-and-power (CHP) PAFC system was available for order from UTC in 1995 at US$3000/kW. To effectively compete in the marketplace with diesel generators, the dispersed cogeneration PAFC should cost approximately US$1550/kW (1995 figures) in the USA and Europe. The perceived advantages of fuel cell technologies over developments of more conventional generators (e.g., ultra-low emissions, siting) are not strong selling points in the marketplace. The ultimate criterion is cost, and therefore fuel cell cost reduction is the key to market penetration. Markets for high-temperature fuel cell system (molten carbonate, MCFC, and solid oxide, SOFC), which many consider to be 20 and 30 years, respectively, behind the PAFC, are discussed. Their high efficiency and high-quality waste heat should make them attractive if technical progress and costs are acceptable. Commercialization of the proton-exchange membrane fuel cell (PEMFC) system is considered for stationary and mobile applications.

Drenckhahn (1996) focussed on solid-oxide fuel cells and the implications for combined heat and power plant. Recently there have been many studies of the application of fuel cells in buildings, including those by Tillemans and de Groot (2002), which evaluated the benefits and barriers of using hydrogen in residential districts. The study identified the efficiency of the reformer for production of hydrogen from natural gas as a key research need, as well as overall cost reduction. Ferguson and Ugursal (2004) reported on the development of a PEM fuel cell model, incorporated into a building simulation model. The model was used to estimate fuel cell performance in response to building energy demands. The results showed that fuel cell size and operating strategy are critical factors affecting the performance of fuel cell CHP systems. Giglucci et al. (2004) installed a beta-version fuel cell CHP system, supplied by H-Power, and submitted it to a series of tests. Results showed that the prototype behaved as expected for a ‘proof-of-concept’ system. Although actual performance was judged as low, improvements were identified that could considerably increase electric and thermal efficiencies, such that primary energy savings greater than 10% should be obtained. Alanne and Saari (2004) reviewed the issues relevant to selecting small-scale CHP technologies (reciprocating engines, gas micro-turbines, Stirling engines, and fuel cells) as an alternative energy source for buildings. Fuel cells were identified as having technical advantages over other technologies in housing applications, although it was thought that the high cost of fuel cells limited feasibility. A cost analysis by Lokurlu et al. (2003) showed that a reduction of fuel cell CHP plant investment costs 1000 €/kWe could result in reduced generating costs compared with conventional engine CHP plant. Clearly this depends on successful cost reduction as well as market rates for heat, power, and fuel. Current costs of fuels cells as high as 10,000-20,000 €/kWe are quoted by Erdmann (2003), as well as possible future costs down to 1200-2000 €/kWe for installation of a complete fuel cell system in addition to a conventional burner. The analysis by Erdmann of future economics of the fuel cell housing market indicates that the market perspective of SOFC systems in the German housing market is quite promising, although again the analysis is sensitive to the possible cost reduction and energy tariffs.

In Europe, ten 200kW PAFC systems were operated by members of the European Fuel Cell Users Group, in a project funded by the EU Joule program (Uhrig et al 1996). The work packages included heat-controlled operation, examination of plant behaviour with varying gas properties, and measurement of emissions under dynamic load conditions. During the trials, the electrical output was pre-selected and the corresponding thermal output was determined as a function of volumetric water flow rate and return temperature. The resulting characteristic curves show that the thermal output depends strongly on the temperature of the heat supplied. The maximum thermal output achieved was around 260kW to a heating system operating at the lowest practicable temperatures (supply 53ºC, return 30ºC). This compares with the manufacturer's data of 200kWe and 900,000 Btu/h at 140ºF (264kWt at 60ºC), and with corresponding efficiency values of 37% electrical and 50% thermal. The results of emission measurements revealed that, in the case of large increases in electrical output, peaks may occur in respect of CO and hydrocarbon emissions. However the emissions drop after a short time, and it was concluded that the overall emissions remain negligible.

The US DOD has operated PEM fuel cells in 'residential applications', with the first units installed in January 2002. Commercial units manufactured by H-Power, Plug Power and Avista Labs with power ranging from 3 to 5 kW have been installed on 12 sites, of which 4 units are operated as CHP systems. Operational data for a period of around 8 months up to September 2002, demonstrates electrical efficiencies in the range 24.5% to 26.7% for some of the non-CHP units.

2.4.2 Fuel cell CHP commercial developments

The Woking Park CHP project, comprising the UK's first fuel cell CHP as well as reciprocating engine CHP, photovoltaics, thermal storage, absorption cooling and private wire was completed in March 2001. The sponsors of the project are the Department of Trade and Industry (DTI), BG plc and the US Department of Defence with the balance of funding being procured by the Council's Thameswey initiative. The system provides heat and power for a swimming pool and leisure centre (DTI New Review, 2000). The 200kWe phosphoric acid fuel cell system (PAFC) manufactured by ONSI (now UTC Fuel Cells) complements two conventional systems, and provides an opportunity to make economic, operational, and environmental comparisons between technologies.

There is keen commercial interest in developing domestic-scale or micro-CHP systems with power in the range 1 - 10kWe (Nurdin, 2001). The PEM fuel cell is favoured for this application, because of its potential for low cost, high power density (small size), high electrical efficiency, low operating temperature, and safe operation. Several manufacturers have announced their intention to market systems within a few years, and Vaillant started an EU-sponsored field trial of a 10kWth and 4kWe CHP system in 2003, and has now around 40 systems installed in Europe. The latest systems, which were developed in cooperation with US Company Plug Power, were exhibited at Hanover Fair in 2004. Johnson Matthey ambitiously predict that in 2010 micro-CHP fuel cell systems could take around 4 million out of a total worldwide market of around 10 million boilers.

A SOFC design has been developed by Siemens/Westinghouse and Mitsubishi, who are currently targeting generating systems in the multi-MW range. Cell efficiencies are in excess of 40%, however the high temperature output can be fed into a turbine to increase the electrical efficiency, or used in a heating application.

Ballard is developing PEM products for a range of applications in transportation and stationary power. In stationary power, product developments range from 1kW to 250 kW, and a 1kWe CHP product for the residential market was announced in 2002, with 81% overall efficiency (electrical efficiency 34%, and thermal efficiency 47%). Limited volumes of the 1kW product were expected to be introduced to the Japanese marketplace in late 2004.

FuelCell Energy, who have been working on fuel cells since the mid-70s and specialise in MCFC, now provide a standard module DHC 9000 which generates 300kW. The MCFC operates at approx

650ºC which generates hydrogen from natural gas in the cell stack itself, eliminating the need for a separate external reformer. The result is a significant reduction in the number of system components, as well as improved electrical efficiencies in the 50-70% range, and a high tolerance to fuel impurities. Steam at 450ºC can also be produced and used for process or district heating.

2.5 Summary

CHP using gas or oil engines as the electricity generator is a well established technology, offering overall CO_2 and fuel savings in suitable applications with base heat and power requirements.

Fuel cells are under intensive development by commercial companies, with underpinning research sponsored by EU and individual government funding. The most important technologies for CHP systems are PAFC, SOFC, and PEMFC.

The economic attractiveness of CHP systems depends on the equipment costs, the energy savings, and the gas and electricity tariffs. In the case of fuel cell CHP, some commercial products are already available with others being field-trialled. However it it believed that prices will have to be reduced significantly to be commercially attractive.

The topics of economics and emissions are expanded in more detail in Chapter 3, Social Cost Benefit Analysis, and Chapter 4 Lifecycle assessment of fuel cell CHP, respectively.

3. SOCIAL COST-BENEFIT ANALYSIS

3.1 Introduction

Cost benefit analysis (CBA) is a useful methodology for facilitating decision-making. It involves the identification and quantification in monetary terms of the costs and benefits relating to a particular plan, programme, project or decision in order to determine if it will produce a net gain or loss in welfare for society as a whole.

Traditionally, environmental impacts were described in qualitative terms alongside or within the CBA. Environmental economics has attempted to extend CBA into social cost-benefit analysis by estimating monetary values for the unpriced effects of projects upon society and the environment. In this way environmental information has been incorporated directly in the CBA decision-making framework on a common basis with other costs. There will always be environmental impacts in CBA that cannot reliably be valued in this way, and it is necessary to account carefully alongside the CBA for such effects.

While the basic approach of CBA appears to be straightforward, in reality it is fraught with difficulties. This is true, however, of any decision-making aid and much of the (critical) attention given to CBA arises because it attempts to go further than many other project appraisal approaches. Nevertheless, it is important to remember that CBA is only a decision-making aid rather than the decision itself: Ultimately, large-scale social decisions have to be made on a political level. The CBA provides information for that decision-making system to be considered alongside distributional, ethical and moral inputs.

The project aimed to carry out a social cost-benefit analysis on fuel cell CHP. This would have included both the internal (private) costs as well as the external or social costs. However as reported in Powell et al (2004) it was found that due to the immaturity of the market the current internal costs are not representative of the likely future costs of this technology once it achieves full market production. Also, for the same reason, many of the externalities associated with fuel cells have not been identified or quantified. Therefore we have carried out a review of the current costs in the literature to see if this casts any light on the future predicted costs. For the external costs the emissions have been calculated in conjunction with the lifecycle assessment, putting an economic value on the gaseous emissions from a range of scenarios including conventional fossil fuel power generation, fossil fuel CHP and fuel cell CHP.

As fuel cells move closer to commercial status practical questions emerge over how they will enter the energy system (MacKerron, 2000). This requires an analysis of the broad range of factors that will impact on financial and economic outcomes (MacKerron, 2000). In this respect an important determining factor in the likely success of fuel cells lies with the changes in the status of competing technologies as well as developments in fuel cells themselves.

With high efficiencies, low emissions and low noise, fuel cells have many potential advantages over traditional power technologies. However there are a range of factors which ultimately determine the preferred power generation technology for a particular application, not just cost. These include reliability, location, emissions, noise restrictions, power and heat requirements, environmental footprint weight as well as the relative cost of the fuel and electricity (ETSU, 2003).

However, for fuel cells to succeed as a commercially viable energy source, a functioning and fully developed market is clearly a necessity. The issue of cost is generally held to be the main barrier to market entry with estimates of stationary fuel cells currently being 2.5 to 20 times too expensive (Pehnt & Ramesohl, 2003). When comparing the costs and benefits of fuel cells with conventional technologies many factors need to be taken into consideration including the: cost of grid electricity, cost of natural gas, operational mode, lifetime of the system, load factor, heat power ratio, demand patterns (Pehnt, 2003).

3.2 Financial Cost Considerations

As already described, the main components of a fuel cell system are the fuel cell stack, the processor and the balance of plant/controls. Broadly speaking the overall cost targets can be divided equally between these three elements (COSPP, 2002). There are many difficulties associated with attempts to quantify fuel cell construction costs and their evolution, including:

- The lack of sizeable ‘quasi-commercial’ projects in existence;
- The commercial confidentiality surrounding estimated construction costs in an increasingly competitive market;
- Difficulties associated with comparing the results of different projects where assumptions and conditions can vary considerably between studies. Such difficulties include whether or not transmission and distribution costs are accounted for in the analysis, whether heat supply costs avoided are factored in variable or total cost terms and what value the discount rate takes (MacKerron, 2000).

It is also difficult to be accurate about the target construction costs necessary to enable fuel cells to be competitive. Much depends on the unique circumstances of an individual project including, for example, assumptions about grid operation or about the ratio between heat and power loads etc. (MacKerron, 2000). It is clear, however, that the target values (in terms of construction costs per kilowatt) at which fuel cell systems need to aim are beginning to fall. In the early 1990s targets of around $1000/kWe were thought to be realistic, while today ranges beginning at $500/kWe are being quoted by fuel cell developers as targets for the products (MacKerron, 2000).

The high cost is mainly due to the lack of commercial scale production, most fuel cell production still being at the demonstration stage. What is clear is that the type and size of fuel cell and associated market area application will impact on the eventual cost.

Operating costs are also difficult to estimate until a number of monitored systems are in operation (Dutton, personal communication). According to several studies (Hart & Hormandinger, 1997 & 1998; Arthur.D.Little Inc, 2000) operating costs for a fuel cell CHP unit will be slightly higher than the standard boiler but with overall costs lower than buying the two services separately. A rough analysis shows the potential attractiveness of CHP, for example with a gas price of 2p/kWh, electricity could be generated by a micro CHP system at 4p/kWh, undercutting domestic mains electricity charges in the UK by about three pence, with additional savings resulting from utilisation of heat. Industrial examples also reflect these competitive generation projections (Brandon & Hart, 1999), however electricity prices for large consumers are much lower than domestic tariffs. Table 3.1 gives an indication of current fuel cell technology costs and those predicted for mature systems.

Differences between current estimated construction costs and projected mass manufacture levels for fuel cell systems can differ greatly - by as much as $950/kWe (€714/kWe) (MacKerron, 2000).

Table 3.2 (ETSU, 2003) compares the capital and maintenance costs of new and existing technologies. The capital cost includes the total equipment cost of the power generation system to the end user. It is important to remember that this can vary significantly even with the same technology, depending on power output, performance of fuel cell type, etc.

Table 3.1: Current and projected combined capital and operating fuel cell costs for stationary systems

Costs (€/kWe)	**Current cost (1999)[1]**	**Current cost (2003)[2,3]**	**Predicted cost [1,4]**
AFC	1741		44-87
SPFC Stationary	478		26
PAFC	2610	5000	870
MCFC	4352	8000	522
SOFC	8703	20,000	522
PEFC		10,000	
Gas CHP	600-900		
Diesel CHP	350-600		
Micro-turbine CHP	500-800	5.0 Euro cents/kWh (generating costs)	3.0 Euro cents/kWh (generating costs)
CCGT	336-504		

[1] Brandon & Hart (1999) converted from $ (€1.00 = $1.149)
[2] Lokurlu et al (2003)
[3] Alstom (2000)
[4] PIU (2002)

Table 3.2: Capital and maintenance costs of new and existing energy technologies (source: ETSU, 2003)

Technology	Capital Cost (€/kW)	Time until maintenance required (hours of operation)	Average maintenance costs (€cents/kWh)
Microturbine	535-841	5000-8000	0.3-1.4 (estimated)
Combustion Turbine	229-765	4000-8000	0.2-0.3
Stirling Engine	1529-38,233		
Fuel Cell (PAFC)	2676-7,647	Yearly: fuel supply system check. Reformer system check 40,000: replace cell stack	0.3-0.7 (estimated)
Photovoltaic	3440-4587	Biannual maintenance check	1% of initial investment per year
Wind Turbine	612-2676	Biannual maintenance check	1.5-2% of initial investment per year
Internal Combustion Engine	229-612	750-1000: change oil and oil filter 8000: rebuild engine head 16,000: rebuild engine block	0.5-1.3 (natural gas) 0.3-0.7 (diesel)

Although the current stage of fuel cell development varies they are generally at the pre-commercial stage (ETSU, 2003). Phosphoric acid fuel cells are commercially available but are not price-competitive with existing technologies. Field trials of solid oxide fuel cell units were conducted in 2001-2003 by Sulzer-Hexis (for residential applications) and Siemens Westinghouse (a 220kW solid oxide fuel cell). New Zealand's Powerco and Australia's Ceramic Fuel Cells Limited (CFCL) have signed an agreement to conduct trials of new solid oxide fuel cell energy systems in New Zealand. The systems, which were developed by CFCL, are combined heat and power units (micro-CHP) that convert natural gas to electricity, delivering both 1 kW of electricity and hot water sufficient for the average home.

Stationary fuel cell systems are unlikely to become competitive until conditions change and some cost reductions are reached. For example, an improved stack running time from 40,000 to 70,000 hours and modified maintenance costs of 0.5-1.0 cents per kWh (c/kWh) instead of 2.5 c/kWh. In addition to investment, fuel and maintenance costs, further costs remain for insurance, taxes and administration (Lokurlu et al. 2003). Through the use of annuity method it has been calculated that the cost of electricity generation by fuel cell systems is still very high – mostly accounted for by the system costs, fuel costs and maintenance costs of such power plants (Lokurlu et al. 2003).

The UK DTI have set out proposed timescales for a "conceivable future" for fuel cells in the UK (DTI, 2003a). Table 3.3 summarises the DTI's goal aspirations for fuel cell developments in the UK over the short, medium and long term.

Table 3.3: Short, medium and long term goals for fuel cell technology/commercialization in the UK

Category	**Short-term 2003-2007**	**Medium term 2008-2012**	**Long term 2013-2023**
MARKETS	Niches. UPS, remote power, some portable power, military.	Premium applications.	Significant passenger car penetration begins at end of period. Widespread.
SALES VOLUMES	~ 10 MW/year	10-100 MW/year	100+ MW/year
COSTS	£2000-3000/kW	£200-400/kW. Custom designs attract premium. Lower cost systems result from R&D based on first generation technology. Established manufacturing standards and modular design also.	£50-100/KW. Stacks are second or third generation technology and use low cost material/manufacture.
FINANCIAL RETURNS	Not viable without incentives. Highest value in IP, particularly stacks and key components.	Value moving downstream towards integration and O&M. Sales are cash positive but do not recoup R&D investment.	Commercial. Majority of value in integration, O&M and traditional support. UK focus on materials, MEAs and integration.
ENVIRONMENTAL BENEFITS	Not calculated or given a monetary value.	Calculated.	Calculated and internalized.

(Source: DTI, 2003a)

3.3 Comparing fuel cells with conventional energy technologies

One of the problems associated with determining the full cost of fuel cells is the need for comparison with other systems, particularly those that are fossil-fuel based. The drive for reduced carbon emissions has led to increased efficiency. The advent of high efficiency, low cost, combined cycle gas turbine systems (CCGTs) has also reduced the construction costs of new power facilities. In most OECD markets, reliable, low-risk CCGT systems ~ 300 MWe can now be installed for less than $500/kWe - a trend that continues to go downwards (MacKerron, 2000).

In general the capital costs of CCGT are currently between $400 – 600/kW (336-504 €/kW) compared to a fuel cell capital costs estimate of between $5000-10,000/kW (4198-8396 €/kW) (Environmental and Energy Study Institute, 2000). It is believed that mass production of fuel cells will reduce these costs but this would obviously require a growing and sustained market demand. Johnson Matthey, a leading developer of stationary fuel cells, has forecast fuel cells to be economically viable at a cost of US $4,000 for niche, stand-by and back-up power applications, reducing to $1000 to $2000 per kW (752-1504 €/kW) for off-grid locations and with a target of $400 - $10,000 per kW (300-7518 €/kW) for widespread applications (COSPP, 2002). More specifically some scientists predict future low temperature fuel cell applications will reduce in cost to $300/kW (252 €/kW) for stationary power (MacKerron, 2000). For high temperature fuel cell systems substantial investment is still required. However, it is estimated that there is potential for these to be manufactured for sale at around $600/kW (504 €/kW), which does not greatly exceed the current price for a gas engine or turbine (Pennycook, 2001). Gas engine based CHP units have a current capital cost of $600-900/$\text{kW}_{e}$, diesel generators 350-600kWe, while micro-turbines are estimated to be 500-800kW_{e} (Alstom, 2000).

However it is important to go beyond purely financial analyses when considering the problem of slow fuel cell development (MacKerron, 2000). A broader analysis that embraces public policy, technological and business factors gives a clearer impression of the current and future market prospects. In this context it is suggested that many of the institutional barriers that presented significant difficulties to the market development of fuel cells have, over recent years, become less problematic (Peters & Powell, 2004). Examples include the liberalisation of the power industry (i.e. opening up of formerly closed monopoly markets to competitive forces), technological changes favouring smaller unit sizes and a set of emerging business alliances that should prove to be beneficial for the market introduction and uptake of fuel cells. [Note: a comprehensive description of these barriers is given in Chapter 5].

3.4 Fuel Cell CHP (combined heat and power)

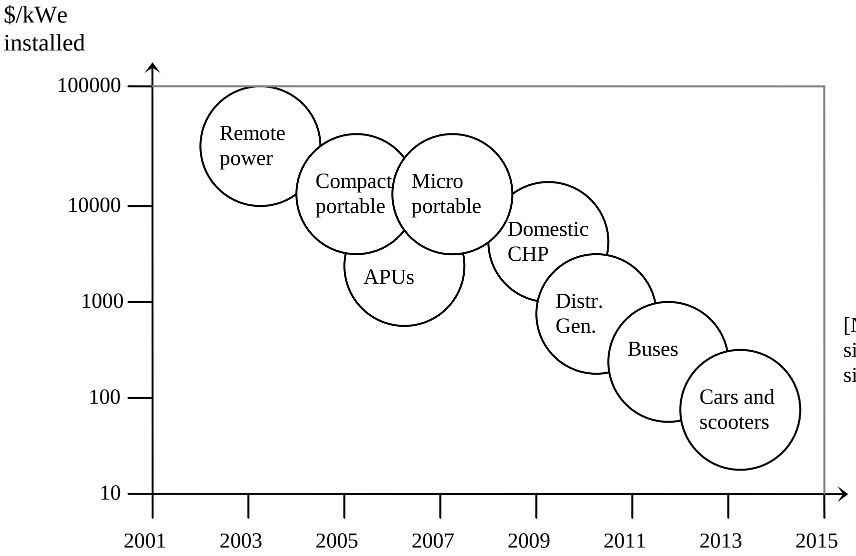
Fuel cell CHP systems are not yet competitive with conventional CHP systems (Lokurlu, 2003) with stationary fuel cells being 2.5 to 20 times more expensive. They will need to become increasingly cost effective in order to achieve a significant market share (Lokurlu et al. 2003). Small, domestic fuel cell CHP systems are 10,000 to 50,000 €/kWe, with larger systems between 5,500 and 18,000 €/kWh (Pehnt, 2003). However the available data do not give a clear indication as to whether the costs include capital and/or operating costs (Brandon & Hart, 1999).

Compared to conventional CHP plants the future operation of fuel cell CHP plants may involve higher capital expenditure (Lokurlu et al. 2003). The reason for this is due to fuel cell CHP having different heat to power ratios to conventional CHP, which do not match the heat and power demand of domestic properties, for example. This can result in the need for additional equipment to provide heat. However fuel cell/gas turbine hybrid systems are being developed to overcome this problem (Arthur.D.Little Inc, 2000). Different maintenance costs for CHP plants are also considered potentially problematic (Lokurlu et al. 2003).

3.5 The Future

The economics of fuel cell systems are different in different market niches (Brandon & Hart, 1999). The fuel cell has the potential to usurp many traditional technologies in a variety of markets, from very small batteries and sensors to multi-megawatt power plants. Each system has very different characteristics and will accept very different prices. For example, a laptop battery substitute that could run for 20 hours instead of two could command a high price, especially if it could be ‘refuelled’ in seconds from a canister rather than recharged over several hours. At the other end of the scale the potential for building modular power plants in which maintenance can be carried out on each module without shutting down the system is worth a significant investment.

There have been various attempts to forecast ‘first mover’ fuel cell applications in terms of full commercial status (e.g. E4Tech, 2004; Peters and Powell, 2004). One example shown in Figure 3.1 (E4Tech, 2004) indicates that in the near future smaller fuel cell applications such as remote power and compact portable technologies will play an important stepping stone role, preparing the way for cost reductions, wider commercialization and the establishment of broader-scale applications in the energy market (e.g. domestic CHP and vehicular applications).



[Note: Bubble size not significant]

Fig. 3.1: Commercial introduction points for fuel cell applications (i.e. point at which fuel cell applications are purchased in significant numbers without subsidy).
Source: E4tech, 2004

Potentially viable residential applications of small-scale fuel cells may occur where connection and transmission costs for grid electricity are high. (e.g. Sammes & Boersma, 2000; Pehnt and Ramesohl, 2003). Focusing on the 1 to 10 kW range, Sammes and Boersma, for example, explore the features of the New Zealand situation, with its specific energy resources and demands. It is shown that various technologies could be applied, with proton exchange membrane, solid oxide, phosphoric acid and alkaline fuel cells competing on almost equal terms, with cost targets of 500 to 700 €/kW. However this application is only likely to be financially comparable with conventional systems in rural New Zealand where grid connection is expensive.

3.6 Conclusion: financial costs

"Fuel cell technologies represent a significant growth area for the UK. As the demand for low carbon alternatives increases - driven by both commercial forces and government legislation - we have the opportunity to develop the UK as a base for manufacture and deployment of fuel cell technologies. We must act now if we are to make the most of this commercial opportunity." *Tom Delay, Chief Executive of the Carbon Trust (DTI, 2003).*

Highly efficient fuel cell based energy conversion systems for a range of applications are emerging as technologies with the potential to reduce primary energy demand and emissions of climate-relevant pollutants. In order to compete with conventional technologies the most important hurdle which needs to be overcome to enable their market success is the reduction of costs. There is uncertainty as to how quickly this will happen (PIU, 2002).

There are several basic designs of fuel cell; while some remain at the laboratory stage others are on the verge of becoming commercially available for niche market applications. Different types of fuel cells have different characteristics. At present, fuel cells are not cost competitive with other technologies in most applications. Estimates of current costs suggest a range from €1500/kW (£1050) to €7,550/kW (£5282) – however the commercial market for fuel cells is currently very limited and many designs are effectively high cost prototypes (PIU, 2002).

It is not yet clear about the rate with which fuel cells will achieve cost reductions and the literature shows that it has not proved possible to generate definitive estimates of future costs. There is widespread agreement, mainly based on engineering assessments, that fuel cells will become competitive in many applications (Brandon and Hart, 1999; PIU, 2002), with mobile applications and decentralised stationary CHP as the initial markets, followed by transport applications. However this may be long term and will depend on an increase in conventional energy, driven by the threat or reality of fossil fuel scarcity, to make the costs competitive.

Considerable public and private sector investments in fuel cells are being made globally on the basis that commercialization for fuel cells is underway. However, it is clear that mass market applications are still many years away (DTI, 2003). The start of commercialization of fuel cells for the UK will be facilitated if markets can be identified where the technology can be convincingly presented as having unique advantages that might justify higher investments.

The DTI's fuel cell Technology Route Map (DTI 2003) asserts that the industry is poised at a key development stage and that, if investment is made now, considerable potential exists for the UK to become a significant player in the world fuel cell market. Only time will tell if this type of positive aspiration will become a reality for the UK with fuel cells progressing to take on a significant role in a sustainable energy future. As things currently stand fuel cells have a long way to go to prove their viability as a complementary element of the clean energy area of the UK energy market.

3.7 External costs

The economic value of non-marketed goods can be measured in monetary terms by either stated or revealed preference techniques. Stated preference involves the use of questionnaires to elicit valuations for non-marketed goods, while revealed preference involves the deduction of these values from actual behaviour in associated markets. In some cases dose-response techniques are a useful aid to valuation. The ideal of valuing changes in provision of an environmental good is the estimation of changes in "total economic value", which comprises all aspects of a good or service for which an individual may be willing to pay. Total economic value therefore consists not only of direct use values, but also contains the value of preserving options for future use, and values not associated with personal use.

3.7.1 Estimation Methods

Environmental valuation is far from being an exact science. The objective of the valuation is to derive a monetary expression of individuals' preferences. This can be achieved in a number of ways but in any event relies on individuals being aware of their preferences and having enough information to determine them. This can be a particular problem for valuation of air pollution, because knowledge of the links between specific pollutants and physical effects is very limited amongst the general public. This means that attempts at direct valuation using stated or revealed preference techniques are founded on shaky ground, because the results derived from them are dependent on the assumptions people make about the damage caused by air pollution that may be entirely false. It does not, however, make the preferences any less valid.

In any event, a common approach to this problem is to make use of dose-response relationships, which are themselves highly uncertain, but which allow quantification of that uncertainty in the form of significance values and confidence intervals for key coefficients. The dose-response relationships give outcomes in terms of health or other physical endpoints that are relatively easy to value in monetary terms using stated or revealed preference techniques, or sometimes, direct market values.

3.7.2 Value Estimates

Many attempts to value air pollution have been made, although not as many as sometimes appear to be the case, because for each original study there may be as many reports which draw on it. Generally speaking, original studies focus on valuation of one or more specific kind of damages, which are drawn together in aggregation studies. Sometimes several aggregation studies appear to suggest convergent results, but this may be a false impression created both by the use of the same original studies and by the inclusion of widely different results and categories of damage which happen to average out. This is particularly the case for global warming damage estimates.

For the purpose of the current research we examined the weight of evidence from existing studies to draw conclusions about the possible values, which may be attached to emissions from waste processing. The most constructive way to achieve this is to look at some of the best and most recent aggregation studies. The values for this study were compiled from the following studies:

- COWI (2000) A study on the Economic Valuation of Environmental Externalities from Landfill Disposal and Incineration of Waste. Report to the EC DG Environment. (COWI, Denmark);
- COHERENCE (2000) Economic Evaluation of Quantitative Objectives for Climate Change (COHERENCE, Belgium);
- ECOFYS (2000) Economic Evaluation of Sectoral Emission Reduction Objectives for Climate Change;
- Pearce, D. W.; Howarth, A.; Hett, T.; Ozdemiroglu, E.; Powell, J. C. and Brisson I. (1998) Life Cycle Research Programme for Waste Management: Damage Cost Estimation for Impact Assessment. R & D Technical Report HOCO_220.

It would be possible to increase the number of reports studied, but this would necessitate a careful deconstruction of the values incorporated, to detect cases in which the same underlying studies had been used. In any event, a range of possible values will result, and for illustrative purposes it is most useful to consider a wide range, in the hope that this will cover most possible realities.

Table 3.4 shows the range of values taken from above studies. Except for the greenhouse gases (CO_2, CH_4, N_2O) all values are damage cost estimates (usually based on health effects) taken from COWI and Pearce *et al*. Both studies, in turn, base their values on previous studies that looked specifically at health effects from waste disposal facilities.

Table 3.4: Range of Economic Values as used in the Study

Emissions	**Range of Economic Values in EURO/kg**	
	low value	high value
CO2 (per kg of C)	0.02	0.1
CH4	0.28	0.5
N2O	5.97	7.5
PM10	10.0	35
SO2	7.0	13
NOx	3.0	20
As	150	999
Cd	18.30	81.4
Cr VI	123	819
Ni	2.53	16.8
Dioxins (TEQ)	2000000	16300000

The CO_2, CH_4, and N_2O values are based on abatement costs as stated in COHERENCE (2000) according to the UK's carbon reduction target (see section 2.3.2.2). Methane and nitrous oxide are calculated using the global warming potential of 21 and 310 times CO_2 equivalence, respectively.

3.7.2.1 Local Air Pollution

It is widely recognised that dioxins and particulate matter from combustion processes have a significant impact on general and respiratory health, including causing premature mortality amongst susceptible groups. However it is very difficult to work out exactly what the relationships are between exposure to particulates and incidences of various health impacts. Valuing these impacts is also difficult, in particular for mortality. Most estimated relationships show how daily mortality varies with particulate concentrations, but these acute effects are difficult to interpret in the sense that those affected may have had little chance of surviving much longer in any event.

Of more interest are the chronic effects of pollution and the influence on longevity and health over a lifetime, but estimating these effects would require enormous amounts of data and controls. The estimated values for particulates, therefore, must be treated as highly uncertain. Other air pollutants having impacts on health are similarly difficult to evaluate. In certain cases there may be double counting, in the sense that some of the damages ascribed to particular pollutants are in fact due to a cocktail of pollutants. Conversely, there may be undercounting where there is synergy among pollutants and the damage done by the cocktail is greater than the individual sum of damages. For example, chemicals adsorbed onto the surface of particulates may be trapped in the lung and consequently causes much more damage than the sum of the damage the chemicals and the particulates would cause individually.

There are several studies looking at the main air pollutants but relatively few looking at metals and emissions to soil and water.

There are two types of liquid effluence from waste disposal which affect soil and water pollution: a) leachate from the disposal of solid residues and b) wastewater from incinerators containing contaminated liquids or sludges. None of the existing studies uses the damage cost approach and results are often based on control costs, linked environmental values or clean-up cost. Due to this unreliable result, economic values for emissions to soil and water are not being used in this study.

3.7.2.2 Greenhouse Gas Emissions

It has been argued that damage costs should be used wherever possible, and that abatement costs are emphatically not an estimate of damage. There is a substantial problem with this in the climate case, because damages will not occur until many years in the future. This means that the choice of discount rate is absolutely crucial in determining the damage estimate for current emissions. To this must be added the great uncertainty regarding both the physical projections of future climates, and the ways in which that will impact on a future economy of uncertain structure with uncertain individual preferences.

However, climate policy is primarily target driven, with entire national economies set targets for cutting emissions. In such a scenario, a strong case can be made for use of a cost-effectiveness criterion. Rather than attempting to find the marginal damage cost of current carbon dioxide emission (which is a extremely difficult task), we could accept that climate policy is target-driven and aim instead to hit that pre-determined target in as cost effective a manner as possible. That would entail equalising marginal abatement cost across all sectors in the economy. Calculation of these costs is difficult, but much more achievable than making damage estimates.

The UK's legally binding target under the Kyoto Protocol is 12.5 % below 1990 emissions levels between 2008 -2012. The UK, however, set itself an even more ambitious goal of 20 % below 1990 level by 2010 (DETR, 2000). According to COHERENCE (2000) an 11.4 % change of emissions in 2010 compared to 1990 would result in a marginal abatement cost of €110 per tonne of carbon avoided.

A 20.1% change would result in the marginal abatement cost of €250 per tonne of carbon. These estimates bracket the realistic expenditures that will be required for the UK to reach its targets over the next ten years. They relate to marginal abatement costs in 2010, and so should be discounted back to the present in making calculations. This is of course sensitive to the discount rate used - but much less so than the estimation of damage costs in 50 or 100 years' time.

The economic valuations of the emissions from conventional and fuel cell CHP scenarios are given in the lifecycle assessment (Chapter 4).

4. LIFECYCLE ASSESSMENT OF FUEL CELL CHP

4.1 Introduction

Fuel cells are often perceived as being an integral component of a sustainable energy future, contributing to the reduction of greenhouse gas emissions. However it is also recognised that the environmental implications of this technology vary significantly depending on the primary energy source used. For sustainable energy production the primary energy either needs to be a renewable energy source or a fossil based source that is linked with carbon sequestration (European Commission 2003). However, currently fuel cells are nearly always fuelled by natural gas or by hydrogen produced using fossil fuels. Consequently, in terms of climate change, fuel cells still have a significant impact on the environment, although they do also provide environmental benefits from reduced local pollution and quiet operation.

It is important, therefore when determining the environmental costs and benefits of fuel cells, to take into account the hydrogen production and end use efficiency, and not just the fuel cell technology. Another factor to take into consideration is the match between the demand and supply of energy particularly for CHP applications. It is unlikely that domestic fuel cell systems can efficiently meet the total needs of a household without additional energy sources, and these extra supplies need to be included in an environmental evaluation. It is clear that fuel cells cannot be considered in isolation, a lifecycle approach is needed.

Some generally accepted environmental benefits that do appear in the literature including low levels of emissions of pollutants such as SO_X, NO_X, and particulates. It has also been suggested that the deployment of fuel cells can help the UK (post 2010) to meet its greenhouse gas commitment (DTI 2001), but other research indicates that CO_2 emissions are of a similar order to gas turbines (Dones and Heck 2000). The varying levels of CO_2 emissions reported are mainly due to the range of efficiencies assumed for different fuel cell and conventional technologies and their applications. One of the problems is that only a few types of fuel cell are in commercial production and much of the required data are only available from the manufacturers. It has been claimed that the only accurate emission data available is for the PAFC (Pehnt 2003), presumably because it is the only fuel cell in commercial production.

Environmental benefits also vary according to the conventional technologies being used in the comparison, and the current electricity fuel mix of the country in question. For example fuel cell CHP applications (fuelled by natural gas) were found to have similar levels of CO_2 emissions where the technology used for comparison was grid electricity (and gas heaters) rather than CCGT (Hart and Hormandinger 1998). Pehnt (2003) found the global warming impact to be slightly higher for a PEFC CHP 200kW plant (natural gas) when compared with a similar sized CHP gas engine, but slightly lower for a CHP SOFC (3 MW plant) compared with a CHP gas turbine.

In addition to fuel cells of various types being compared with conventional technologies comparisons have also been made between the primary energy source such as natural gas and renewable energy. In a comparison between hydrogen produced by the central steam methane reforming plant (SMR) and by wind turbines Spath & Mann (2001) find the resource requirement is higher for the wind/electrolysis system, while the air emissions and fossil energy consumption were higher for the SMR system.

Another consideration is in what part of the process the emissions occur. Where the production of hydrogen (from the reformation of natural gas) is considered separately (Spath and Mann 2001) greenhouse gas emissions mainly result from hydrogen plant operation, whilst other gaseous emissions result from natural gas production and transport. However if the hydrogen is produced via electrolysis using wind turbines to provide the power, the environmental impacts almost entirely occur during the manufacturing stage of the wind turbines (Spath and Mann 2001).

One of the best techniques for comparing the resource requirements and environmental emissions from alternative technologies is lifecycle assessment. Numerous evaluations of fuel cell applications have been carried out including applications for the automotive sector (eg (Contadini and Moore 2003); (Karlstrom 2002) but relatively few use a lifecycle approach particularly for stationary combined heat and power (CHP) applications. Also the assumptions used in these studies are sometimes rather general whilst others are not relevant to the UK situation. In addition most do not include the manufacture of the fuel cell system.

In order to explore the environmental costs and benefits of stationary fuel cell CHP in the UK this project explored alternative methods of providing heat and power to a 500-house residential housing estate both with and without fuel cells. The objectives of this study were:

- To analyse the main energy and material flows involved in fuel cells production and use;
- To evaluate the life cycle atmospheric emissions of fuel cells;
- To compare fuel cells for stationary applications with conventional technologies, for electricity production (power plants) as well as for co-generation (CHP).

Following on from this the same methodology was applied to the Grove Development case study developed in chapter 7. This explores the environmental impacts arising from alternative methods of meeting the heat and power demand profiles of the Grove Development (section 7.6).

4.2 Methodology

4.2.1 Lifecycle Assessment

To assess the environmental costs and benefits of fuel cell CHP a lifecycle assessment (LCA) has been undertaken. According to ISO 14040 (1997), an LCA comprises four major stages: goal and scope definition, life cycle inventory, life cycle impact assessment and the interpretation of the results. The goal and scope phase defines the purpose and extent of the study and includes a description. This research compares the environmental impacts of alternative methods of meeting the heat and power demand of 500 households both with, and without, fuel cells.

The Life Cycle Inventory (LCI) constitutes a detailed compilation of all environmental inputs (material and energy) and outputs (air, water and solid emissions) during each stage of the life cycle. This includes the manufacture of the fuel cells and other equipment including pipelines and transport.

This study includes resource use, greenhouse gases, gaseous pollutants and liquid pollutants. Greenhouse gases include CO2, CH4, N2O, HCF, PCF, SF6. Global warming potentials (GWP), using CO2 equivalent factors, are also calculated using the equivalency factors reported in IPCC (1996; 2001). SO2, NOx, particulates, HCl, HF, CO, NMVOC, H2S, & NH3, are included in the analysis, plus the acidification potential (AP), expressed in SO2 equivalents, and the tropospheric ozone precursor potential (TOPP), based on EEA (2000). Liquid effluents include the environmental indicators AOX, BOD, COD, as well as N, P, and inorganic salts.

The Life Cycle Impact Assessment (LCIA) phase quantifies the relative importance of all environmental burdens obtained in the LCI. According to ISO 14042, the general framework of an LCIA method is composed of two mandatory elements (classification and characterisation) and three optional elements, normalisation, grouping and weighting (Hertwich 2002). The classification stage assigns the inventory results to different impact categories such as global warming, while the characterisation stage calculates a category indicator result for each impact category using characterisation factors such as carbon dioxide equivalents (ISO 2000). Following this, a wide range of weighting methods can be used (Hertwich et al, 1997; Powell et al,. 1997) including economic valuation used in this study (Table 4.1). These costs represent the monetary value of damages or the avoidance associated with emissions or residues.

Table 4.1: Range of economic values used in the analysis

Air pollutants	**Economic values [€/kg]**	
	High	Low
SO2	7.0	13.0
NOx	3.0	20.0
Particulates	10	35
CO2[4] (per kg of C)	0.02	0.1
CH4	0.28	0.5
N2O	5.97	7.5
As	150	999
Cd	18.3	81.4
Cr VI	123	819
Ni	2.53	16.8
Dioxins	2000000	16300000

Sources: COWI (2000); COHERENCE (2000); ECOFYS (2000); and Pearce, et al, (1998)

4.2.2 Gemis

The software used for the LCA is GEMIS, a public domain lifecycle assessment program and database for energy, material, and transport systems, developed by Öko-Institut and Gesamthochschule Kassel (GhK). GEMIS includes the total lifecycle in its calculation of impacts - i.e. fuel delivery, materials used for construction, waste treatment, transport and auxiliaries. (More information can be found on the GEMIS website: http://www.oeko.de/service/gemis/en/index.htm)

4.3 Key assumptions

4.3.1 The energy demand: domestic energy consumption in a multi-residential application

The domestic energy demand for a housing estate of 500 properties was computed on the basis of the UK aggregate energy balance 2002, taking into consideration the fuel mix for domestic energy (DUKES, 2004), the total number of households (Census 2001), and the balance between domestic heat and power demand in the UK. Thus for the 500-house residential area, a 37 TJ/a thermal demand and a 10 TJ/a electrical demand were assumed. This means that the H: P ratio for the UK domestic sector is 3.9: 1.

4.3.2 Main energy related data

Natural gas is one the main input of the UK energy system and of the analysed fuel cells. Therefore it is important to analyse all the chain of processes from offshore gas extraction (and import) to pipeline distribution and use in the technologies.

According to the International Energy Agency[5], in 2000 the UK import of natural gas was 1.99% of the total supply. Taking into account the most recent pathways for UK imports and export of natural

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[4] other GHGs are calculated using their CO2-equivalent

[5] Source: http://www.eia.doe.gov/pub/international/iea2001/table42.xls

gas[6], it can be seen that 55% of the UK import of natural gas comes from Norway (7018 GWh) and the remaining part arrives through the UK-Belgium interconnector (5845 GWh). These figures were used to define an updated natural gas mix for the UK (98.01% indigenous production, 1.09% imports from Norway, 0.9% imports from Belgium) which is graphically represented in Figure 4.1.

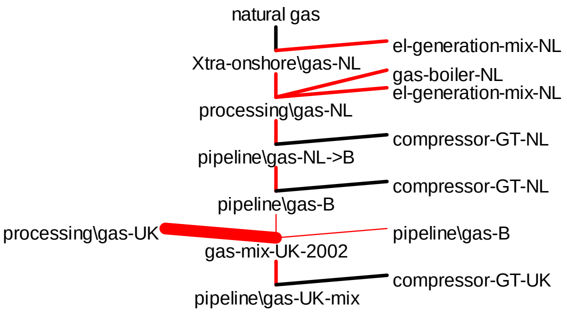

Figure 4.1: Process chain of the UK natural gas mix.

The electricity generation mix has been updated according to the Aggregated energy balance 2002 (DUKES, 2004). From this data it can be obtained the following generating mix for electricity: 37% coal, 25% nuclear, 35% gas, 1% oil, 2% hydro and 1% other solid fuels that has been used to update the model database.

4.3.3 Modelling the fuel cells

The main technical data are summarised in Table 4.2. The analysed SOFC internally reforms natural gas into hydrogen and has been modelled with GEMIS as a unique "black box" (Figure 4.2). This choice was fostered for a practical reason: fuel cell manufactures and scientific literature usually refer to the overall efficiency of the technologies, without distinguishing between internal reformer and the core of the fuel cell.

Table 4.2: Technical data for solid oxide fuel cells

		Reference
Typology	tubular SOFC, with an internal reformer	Siemens-Westinghouse (ETSU, 2003)
Input fuel	Natural gas	
Capacity (kW)	100	Karakoussis et al 2001
Operating time (h/y)	8000	Karakoussis et al 2001
Life time (y)	5	Karakoussis et al 2001
Electrical efficiency (%)	41	(Pehnt 2003)
Thermal efficiency (%)	37	(Pehnt 2003)
Overall efficiency (%)	78	(Pehnt 2003)
H:P ratio	0.9	Calculated as Eff_{th}/Eff_{e}

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[6] Source: http://www.dti.gov.uk/energy/inform/energy_trends/articles/bpjan2001.pdf

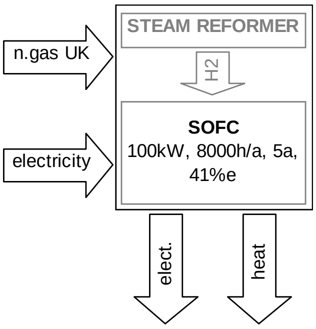

Figure 4.2: The 'black box' model of the SOFC fuel cell

Natural gas is the main input of the analysed fuel cells. The model calculates the amount of natural gas from the technology efficiency and the fuel LHV. The electricity input includes all the energy required for manufacturing the positive-electrolyte-negative (PEN) and all the remaining components (balance of plant manufacture, BoP) (Karakoussis et al 2001). The total amount (2390 MJ/kW=0.215 TJ/TJ) takes into account the electricity needed for materials production (2035 MJ/kW) as well as the electricity for manufacturing processes (355 MJ/kW), with reference to a tubular 100 kWh SOFC.

Detailed data on material flows involved in manufacturing the tubular SOFC system are provided by Karakoussis et al 2001. Unfortunately, neither GEMIS nor BOUSTEAD databases contain data on these materials. Thus an estimate of material consumption was derived by the life cycle inventory of a 1 kW PEM, obtained by White et al (2001) (Table 4.3).

Table 4.3: Material flows involved in the life cycle of a fuel cell.

		Life Cycle(kg/kW)	(kg/MW)	GEMIS's materials
carbon steel	27.5%	23.4	23400	metal\steel-D-mix
graphite	21.4%	18.2	18200	
stainless steel	19.7%	16.8	16800	metal\steel-D-mix
lead	13.4%	11.4	11400	metal\lead-D-mix
aluminium	7.8%	6.64	6640	metal\aluminium-mix-D
copper	3.7%	3.18	3180	metal\copper-D-mix
sulphuric acid	1.4%	1.2	1200	chem-inorg\sulphur acid
polypropylene	1.3%	1.08	1080	chem-org\PP-APME-99
polycarbonate	0.9%	0.74	740	chem-org\PC-ISI
epoxy	0.8%	0.71	710	chem-org\epoxy resin-ISI
pvc	0.6%	0.53	530	chem-org\PVC-mix-DE
polyethylene	0.6%	0.5	500	chem-org\PE-ISI
epdm	0.2%	0.17	170	chem-org\rubber_EPDM_UK
Ni-nickel	0.2%	0.16	160	
cobalt	0.2%	0.16	160	
titanium	0.02%	0.013	13	
palladium	0.12%	0.1	100	precious metal\Ptd-primary-mix-Western-world
platinum	0.12%	0.1	100	precious metal\Pt-primary-mix-world
	100%	assumed (<1)		

Source: White et al. 2001.

Because CHP processes generate more than one main product, an allocation is needed to distribute the environmental and cost effects between the main product, and the coupled product. In GEMIS, a credit for the couple product is usually allocated so that the CHP process is modelled on a net base. CHP technologies are usually modelled with reference to the electricity output (efficiency, emissions factors, etc.). Thus, to take into account the co-generated heat a negative flow of credit-heat has to be defined.

4.3.4 Economic assumptions

Due to the immaturity of the fuel cell market with little full scale production the financial cost of fuel cells is currently very high (Peters & Powell, 2004). Although the costs will reduce as the market expands it is not possible to predict the future price of fuel cells, therefore the financial cost has not been included in this model. However the external cost of the environmental costs and benefits have been included as a means of aggregating the gaseous emissions.

4.4 Analysed scenarios

The scenarios used in this study involve the combination of demands (e.g. for heat, electricity, and transport) with supply processes (e.g. heating system, power plant). For each scenario case the lifecycle emissions, resources, and external costs have been calculated. Three main scenarios are analysed, the base case, CHP and fuel cell CHP, each of them split into several different cases. The main characteristics are summarised in Table 4.4.

Table 4.4: The three main scenarios used in this study

scenario	case	heat	power
BASE	BASE1-gas	gas heaters	electricity grid
	BASE2-mix	heaters: domestic UK fuel mix	electricity grid
CHP	CHP1-el	gas ICE + gas heating plant/Electrical demand	
	CHP2-th	gas ICE + gas heating plant /Thermal demand	
	CHP3-CCGT	CCGT	
	CHP4-stirling	Stirling micro-CHP/Thermal demand	
FC	FC1-el	SOFC + gas heating plant /Electrical demand	
	FC2-th	SOFC + gas heating plant /Thermal demand	

4.4.1 The BASE scenario

The BASE scenario describes the current situation where electricity is provided by the local grid and the heating demand is fulfilled by conventional on-site boilers. It was included to analyse the effects of using different combinations of conventional technologies for satisfying the heat and power demand of the residential district. In this scenario, central heating systems were compared.

Table 4.5 provides an overview of the generation and balancing supply scheme.

BASE1 is focused on a conventional system, present in most British houses, where heat is provided by a natural gas central heating system and the electrical grid provides electricity. The 10 kW heating system is 85% efficient, and is fed with typical UK natural gas (Figure 4.3) (CH4 content: 86% volume, LHV: 46.96 MJ/kg, cost: 2840 Euro/TJ_LHV). The high-pressure pipeline for natural gas transport is based on a 200-km average distance, and takes into account average losses of 0.7%. This system is modelled taking into account atmospheric burner, auxiliary electricity, and heat distribution in the building. The electric grid is modelled as reported in Figure 4.4.

BASE2 differs from the previous case in that the heating supply is based on the average UK fuel mix of the domestic sector. Four technologies for central heating were taken into account, electricity (20%), gas (75%), oil (2%) and coal (3%) (Figure 4.3 to Figure 4.7).

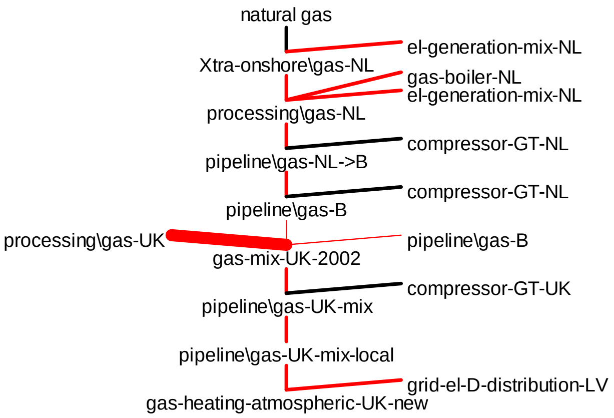

Figure 4.3: Process chain of centralised UK heating systems, fired with natural gas

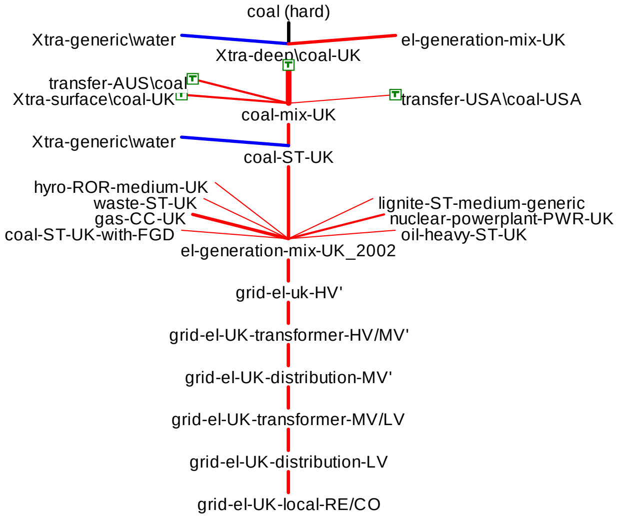

Figure 4.4: Process chain of the UK electrical grid feeding the residential district

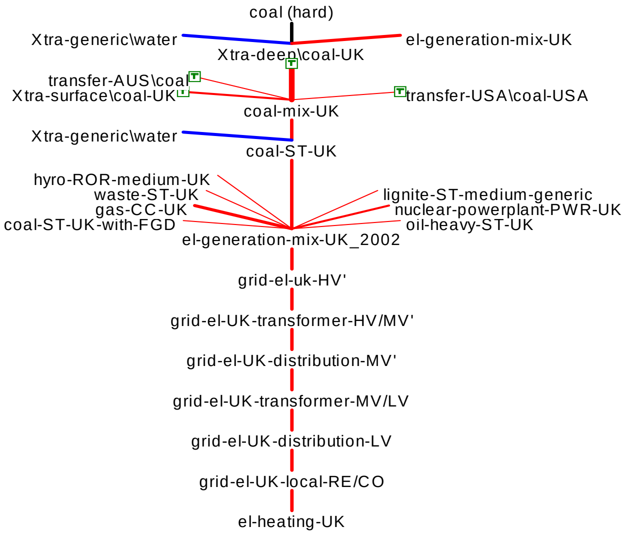

Figure 4.5: Process chain of centralised UK heating systems, fired with electricity.

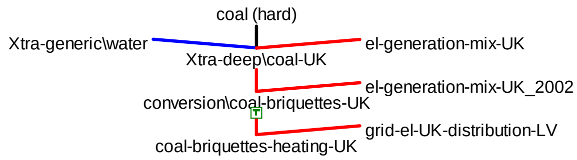

Figure 4.6: GEMIS process chain of centralised UK heating systems, fired with coal

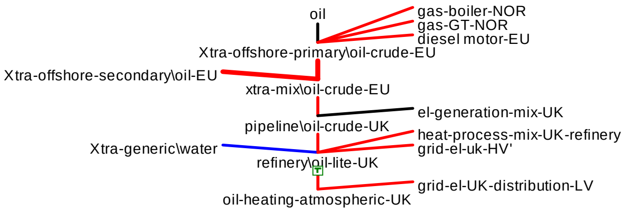

Figure 4.7: GEMIS process chain of centralised UK heating systems, fired oil

4.4.2 The CHP scenario

The **CHP** scenario includes co-generating plants for meeting the heat and power demands. At least two CHP units were selected in preference to one larger unit to maximise flexibility of operation, particularly during periods of low demand and during routine maintenance. These CHP units are generally coupled with conventional boilers to cover the peak load demand. The local heating distribution system has been included in this study. An average 10 km length of the pipelines was assumed, with an average CH4 leakage rate of 0.7%.

Table 4.5 summarises the characteristics of the scenarios.

CHP1-EL consists of two 250 kWe gas-fired internal combustion engines (ICE), 34.4% electrical efficiency, H:P=1.5:1, with the gas provided by the average UK gas pipeline (Figure 4.8). In this case the activity of ICE plant was set on the electricity demand, whereas the remaining heating demand is fulfilled by a 1 MW gas-fired heating plant with draft burner, which includes also auxiliary electricity, Eff_th: 87.5% (Figure 4.9).

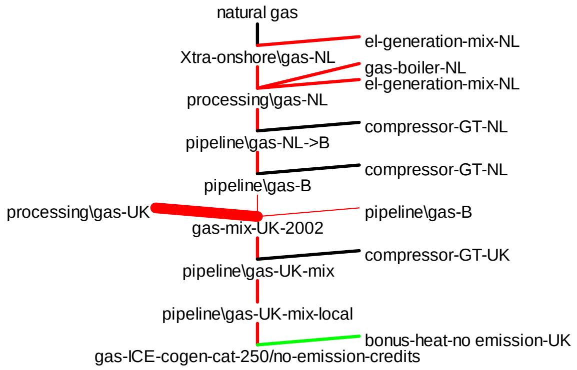

Figure 4.8: Process chain of the ICE cogeneration plant

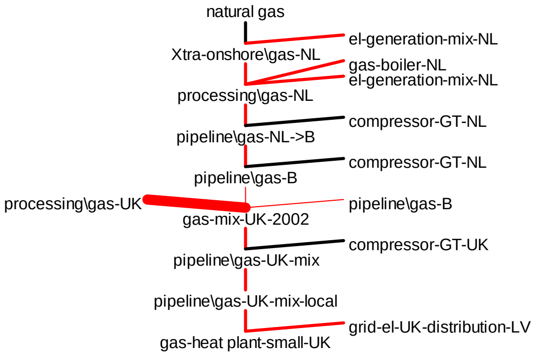

Figure 4.9: Process chain of a gas-fired heating plant.

CHP1-TH, is based on the same technological mix as CP1, but with the ICE and gas-fired heating plants based on the thermal demand. In this case, the excess electricity is sold to the electrical grid.

CHP3-CCGT includes a 20MWe gas-fired combined-cycle gas turbine (CCGT) cogeneration plant, with low-NOx burner, (Eff$_e$ 40% H:P=1.11:1) (Figure 4.10). This large plant produces more electricity and heat than required thus the excess is provided to the electricity grid and to a district-heating grid. CCGT systems have greater overall efficiency, compared with alternative conventional schemes. The minimum size for investment in this technology is assumed to be 20 MW heat.

CHP4-stirling includes a micro-cogeneration gas Stirling engine for each household (5 kW 24% electrical efficiency, H:P=2.85:1[7]), whose utilisation is based on the fulfilment of the thermal demand. Again, the excess electricity is "sold" to the electrical grid. A Stirling engine is an external combustion device whose efficiency is potentially greater than that of internal combustion or gas turbine devices[8]. It has only recently been used for micro CHP boilers where there is a need for small engines with a capacity between 0.2 and 4 kWe.

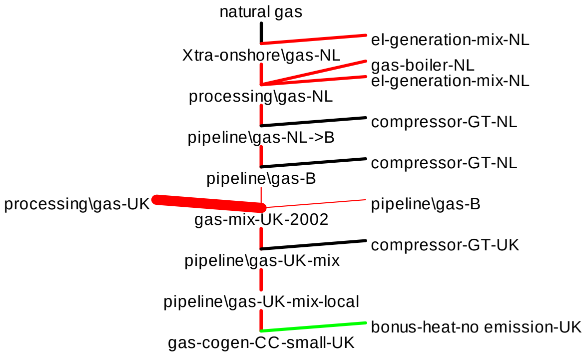

Figure 4.10: Process chain of a gas-fired combined-cycle (CC) cogeneration plant.

4.4.3 The fuel cell (FC) scenario

The **FC** scenario analyses the effects of using small-scale fuel cells in residential schemes. The 100 kW SOFC (Eff$_e$ 41%, H:P=0.9:1) (Figure 4.11)(Table 4.5). Due to their high electrical efficiency, fuel-cell systems deliver less heat than ICE co-generators. Consequently, they either need additional heat from gas heating to meet the end-use demand, or they are designed meet the heat demand, selling excess electricity to the grid.

FC1-EL utilizes five SOFC units to meet the electric energy demand with two gas heating plants providing the additional heat requirement.

FC2-TH is similar to the previous case but is based on twenty SOFC units in a system designed to meet the thermal energy demand with excess electricity being sold to the grid.

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[7] Pehnt WWF, Table 2, p. 16

[8] http://www.prochp.com/Handbook/atext.html

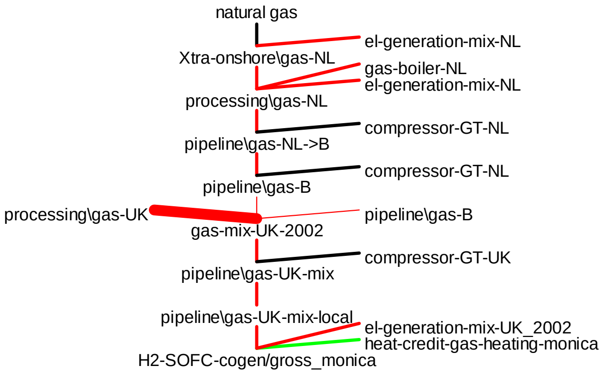


Figure 4.11: Process chain of the SOFC.

Table 4.5: Characteristics of scenarios

Scenario	***Generation Thermal (units)***	***Units***	***Operating time [h/a]***	***electric power [MW]***	***electricity [TJ]***	***thermal power [MW]***	***thermal energy [TJ]***	***Balancing supply***	***Remaining demand [MW]***	***Remaining demand [TJ]***
BASE1	gas heat	500	2060	0	0	5	37	electrical	0	10.00
	sum			**0**	**0**	**5**	**37**			
BASE2	elec heat	100	2200	0	0	1	7.92	electrical	0	10.00
	coal heat	15	2200	0	0	0.15	1.19			
	oil heat	10	2200	0	0	0.10	0.79			
	gas heat	375	2010	0	0	3.75	27.10			
	sum			**0**	**0**	**5**	**37**			
CHP1-EL	gas-ICE	2	5560	0.50	10	0.75	15			
	gas-heat	1	6110	0	0	1	22			
	sum			**0.5**	**10**	**1.75**	**37**			
CHP2-TH	gas-heat	1	2000	0	0	1.00	7.20	electrical	-1.00	-9.87
	gas-ICE	4	5520	1	19.87	1.50	29.81			
	sum			**1.00**	**19.87**	**2.50**	**37.01**			
CHP3-CCGT	gas-cogen	1	500	20	36	22.2	39.96	electrical	-20.00	-26.00
								thermal	-22.22	-2.96
	sum			**20**	**36**	**22.2**	**39.96**			
CHP4-STIRLING	gas stirling	500	3430	1.5	18.50	3	37.00	electrical	-1.35	-8.50
	sum			**1.35**	**18.50**	**2.7**	**37.00**			
FC1-EL	SOFC	5	5560	0.50	10.00	0.45	9.00			
	gas heat	2	3890	0	0	2.00	28.00			
	sum			**0.50**	**10.00**	**2.45**	**37.00**			
FC2-TH	SOFC	20	5710	2.00	41.11	1.80	37	electrical	-2.00	-31.00
				2.00	**41.11**	**1.8**	**37**			

ICE – internal combustion engine; CCGT – combined cycle gas turbine;

4.5 Results

The results are provided in Figure 4.12 to Figure 4.21.

4.5.1 Resources

The BASE2 scenario utilizes the most resources, followed by BASE1 and FC1-el (Figure 4.12). The resources used are dominated by natural gas with some scenarios (CHP1-el) using relatively few other resources. Other scenarios, in particular BASE2-mix, use a range of resources due to domestic heating being based on a UK mix of fuels. Most of the CHP cases and FC2-th save oil and coal as they 'sell' excess energy to the grid or district heating system, which displaces the average fuel mix.

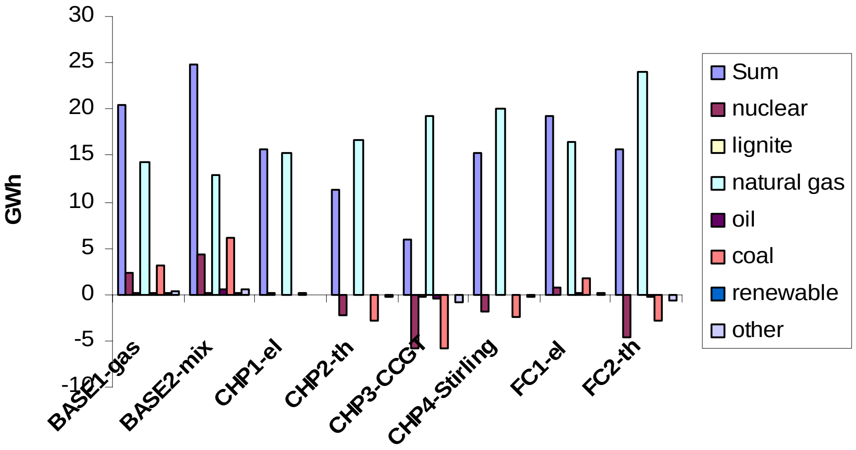


Figure 4.12: Renewable, non-renewable and other resources used in each scenario

4.5.2 Greenhouse gases

The greenhouse gas emissions from the different scenarios vary considerably (Figure 4.13). Although greenhouse gas savings can be identified when comparing the average fuel mix for UK domestic heating (BASE2) with gas heating only (BASE1-gas) a far greater emissions saving can be made by the introduction of CHP, particularly when excess electricity is exported. Exporting excess electricity to the grid displaces grid electricity and the associated emissions. The CCGT system (CHP3-CCGT) has particularly low greenhouse gas emissions due to the high efficiency of the plant plus, being oversized for the modelled district, both electricity and heat are exported.

The fuel cell case that meets the thermal demand (FC1-th) produces the least greenhouse gases of all the scenario cases, while the fuel cell case FC1-el produces less greenhouse gases than both the BASE cases, slightly less than two of the CHP cases, CHP1-el and CHP4-stirling, but more than CHP2-th and CHP3-CCGT. The most predominant greenhouse gas can be seen to be CO2 with CH4 also making a significant contribution particularly where coal is utilised (BASE2-mix) as methane emissions are strongly associated with coal mining.

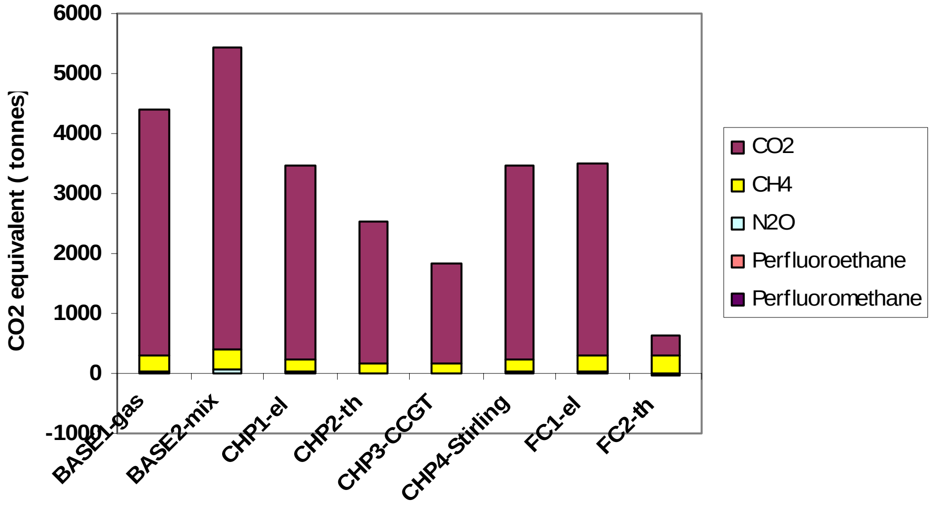


Figure 4.13: Greenhouse gas emissions, expressed as CO2 equivalents, for each scenarios.

4.5.3 Gaseous pollutants

Where appropriate, gaseous pollutants are aggregated according to their acidification potential, SO2 equivalents (SO_2, NO_x, HF, HCl, H_2S & NH_3) (Figure 4.14), and tropospheric ozone precursor potential (TOPP) (NO_x, NMVOC, CO & CH_4) (Figure 4.15). The results for particulates are given in Figure 4.16 and Figure 4.17, the remaining emissions. Further details are provided in Table 4.10.

The results indicate that compared with the base scenarios the CHP scenario generally results in lower emissions with emission savings for many of the pollutants, particularly SO2 equivalents for CHP2, 3 and 4 (Figure 4.14). The CCGT case (CHP3-CCGT) produces the least acidic gases overall, with the fuel cell scenario, particularly FC2-th, producing the most. The main acidic gas is SO2, followed by NOx.

In contrast the CCGT case produces the most TOPP compared with the other CHP cases and the fuel cell scenario, whereas the fuel cell case FC2-th produces the least TOPP overall (Figure 4.15). Fuel cell case FC1-el compares favourably only with the BASE scenarios and CHP3-CCGT.

A similar pattern to SO2 equivalents emerges for particulate emissions (Figure 4.16) with the CHP scenario mainly resulting in emission savings. The fuel cell scenario has lower emissions than the BASE scenario, but, unlike the acidic gases the fuel cell case that meets the electrical demand (FC1-el) has more particulate emissions than FC2-th.

The results of the remaining gaseous pollutants (As, Cd, Cr, Cu, Hg, Ni, PAH, PCDD/F & Pb), shown in Figure 4.17, indicate a similar level of emissions for all scenarios apart from CHP3-CCGT, which has considerably higher emissions for all the pollutants. Excluding the CHP3 results the pollutant emissions are highest for the BASE scenarios and FC2-th, and lowest for the CHP scenarios.

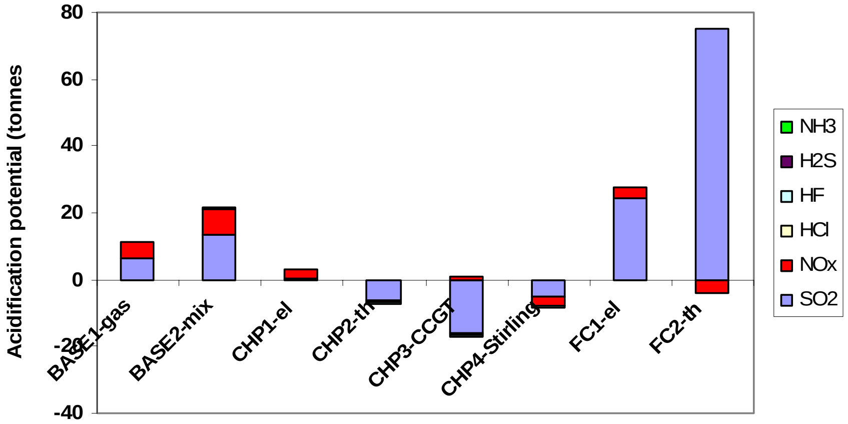


Figure 4.14: Gaseous pollutants expressed according to their Acidification Potential (tonnes SO2 equiv.)

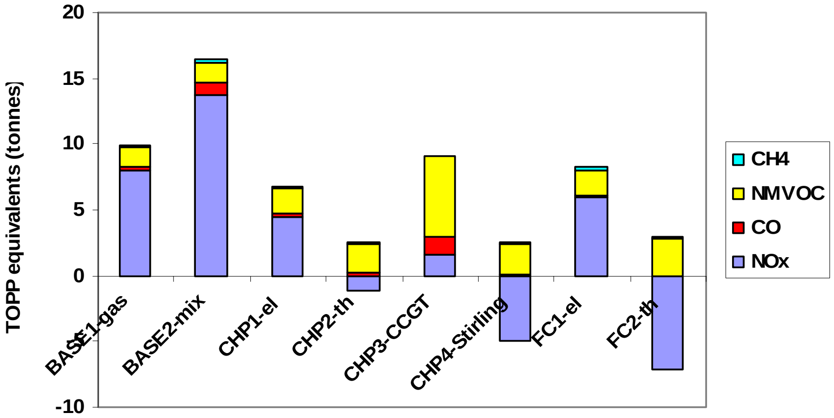


Figure 4.15: Gaseous pollutants expressed according to their Tropospheric Ozone Precursor Potential (TOPP) (tonnes)

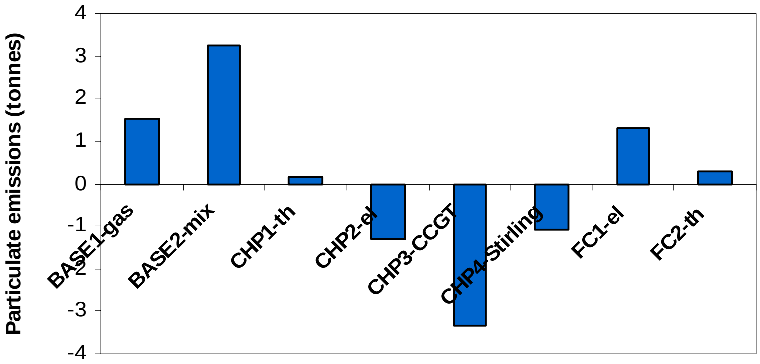


Figure 4.16: Gaseous particulate emissions (tonnes)

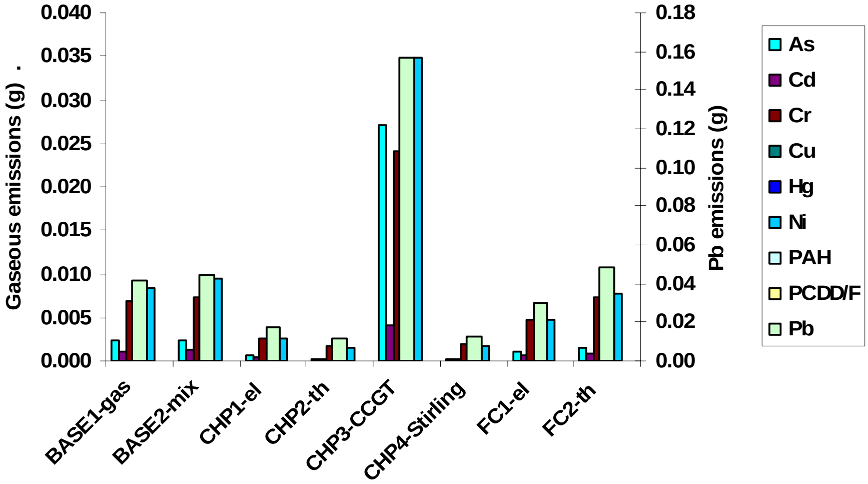


Figure 4.17: Gaseous emissions: arsenic (As), cadmium (Cd), chromium (Cr), copper (Cu), mercury (Hg), nickel (Ni), PAH, PCDD/F, & lead (Pb)

4.5.4 Liquid effluents

The results for the liquid effluents are given in Figure 4.18, and Figure 4.19. The BOD, COD and inorganic salts emissions (Figure 4.18) have a similar relationship across the scenarios apart from the combined cycle gas turbine case (CHP3-CCGT) where there are far greater COD & BOD emissions compared to inorganic salts. The CHP3-CCGT case does also not follow the general pattern of CHP emissions being lower than the base cases. The FC1-el case is of a similar order to the base cases, whilst the FC-th case is greater than the base cases, although not as significantly as the CHP3-CCGT.

The CHP scenario effluent emissions of phosphorus, AOX and nitrogen are lower than the BASE scenarios but the fuel cell scenario emissions are greater than the CHP scenarios, particularly the FC2-gas case, which is the least favourable case (Figure 4.19).

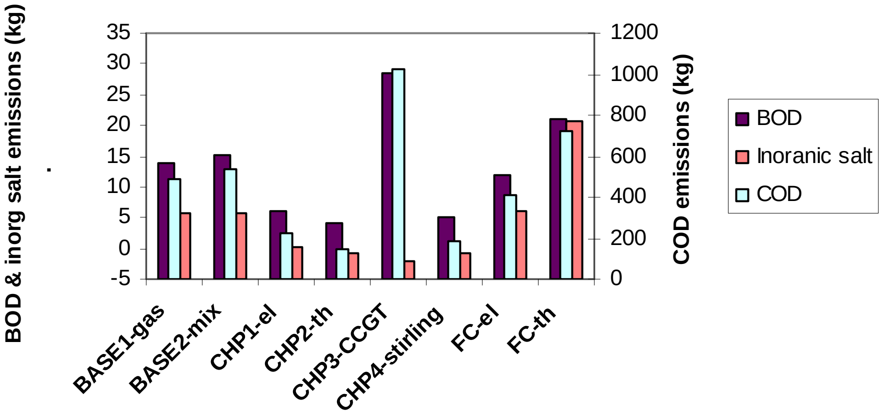


Figure 4.18: Liquid effluent emissions: biological oxygen demand (BOD), chemical oxygen demand (COD) & inorganic salts

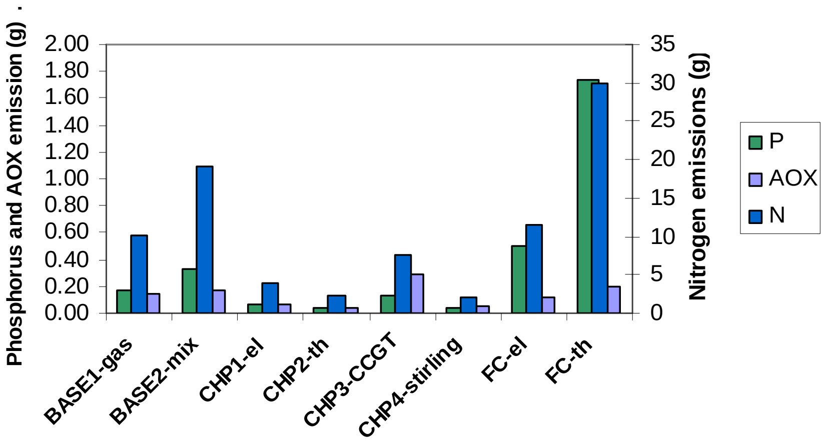


Figure 4.19: Liquid effluent emissions: phosphorus (P), AOX, and nitrogen (N)

4.5.5 External Costs

The results from applying high and low monetary values (Table 4.1) to the gaseous emissions indicate that the CHP scenarios perform the best, with most resulting in a saving rather than a cost (Figure 4.20). Overall the fuel cell scenarios perform worse than the BASE as well as the CHP scenarios, with FC1-el having a higher cost than BASE1-gas and only slightly lower than BASE2-mix. FC2-th performs worse than both BASE cases as well as the CHP scenario. Although the application of high and low monetary values gives different results they do not influence the overall rank order. When the results are explored in more detail (Figure 4.21) using mean monetary values, it can be seen that the external cost of SO2 has the greatest impact particularly for the fuel cell scenario. Carbon dioxide equivalents and NOx emissions are also important.

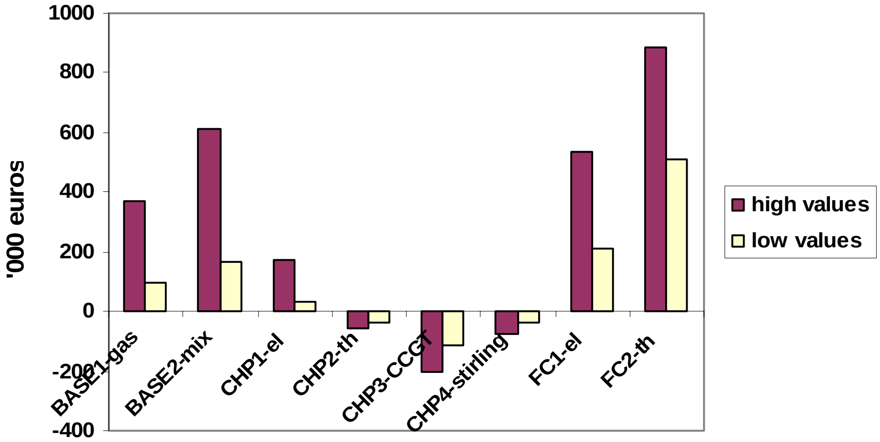


Figure 4.20: Monetary valuation of gaseous emissions using both high and low values (euros)

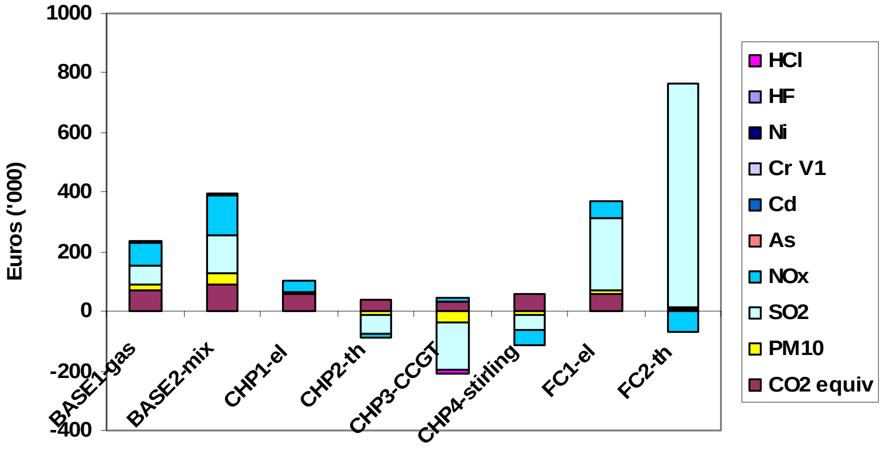


Figure 4.21: Monetary valuation of individual emissions using average values (euros)

4.6 Discussion

The results from this analysis are complex with no clear 'winner' over all criteria. However for many emissions a basic pattern has emerged with the BASE scenario being the least favourable scenario and the CHP scenario generally being the best option. However this is not always the case, for greenhouse gas emissions and TOPP the fuel cell case FC2-th is most favourable, while for some gaseous pollutants (As, Cd, Pb & Ni), BOD and COD CHP3-CCGT is the worse case.

Exploring the BASE scenario in more detail it can be seen that an increase in the natural gas share, from the UK heating fuel mix (BASE2) to an extreme situation where gas is the only fuel (BASE1), leads to:

- a substantial reduction of all the local air pollutants (e.g. –51% SO2, -42% NOX, -53% particulates, -77% CO) and greenhouse gases emissions (-18% CO2, -23% CH4, -47% N2O);
- a lower use of primary energy (-18%) and raw materials (-44%);
- a reduction of liquid waste (e.g. –9% both COD and BOD5).

The introduction of CHP gas-fired internal combustion engines (ICE) supported by gas-fired heating plants result in a reduction of most pollutant emissions compared to the base scenario where heat and electricity are provided separately. In particular, moving from the BASE2-gas situation towards the CHP1-el scheme (where the ICE's capacity is set to fulfil the electricity demand) the following reduction can be achieved: –97% SO2, -68% NOX, -96% particulates, -76% CO; -36% CO2, -39% CH4, -59% N2O.

Further environmental benefits are achieved when the utilisation of the ICE is increased in order to meet the thermal demand, with excess electricity being 'sold' to the grid. This trend is identified by the CHP1-th scenario. The negative values are due to the emission credits from replacing the grid electricity with that provided by the more efficient CHP scheme. The increase in the ICE capacity from CHP1-el to CHP1-th gives the following reductions in greenhouse gases: - 27% CO2, -25% CH4, -70% N2O.

The introduction of a gas-fired combined-cycle (CC) cogeneration plant, described by the CHP3-CCGT case, induces further reductions of greenhouse gases and almost all the local air pollutants but an increase of CO and NMVOC compared to the baseline scenario (BASE2) and CHP3-CCGT. In particular the reduction of CO2, acidic gases, and particulates are due to the excess energy produced that displaces both heat in the district heating scheme and 'grid' electricity. However, although it is useful for comparative purposes, the CCGT case is unrealistic for the relatively small number of properties as the power plant is oversized for the demand and would therefore be an expensive option. The high level of toxic pollutants (As, PAH, Pb etc).are almost entirely due to coal fired electricity to manufacture the steel for the plant. However this high level seems excessive and needs further investigation.

Compared with BASE2 the fuel cell scenario indicates a general reduction of greenhouse gases and most local air pollutants but an increase of SO2 and NMVOC. However when compared with BASE1 and the CHP scenarios the benefits are not so clear, with CHP often performing better. Although FC2-th results in saving greenhouse gases, FC1-el has much higher emissions than the CHP scenario. The significant difference between the greenhouse gas emissions from the two fuel cell cases is mainly due to the 'sale' of the excess electricity generated by the FC2-th case, resulting in the displacement of the more inefficient average fuel mix of grid electricity**.**

The high acidic emissions produced by the fuel cell scenario can be explained by looking at the contribution of single processes to the overall emission: about 84% of this pollutant is emitted during the manufacturing stages of precious metals (platinum and palladium) which are used in constructing the fuel cells. FC-th has far greater SO2 emissions as the case includes the manufacture of 20 fuel cell stacks (in order to meet the thermal demand) compared with only 5 in the FC1-el case.

The BOD and COD emissions, that are particularly high for CHP2-CCGT and FC-th, are associated with the use of coking coal in the manufacturing of the plant, particularly for the fuel cells. In general the liquid effluent emissions provided in the GEMIS data do not seem to be entirely reliable, mainly due to variation in the quality of the data across the scenarios. For example some effluent emissions are not accounted for in some processes. Therefore, until better data is available, it would seem better to concentrate on the gaseous emissions that overall seem more reliable.

4.7 Grove Case Study

Following on from the above analysis, a further LCA has been undertaken based on the case study developed in chapter 7. This explores the environmental impacts arising from alternative methods of providing energy to the Grove Development. Similar scenarios are used in this analysis although it is adapted to provide heat and electricity to the 1250 properties. The characteristics of the scenarios are summarised in Table 4.6.

4.7.1 Grove Development: results and discussion

The results of the Grove Development scenarios show a very similar pattern to the first analysis, although there are some differences in that energy systems that were oversized in the first analysis operate more efficiently with a larger development (Figure 4.22, Figure 4.23). This also applies to the manufacturing of, for example the CCGT plant. The pattern of energy requirements is similar with the significant demand for gas being balanced, to some extent, by the displacement of coal and nuclear energy in the scenarios that produce excess electricity. This result is reflected, to some extent, in the carbon emissions, with the scenarios that produce excess electricity displacing electricity with higher carbon emissions per energy unit. In addition to this the fuel cell scenario uses more energy in the manufacture of the precious metals used in the SOFC. Therefore, although FC2-th exports more electricity than CHP3-CCGT, on balance the fuel cell scenario uses more energy resources.

The monetary valuation of the gaseous emissions from the Grove Development provides a useful summary (Figure 4.24)(Table 4.12). As with the initial analysis it can be seen that acid gas emissions dominate the valuation for the fuel cell scenario, reflecting the impact from manufacturing the fuel cells.

Table 4.6: Characteristics of the scenarios to provide heat and power to the Grove Development.

Scenario	*Generation Thermal (units)*	*Units*	*Operating time [h/a]*	*electric power [MW]*	*electricity [TJ]*	*thermal power [MW]*	*thermal energy [TJ]*	*Balancing supply*	*Remaining demand [MW]*	*Remaining demand [TJ]*
BASE1	gas heat	1250	1012	0	0	12.5	45.55	electrical	0	15.67
	sum			**0**	**0**	**12.5**	**45.55**			
BASE2	elec heat	250	1013	0	0	2.50	9.12	electrical	0	15.67
	coal heat	37	1011	0	0	0.37	1.35			
	oil heat	25	1013	0	0	0.25	0.91			
	gas heat	938	1012	0	0	9.38	34.17			
	sum			**0**	**0**	**12.5**	**45.55**			
CHP1-EL	gas-ICE	3	5804	0.75	15.67	1.13	23.51			
	gas-heat	2	3061	0	0	2.00	22.04			
	sum			**0.75**	**15.67**	**3.13**	**45.55**			
CHP2-TH	gas-heat	1	2527	0	0	1.00	9.10	electrical	-1.50	-8.63
	gas-ICE	6	4500	1.50	24.30	2.25	36.45			
	sum			**1.50**	**24.30**	**3.25**	**45.55**			
CHP3-CCGT	gas-cogen	1	570	20	41.03	22.2	45.55	electrical	-20.00	-25.36
	sum			**20**	**41.03**	**22.2**	**45.55**			
CHP4-STIRLING	gas stirling	1250	1687	3.75	22.77	7.5	45.55	electrical	-3.38	-7.10
	sum			**3.75**	**22.77**	**6.75**	**45.55**			
FC1-EL	SOFC	7	6219	0.70	15.67	0.63	14.10			
	gas heat	2	4367	0	0	2.00	31.44			
	sum			**0.70**	**15.67**	**2.63**	**45.55**			
FC2-TH	SOFC	26	5407	2.60	50.61	2.34	45.55	electrical	-2.60	-34.94
	sum			**2.60**	**50.61**	**2.34**	**45.55**			

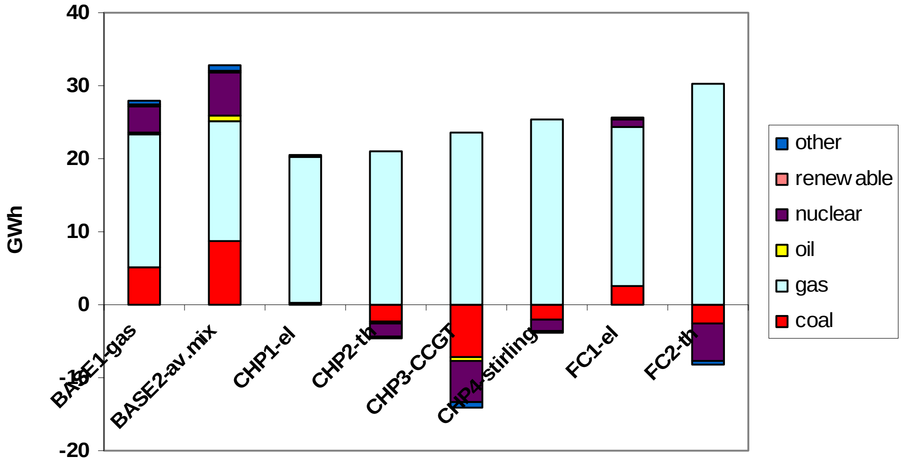


Figure 4.22: Energy resources used and displaced in the Grove Development case study (GWh)

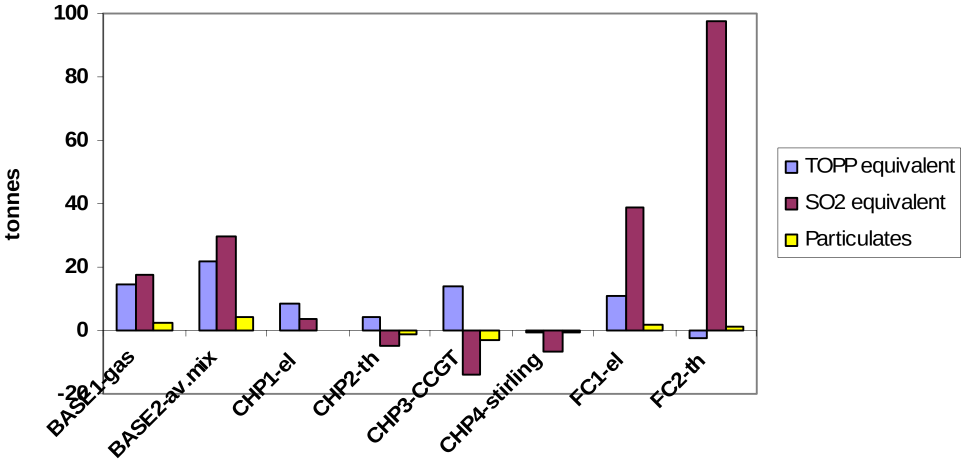


Figure 4.23: Tropospheric Ozone Precursor Potential, Acidic Potential (SO2 equivalent) & particulate emissions for the Grove Development case study

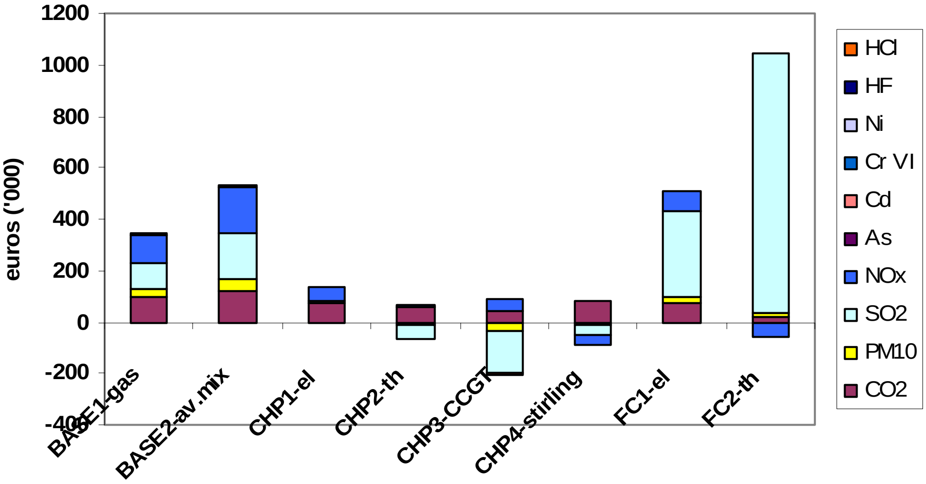


Figure 4.24: Monetary valuation of gaseous emissions from the Grove Development case study using average values

4.8 Conclusions

The two analyses carried out for this study has provided a useful insight into the environmental impacts arising from alternative methods of providing heat and power to a housing development. The main findings are as follows:

- Increasing the proportion of gas for domestic heating results in a reduction of most emissions;
- The introduction of gas fired CHP reduces emissions substantially compared with grid electricity and gas-fired central heating;
- Producing excess energy has positive results for all scenarios when it displaces more polluting sources, particularly when the displaced energy is less efficiently generated. For example when CHP electricity displaces grid electricity that includes less efficient coal-fired electricity. However there may be significant financial penalties to producing oversized plant, particularly for fuel cells;
- Despite its potential importance as a future energy provider, stationary fuel cell CHP does not compare favourably with CHP for most emissions. This is partly due to the manufacturing impacts and the heat:power ratio of fuel cells;
- A lifecycle approach is important as the manufacturing stage has significant impacts particularly the manufacture of precious metals for the fuel cells. However this impact will vary with the different types of fuel cell;
- A lifecycle approach is also important as it is necessary to take into consideration the heat and power balance due to the different heat:power ratios of CHP (eg internal combustion engines) and fuel cells;
- Further research is required to explore alternative fuel cell technologies plus the use of renewable energy for hydrogen production.

Appendices to Chapter 4

Table 4.7: Greenhouse gases (kg)

Option [kg]	CO2 equivalent	CO2	CH4	N2O
BASE1-gas	4415861	4117341	11702	98
BASE2-av.mix	5432106	5025109	15282	185
CHP1-th	3462879	3223338	9433	76
CHP2-el	2542465	2373735	7061	23
CHP3-CCGT	1847977	1691122	6414	35
CHP4-Stirling	3456967	3209374	9966	63
FC1-el	2933641	2632007	11996	80
FC2-th	-1660125	-1927751	12362	-81

Table 4.8: Energy impacts (MWh)

Option [MWh]	Sum	nuclear	lignite	natural gas	oil	coal	renewable	other
BASE1-gas	20441	2368	144	14287	181	3076	57	328
BASE2-mix	24800	4357	182	12808	599	6178	94	581
CHP1-th	15726	123	8	15357	19	195	3	23
CHP2-el	11197	-2162	-58	16640	-142	-2768	-43	-271
CHP3-CCGT	5902	-5813	-266	19205	-379	-5798	-112	-936
CHP4-Stirling	15338	-1854	-41	20015	-122	-2390	-37	-234
FC1-el	19193	701	26	16506	96	1736	33	95
FC2-th	15587	-4704	-125	24108	-179	-2886	-20	-608

Table 4.9: Economic valuation of gaseous emissions (euros)

Option [€]	CO2 equiv	PM10	SO2	NOx	HF	HCl	As	Cd	Cr V1	Ni	total
BASE1-gas	72420	17258	65037	75416	507	2885	1.35	0.06	3.23	0.08	233528
BASE2-mix	89087	36680	132374	128816	1052	5739	1.33	0.06	3.43	0.09	393753
CHP1-th	56791	1641	3814	41826	26	152	0.32	0.02	1.25	0.03	104251
CHP2-el	41696	-14721	-60663	-10513	-483	-2738	0.16	0.01	0.80	0.02	-47420
CHP3-CCGT	30307	-37720	-160448	14924	-1290	-7288	15.55	0.20	11.36	0.34	-161488
CHP4-stirling	56694	-12197	-52593	-46435	-420	-2381	0.18	0.01	0.86	0.02	-57331
FC1-el	57132	14870	241677	56020	362	1949	0.60	0.03	2.22	0.05	372011
FC2-th	9857	3313	753610	-66711	-225	-1699	0.84	0.05	3.45	0.07	698148

Table 4.10: Air pollutants (kg)

Option [kg]	TOPP equivalent	SO_2 equivalent	SO_2	NOx	HCl	HF	Particulates	CO	NMVOC	H_2S	NH_3
BASE1-gas	9884	11409	6504	6558	329	31.68	1534	2129	1485	0.061	0.016
BASE2-mix	16434	21716	13237	11201	654	65.73	3260	9395	1521	0.045	0.039
CHP1-th	6731	2932	381	3637	17	1.65	146	2273	1911	0.075	0.002
CHP2-el	1419	-7025	-6066	-914	-312	-30.15	-1309	2245	2188	0.092	-0.013
CHP3-CCGT	9142	-15999	-16045	1298	-830	-80.58	-3353	12771	6064	0.116	-0.034
CHP4-Stirling	-2416	-8351	-5259	-4038	-271	-26.24	-1084	599	2304	0.107	-0.011
FC1-el	8221	27791	24168	4871	222	22.58	1322	1668	1927	0.079	0.127
FC2-th	-4105	71131	75361	-5801	-194	-14.06	294	-398	2843	0.141	0.457

Table 4.11 Liquid effluent emissions (kg)

Option [kg]	P	N	AOX	COD	BOD	Inorganic salt	As	Cd	Cr	Hg	Pb
BASE1-gas	1.71E-04	1.01E-02	1.47E-04	489.33	13.77	5.82	7.00E-10	1.71E-09	1.69E-09	8.55E-10	1.12E-08
BASE2-mix	3.23E-04	1.91E-02	1.71E-04	535.72	15.11	5.82	5.37E-10	1.31E-09	1.30E-09	6.56E-10	8.56E-09
CHP1-el	6.48E-05	3.80E-03	6.59E-05	220.32	6.18	0.13	4.18E-12	1.02E-11	1.01E-11	5.10E-12	6.66E-11
CHP2-th	3.92E-05	2.27E-03	4.51E-05	148.82	4.13	-0.77	-1.54E-11	-3.76E-11	-3.72E-11	-1.88E-11	-2.45E-10
CHP3-CCGT	1.36E-04	7.71E-03	2.95E-04	1021.38	28.53	-2.00	-1.91E-08	-4.67E-08	-4.62E-08	-2.33E-08	-3.05E-07
CHP4-stirling	3.76E-05	2.18E-03	5.30E-05	180.77	5.03	-0.67	-1.63E-11	-3.99E-11	-3.95E-11	-1.99E-11	-2.60E-10
FC-el	5.03E-04	1.16E-02	1.18E-04	413.81	11.87	5.96	3.94E-12	9.61E-12	9.51E-12	4.81E-12	6.27E-11
FC-th	1.73E-03	2.98E-02	1.93E-04	717.61	21.05	20.76	-5.62E-11	-1.37E-10	-1.36E-10	-6.86E-11	-8.95E-10

Table 4.12 Grove Development: economic valuation of gaseous emissions (euros)

Option [€]	CO2	PM10	SO2	HF	HCl	NOx	As	Cd	Cr VI	Ni	total
BASE1-gas	98389	27017	101695	793	4509	113912	2.11	0.095	5.71	0.135	346323
BASE2-av.mix	117481	49258	178965	1418	7788	175287	2.03	0.097	5.70	0.143	530206
CHP1-el	73787	2051	4139	28	161	54397	0.43	0.023	1.68	0.034	134563
CHP2-th	60623	-12244	-52216	-417	-2366	8690	0.29	0.016	1.28	0.025	2072
CHP3-CCGT	39238	-35842	-158443	-1264	-7168	46307	1.40	0.077	5.93	0.115	-117165
CHP4-stirling	79108	-9355	-43210	-348	-1972	-36054	0.30	0.017	1.32	0.026	-11828
FC1-el	73202	21089	339499	515	2781	73809	0.81	0.044	2.98	0.062	510899
FC2-th	22746	12457	1010832	-46	-812	-56736	1.18	0.066	4.73	0.102	988447

5. IDENTIFICATION OF BARRIERS AND SOLUTIONS

5.1 Non-technical summary

This Chapter explores the opportunities and barriers to the development of stationary fuel cell technology in the UK, based on stakeholder interview findings. Stationary fuel cells offer a significant way forward towards sustainable energy but there is still a long way to go, at a technical and non-technical level, before they become an established, mainstream technology. Technically there is a need to extend the knowledge base for fuel cells, to improve their efficiencies, reliability, lifetime and material performances. Several issues also surround the sustainable production and storage of hydrogen and the development of a hydrogen infrastructure. Non-technical issues include cost, education and training, regulatory barriers, government commitment and issues surrounding the future of energy distribution.

Increased Government support both in terms of legislative reform and financial support is necessary to enable fuel cells to reach commercialisation and to establish a sustainable position in the market. If stationary fuel cells are to be taken seriously a significant change of attitude is required within the government and the energy industry, combined with proactive action. Subsidies for demonstration models could be one way forward.

More working demonstrations would not only display the government's commitment to fuel cells but would also provide a test bed for independent assessment of their environmental and social impacts. Financial support for the integration of fuel cell CHP into new housing developments would provide an ideal opportunity, particularly if they are combined with other integrated forms of renewable energy. The project would need to be independently monitored and evaluated and the results publicised widely.

Although fuel cells can provide environmental benefits associated with reduced local pollution and quiet operation there remains a question mark over the carbon implications. It is important to recognise that the environmental implications of this technology vary significantly depending on the source of fuel used to power them (e.g. natural gas) and their application. As has already been discussed in Chapter 4, fuel cells cannot be considered in isolation, a lifecycle approach is needed.

As already reported in Chapter 3, vehicular fuel cell applications have attracted high profile attention in recent times but it is felt that problems surrounding the establishment of a hydrogen infrastructure will slow down their large scale market emergence. In terms of niche market penetration mobile applications (e.g. phones) followed by smaller CHP units are thought to be more promising in the medium term.

5.2 Introduction

The purpose of this part of the research was to explore the barriers and opportunities to the development of stationary fuel cell technology in the UK by discussing the key issues with stakeholders in a series of semi-structured interviews. Part of the objective was also to explore areas where initial fuel cell advances are most promising. The areas covered in the interviews included; what is the nature of the problems delaying the development of the fuel cell market? Did the participants consider the slow process as normal for a new application of this technology? The answers given by the participants are presented here. The participants included fuel cell manufacturers, users and potential users and research experts – all stakeholders who have an on-going interest in the development and application of fuel cells and CHP in the UK.

The interviews were designed to address the following key objectives:

- to gain an understanding of the participants' background, knowledge and interest in these technologies;
- to find out what the participants think the main barriers are preventing fuel cells from taking on more prominence in the UK energy market;
- to ask participants how they see electricity generation in the UK evolving and where the most practical opportunities for fuel cells and related technologies are likely to be in the future, and
- to explore with them the broader implications and challenges posed by the introduction of a hydrogen economy.

5.3 Methodology

The methodology comprised the construction and administration of a schedule of interviews designed to investigate with a range of stakeholders their thoughts on the key drivers and barriers to the development of fuel cells. The stakeholders included manufacturers (or ex-manufacturers), users, potential users and experts. Owing to time constraints and the desire to obtain good quality data from the stakeholders involved, it was decided that an approach which drew on the methods and techniques of semi-structured interviewing would produce the best results.

The selection of individuals (Figure 5.1) for this piece of research was based on the identification of suitable participants mainly arising from work carried out for the preliminary stage of this research project (details of which can be found in Powell et al, 2004) and subsequent contacts established as a result of this research.

Fig. 5.1: Categories and numbers of interview participants

Category	***Number of participants***
Fuel cell manufacturers/fuel cell component manufacturers	3
Experts	2
Users	2
Potential users	2
Industry funded fuel cell membership organisation	1
Total	10

The key questions to be asked (Figure 5.2) were designed to be sufficiently open-ended to enable semi-structured discussions to take place where participants would feel able to develop their ideas and opinions within the scope of the interview. As the survey sample consisted of ten 'elite' participants this was deemed the best approach likely to enable the most information to be gleaned from each participant.

Fig. 5.2: List of key questions put to interview participants

1. Please outline your own interest in fuel cells and give a brief background to your organisation.
2. What do you see as being the main barriers preventing a swifter development and uptake of fuel cell technology?
3. On the specific issue of the regulatory regime what changes do you think might be necessary to give fuel cells and related technologies a better chance?
4. Where do you believe the most likely opportunities for fuel cells lie in the near future?
5. What will be the main driving forces enabling a realisation of these opportunities for the development and uptake of fuel cells?
6. As far as the UK is concerned do you see stationary application for fuel cells becoming a reality in the near future or is it more likely that other applications (e.g. transportation and smaller mobile applications) will be the main areas for market penetration and expansion?
7. It has been suggested by some that a move away from the centralised ‘grid’ energy system to a distributed network of ‘embedded islands’ would favour green energy technologies including fuel cells and CHP. Do you agree, and/or think, this is likely or a good idea?
8. What is your ‘ideal world’ forecast for fuel cells/CHP/renewables in the future?

The specific detail of what was discussed with the participants for this project varied from interview to interview in accordance with the particular background and knowledge of the individuals concerned and the different organisations with which they were associated. Nevertheless, the core objectives (described in the introduction to this chapter) together with the key question areas (Figure 5.2) provided a ‘control framework’ for each separate interview.

5.4 Barriers and opportunities for fuel cells in the UK

5.4.1 Government support, legislation and cost

“The Government makes statements but does act on them in a joined up way. NETA and the connection of small generators to the grid is a barrier to small generators in general, especially regarding the bureaucracy and costs involved.” **Fuel cell user**

For the participants of this research the key barriers to the development of fuel cells relate to governmental and legislative issues. There is a strong feeling that insufficient governmental support has been given to enable fuel cells to develop properly as a credible alternative energy technology. It is generally felt that government intervention, in the form of legislative drivers and support are required to promote the development and commercial viability of fuel cells. Appropriate legislative reforms, particularly relating to the New Electricity Trading Arrangements (NETA) are also considered essential.

“The regulatory regime… inhibits small generators.” **Fuel cell expert**

For most of the participants ‘government support’ includes financial support, through some form of subsidy or taxation. Despite funds from the DTI (£92M over 12 years), the Carbon Trust’s Low Carbon Innovation Programme and the Engineering and Physical Science Research Council (EPSRC) cost factors were still considered to be a substantial barrier to fuel cell development. Participants highlighted the prohibitive development costs involved in progressing the technology, in that it inhibits development and restrict the commercial viability of potential product applications. This supports the findings of the European High Level Group (EC, 2003) that recognises hydrogen and fuel cells do not currently offer sufficient short-term end-user benefits to justify their high costs compared to conventional technologies. The necessity of further governmental support for demonstration as well as development projects is considered vital in order to give fuel cell technology a better chance of market penetration and survival.

"The issue of cost is the foremost barrier – if we could get cheaper fuel cells working in peoples' homes we might be able to use excess industrial hydrogen to power them." **Fuel cell manufacturer**

"The government does not fund the transfer of technology into the commercialisation/manufacturing phase. There is a need for more government-funded demonstration projects." **Fuel cell manufacturer**

It is interesting to note, however, that in some areas of the literature the price of the products (particularly in terms of mobile applications – a key emerging niche market) is not considered to be the main factor that will prevent consumers from deciding to choose a hydrogen/fuel cell product in preference to another (possibly cheaper) alternative (Evers, 2003). Rather, it is suggested that increased awareness of the technology will have the greatest consumer impact, encourage desire for hydrogen/fuel cell powered products and catalyse the development of other fuel cell products and services that are not currently available (Evers, 2003). However this would seem to apply more to products that are purchased for their lifestyle image (e.g. cars and laptops) rather than utility products like heating systems.

5.4.2 Lessons from Europe and the importance of education

"Stronger, better designed legislative drivers are causing certain other EU countries to look very seriously into alternative energy solutions. This force will hopefully gather momentum in the UK as well where government support for fuel cells has been almost non-existent until recently." **Fuel cell manufacturer**

Several participants believe that some European countries, having developed environmentally-driven policies and regulatory measures, have had a much greater success in encouraging the development of sustainable energy in general than in the UK. Certainly at a European level the European High Level report (EC, 2003) provides an ambitious 'roadmap' to stimulate and fund research on hydrogen and fuel cell development. At the same time the DTI published a UK version (DTI, 2003), a discussion document intended to be the starting point for a UK fuel cell vision, but this was not mentioned by the participants. Although an offshoot of this, UKFC, an industrial organisation (and one of the participants) was considered useful (by the other participants) but mainly for awareness raising only.

A need to educate at all levels was identified with the purpose of drawing greater attention to the environmental damage caused by conventional energy generation and the depleting quantity of fossil fuels available as well as increasing awareness of the opportunities offered by fuel cells. This would raise the environmental benefit profile of fuel cells for potential users, policy makers and local planners.

"Education at all levels is essential if fuel cells are to take on greater prominence and be accepted as a potentially clean source of energy. People will need to know all of the facts about this technology – its strengths and weaknesses." **Fuel cell manufacturer**

5.4.3 Status of technology and environmental considerations

Fuel cells are still regarded as being a relatively 'young' technology and therefore still having much to prove as an alternative energy carrier. The practicality of developing fuel cells to a position of prominence in the energy market is also considered a barrier particularly when it is thought that there is a considerable vested interest for many large organisations to maintain the status quo. It was considered that if the government is seen to back the fuel cell industry this would help to overcome the perceived inertia of the energy industry.

The lack of evidence that fuel cells are significantly less damaging environmentally than conventional power sources when fuelled by hydrogen produced from fossil fuels is of concern to several participants. However a number recognise the benefits from reduced local pollution and quiet operation, an important concern in an urban environment. If however alternative, more sustainable means of hydrogen production are deployed then fuel cells are considered to offer an attractive, environmentally beneficial energy alternative.

"Fuel cells could be used in a package of renewable systems to enable the reduction of carbon dioxide and other major greenhouse gases, helping to meet the targets set by central Government. This meeting of targets is also useful with respect to securing future funding, and so this should be seen as a key incentive for local authorities to really make an effort in setting up these sustainable energy systems." **Potential fuel cell user**

There is however still the question of whether it is better to use renewable energy directly rather than to use it to make hydrogen for stationary applications. In addition it is recognised that the production of hydrogen from natural gas is currently the most economically viable method and that fuel cells may need to go through a transition phase of using natural gas before biofuels and renewables are used. It is interesting that the participants did not mention combining carbon sequestration with fuel cells using fossil fuel hydrogen as an alternative way forward. This may reflect the relatively early stage of development of carbon sequestration.

5.4.4 Hydrogen, distributed energy and niche markets

"Smaller scale CHP applications will be the first to become fully established, then progressing up to larger megawatt scale systems and beyond." **Fuel cell expert**

A clear advantage, identified by some participants was that of overcoming problems of intermittency associated with several forms of renewable energy. Hydrogen can provide a useful means of energy storage to even out the fluctuating requirements of supply and demand but until renewables form a substantial part of the UK's energy demand this can also be met by linking to the grid, so is only significant for isolated distributive systems. However the current regulatory system can inflict a significant financial penalty on imports and exports to and from the grid.

There was a diversion of opinion among the participants as to whether distributive systems (or distributed generation – DG) were likely to become more predominant in the future. This split of opinion is reflected by the following example quotations:

i) 'Pro-DG' stance: "Distributed generation is an attractive proposition that could include mini grids and provide certain building complexes (e.g. hospitals, offices etc.) with their own power sources. Fuel cell power stations supplemented by solar/wind feeding grids may well provide possibilities for the future." **Fuel cell user**

ii) 'Anti-DG' stance: "It's a bit like buying a car that is suitable for pulling a caravan even though 90% of the time it is only used by one person travelling to work and back." **Potential fuel cell user**

Some participants consider the current centralised grid system to be an inefficient means of distributing energy and that smaller, localised supply networks represent the only sensible approach for a sustainable future. Others argue that the practicalities of altering an already established grid network realistically precludes distributed generation as a viable alternative in the foreseeable future. One participant considers that more governmental and regulatory support is required for distributive networks. This might have the effect of encouraging the development of technologies suited to smaller scale generation such as fuel cells and renewable energy.

The majority of participants consider that stationary and mobile fuel cell applications would be the most likely area for serious advances for fuel cells in the medium term.

"Portable electronics will be the first major fuel cell application (possibly being introduced next year – 2004)." **Fuel cell membership organisation representative**

Although vehicular applications have attracted high profile attention in recent times it is felt that problems surrounding the establishment of a hydrogen infrastructure coupled with the long-term aims of car manufacturers and the oil industry would slow down the large scale market emergence of fuel cell vehicles for the time being. For this reason the participants believe that applications involving mobile phones, laptop computers and smaller CHP units will overtake automotive development in terms of niche market penetration.

5.4.5 The future in an ideal world

The participants were asked to describe their 'ideal world' forecast for fuel cells, CHP and renewable energy in the future. Below is a small selection of quotations from the interviews that reflect the range of views given.

"I would like to see more demonstration projects leading to financially viable market opportunities for fuel cells. They should take on more importance as an element of sustainable energy for the UK." **Fuel cell user**

"We need to know all the facts [and] set that alongside the importance of scaling down fossil generation. We owe this to the future generation but [first] need to prove that the technology works." **Potential fuel cell user**

"In reality fuel cells will never totally replace the current energy production and supply systems that we have in the UK but they will increasingly be able to represent an important aspect of a cleaner, greener energy system. Greater investment in the design and research of new and renewable energy is certainly required." **Fuel cell manufacturer**

"I would like to see progress towards a hydrogen economy in an ideal future. This would present opportunities for fuel cells in all their different forms and application possibilities. Waste is a source of hydrogen that should be utilised and the process of pyrolysis requires further research and development." **Fuel cell membership organisation representative**

5.5 Conclusions

The stakeholder interviews discussed in this chapter have helped to clarify the barriers to and opportunities for the development of fuel cell technology in the UK. The interviews revealed the opinions and ideas of individuals who have an on-going interest in the development and application of fuel cell technology. Their responses indicate that both at a technical and non-technical level there is still a long way to go before fuel cells will become an established, mainstream technology. The participants recognise the need to extend the knowledge base for fuel cell technologies, to improve their efficiencies, reliability, lifetime and material performances. However the research found there are also a significant number of non-technical aspects that need to be addressed.

Three main conclusions can be drawn from this research. Firstly, the overall impression from the participants was that stationary fuel cells offer a significant way forward towards sustainable energy. However, although fuel cells can provide environmental benefits associated with reduced local pollution and quiet operation there remains a question mark over the carbon implications. In addition, there are several issues surrounding the sustainable production and storage of hydrogen and the development of a hydrogen infrastructure. It is important to recognise that the environmental implications of this technology vary significantly depending on the source of fuel used to power them (e.g. natural gas) and their application. Fuel cells cannot be considered in isolation, a lifecycle approach is needed.

Secondly, it was widely felt that the Government has not shown sufficient support for fuel cells to date and that further backing – both in terms of legislative reform and financial assistance – will be necessary to enable fuel cells to reach commercialisation and to establish a sustainable market position for them. Although some moves have been made towards encouraging the fuel cell industry most participants did not consider the government was truly convinced by the hydrogen economy or fuel cells in particular. If stationary fuel cells are to be taken seriously a significant change of attitude will be required within the government combined with proactive action. Hopefully reforms within the new electricity trading regulations called BETTA (British Electricity Trading and Transmission Arrangements) will address some of the regulatory barriers identified by participants in this research.

Thirdly, the lack of demonstration models in the UK is seen as extremely detrimental to their development. Currently the only example of fuel cell CHP in the UK is at Woking Borough Council, although others are planned in the Tees Valley. More working demonstrations would not only display the government's commitment to seriously considering fuel cells but would also provide a test bed for independent monitoring and evaluation of their environmental and social impacts. Financial support for the integration of fuel cell CHP into new housing developments would provide an ideal opportunity, particularly if they are combined with other integrated forms of renewable energy. The project would need to be independently monitored and evaluated and the results publicised widely.

In terms of the future, most participants envisage a place for fuel cells as part of sustainable energy strategy. Although none could see fuel cells as being a panacea for a perfect, zero emissions energy future, there was a general feeling that important advances can be made if they could be coupled with other technologies including renewable energy and combined heat and power.

6. SYSTEM MODELLING

6.1 Introduction

The specific objective in this project was to evaluate the economic and environmental benefits of using CHP on potential sites within a typical urban environment. This requires a software tool capable of simulating the heating and power requirements for groups of various building types in a target application, simulating conventional and fuel cell CHP system operation, and analysing the fuel usage and associated emissions.

The original project work plan included development of custom software tools, however it was soon realised that this might duplicate existing conventional CHP analysis tools. The availability and features of software tools were reviewed. It was found that no single tool satisfied all requirements. Two tools (CHP Sizer, and BCHP screening tool) were selected and procured, and further custom software required to complete the analysis was written.

This chapter describes the software modelling requirements of this project, the features of the selected software tools, and the way they were used.

6.2 Requirements of the computer model

The overall aim of modelling is to calculate fuel used, power imported or exported, emissions, and economics for groups of buildings of mixed types, such as residential, schools, offices, etc, when energy is supplied by a CHP system. The overall process is illustrated in Fig 6.1, which includes inputs for building definition, occupancy and usage patterns, meteorological conditions, measured annual or detailed profile data for heat and power; and CHP system definition. The outputs include fuel used, economics, and emissions data.

There are basically two ways of producing the heat and power profiles:

a) Measurement at required time intervals over the course of one year;

b) Modelling, based on a complete building definition, together with meteorological and building usage conditions. Meteorological data can consist of information for a typical year or a specific year, and can be detailed (e.g. Typical Meteorological Year, TMY2, data) or reduced (e.g. degree day data).

Generation of heat and power profiles based on building energy modelling tend to be rather complex, and depend strongly on assumed usage patterns. The electrical load is based on a usage pattern of installed appliances and lighting, and the heating demand is based on the building parameters, the desired temperature profile, occupancy pattern, incidental gains, and the heating control system. Estimated heat and power profiles may suffer from inaccuracies due to lack of information about the building parameters or usage. However the main advantage of these analytical approaches is that they allow analysis of the effect of energy saving measures and change of usage patterns. The full modelling approach can be complex, and various intermediate methods including both modelling and measurement are possible. The most obvious and useful method involves measurement of the annual energy consumption, and then estimating the energy profiles of target buildings based on meteorological data, or on the measured profiles of similar buildings.

Several building simulation programmes have been used in Tyndall projects, for example BREDEM (Anderson, 2001) has been used in Tyndall Project T2.23 ‘The 40% House’ project, while The Martin Centre, Cambridge used a combination of modelling approaches, including the use of a thermal resistance model developed at the Martin Centre, in Tyndall project IT1.33 'Microgrids: distributed on-site generation'.

The next step is to simulate the performance of the CHP system. CHP definition includes the type (e.g. reciprocating engine, fuel cell, etc), the control strategy (e.g. electric led with heat rejection; or heat led without heat rejection), and the efficiencies of the CHP system and other heating boiler. Tariffs for delivered fuel and power are required for investigation of the economics.

The principle outputs can be grouped under operational data, economic data, and environmental data. Operational data includes hours run, heat utilisation, displaced electricity, heat supplied, fuel used, electrical, heat, and total efficiencies. Economic data includes capital cost, electricity savings, additional fuel cost, maintenance cost, net savings, and payback. Environmental data includes primary energy savings, carbon emission savings, and emission of other pollutants.

Generally CHP systems are best suited to applications where there are steady heat and power demands through the year, which would permit the CHP system to operate for long periods supplying base load heat and power. The list of suitable applications includes swimming pools, leisure centres, and hotels, as well as some continuously operating process industries. CHP can also be used in community heating systems or for a group of mixed use buildings as well as for individual buildings. The composite demand profiles for a community heating CHP system can be produced by combining simulated or measured profiles for each building type according to existing geographical or proposed optimum groupings.

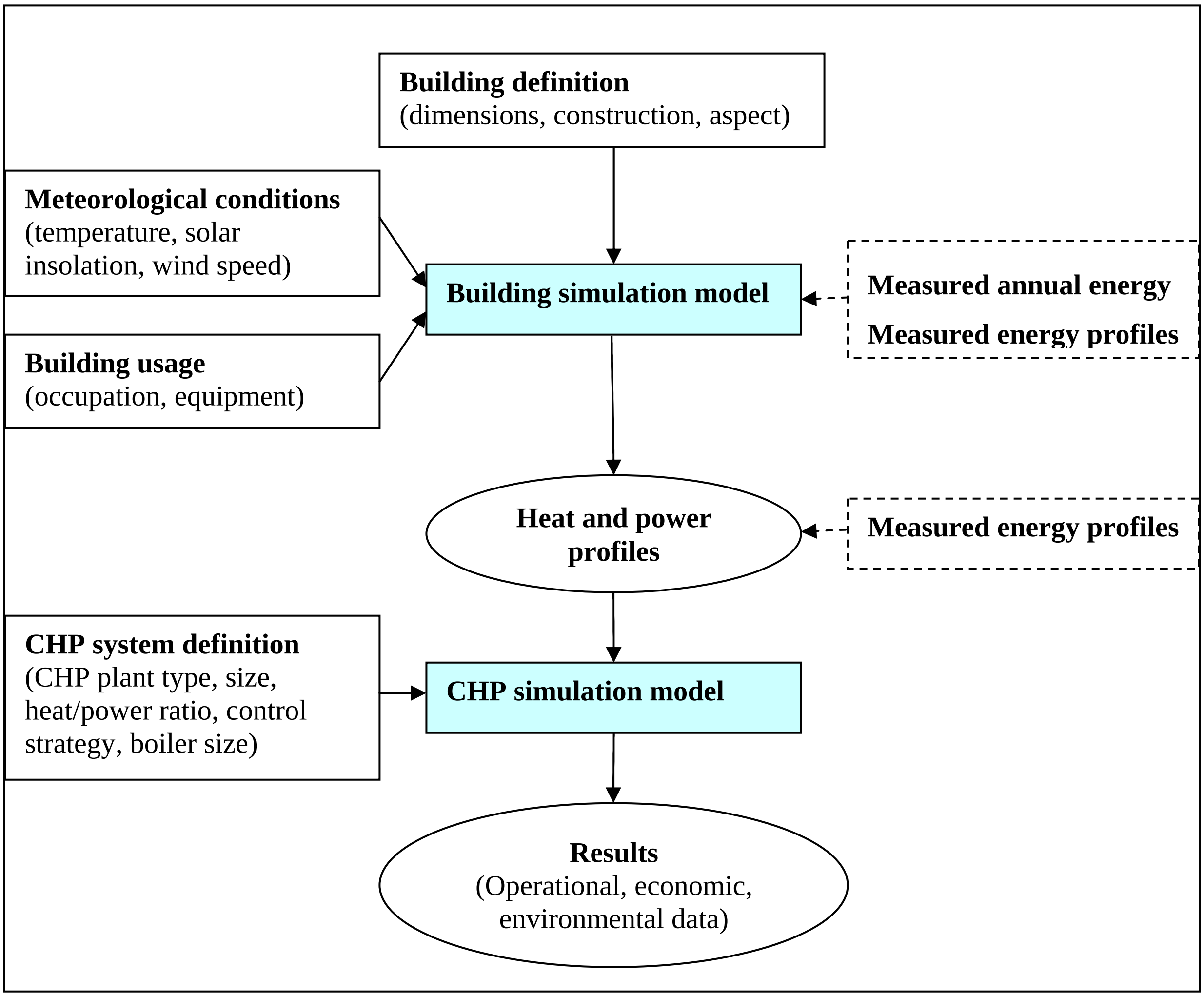


Fig. 6.1. Block diagram of the modelling process

6.3 Review of available software tools

Rather than conduct full building simulations, the project obtained existing typical heat and power profiles, and use these to produce profiles of various building types according to annual energy demands. The process of estimating profiles using annual energy demand data is described in more detail later.

Several CHP analysis tools have become available in recent years. Therefore the availability and features of available tools were reviewed. Published surveys of CHP software have been consulted, including that by Oak Ridge National Laboratory, USA (Hudson, 2003). The surveyed software includes the US Department of Energy (US DOE) Building CHP (BCHP) Screening Tool, which uses the powerful DOE-2 building energy simulation engine, and is able to evaluate CHP in commercial buildings by energy and cost impacts. Although the associated data bases are for the USA and are embedded in the code, it was clear that the software would be useful for this study, and after some negotiation Version 1.2 was made available by Oak Ridge National Laboratory free of charge. There are also numerous spreadsheet tools available (e.g. US DOD Fuel Cell Evaluation worksheet, US DOD CHP Application documents and publications), which are relatively simple, and are intended to give a rapid economic analysis.

In the UK, software for the analysis of CHP on potential sites has been developed by Action Energy and is available from the Carbon Trust (CHP Sizer Version 2).

Of the available tools, two were considered to be most applicable to the project:

a) **CHP Sizer tool**, provided by Action Energy (originally developed by the Energy Efficiency Best Practice Programme);

b) **BCHP Screening tool** - developed by Oak Ridge National Laboratory, for US DOE. We were privileged to receive permission to use the software in Feb 2004, which was only granted after making the ORNL Export Control Manager aware of our non-commercial intended use, and his subsequent consideration of the export restrictions of the various agencies.

Both tools are intended as 'screening tools' for specific target sites. They are not intended to be used as detailed design tools, and successful assessment of candidate systems should be followed by a full design appraisal before committing to an implementation. Nevertheless it seems likely that the results obtained from using the models will be highly relevant for making comparisons.

6.4 CHP Sizer software tool

This tool is based on research conducted at Cardiff University, and a complete description of the background to the model is available in academic papers by Williams et al (1996, 1997, 1998, and 1999). The tool includes a model which predicts heat and load profiles for buildings with defined parameters using a database of monitored heat and power profile data from typical existing buildings. The database in the initial version 1.2 (June 2000) of the software covered UK hospitals and hotels, using actual energy profile data collected from buildings in the UK. Version 2 was issued in February 2004 and extends application to leisure centres and residences for university students, and four application types are provided, where energy profiles for new building or existing buildings are generated from annual average demand, using degree day information, and typical profiles in the database. The tool also allows entering heat and power profiles for other scenarios (e.g. housing), using data measured on an existing application or obtained by simulation of a new application, and this mode of operation was used. Output data is provided as annual totals, but time-series data is not provided.

The flexible nature of the CHP sizing software means that it is may be used by environmental consultants, consulting engineers, facilities managers (who may wish to initially explore the possibilities of CHP for a range of buildings), and CHP suppliers (who may wish to provide verification of their own sizing techniques to potential clients). The software enables the user to undertake a preliminary evaluation of CHP for a building, and favourable results would indicate that a detailed feasibility study should be conducted. However the tool does have limitations and it is not intended to be a definitive sizing tool or to be used for non-standard systems.

The software contains a database of reciprocating engine CHP systems from 50kWe to 1.5MWe. This database has been derived from manufacturer's actual data. For each plant size, the following core data is stored: electrical output, heat output, fuel input, capital cost, and maintenance cost. In addition, information is also stored on performance under modulation. A user’s own data may be added to the database.

Additional results are provided for displaced boiler replacement cost, Climate Change Levy (CCL) electricity & fuel cost savings, and total electricity & fuel cost savings. The tool is used in five consecutive steps:

Step 1: Entering building parameters, or heat and power profiles

Three starting points are possible, parameters may be entered for a new building, parameters may be entered for an existing building, or heat and power profiles may be entered directly:

- For a new building, basic parameters are entered for the building type (hospitals, hotel, leisure centre, student residences), size, and location. The model estimates heat and power profiles using the entered data, and databases of typical energy profile data, and degree day information;

- For an existing building, the average energy demands for electrical power and heating (space heating and hot water), and location are entered. For existing and new buildings, the model estimates heat and power profiles using the entered data, and databases of typical energy profile data, and degree day information;

- Alternatively, available heat and power profiles can be entered for any building type in the form of half-hourly electricity demand for 1 year, and average heat demand in 3 bands (00:00-07:00; 07:00-17:00; 17:00-24:00) for a typical day in each month. In this case the heat and power profiles are not predicted by the model, and the model is applicable to any application type.

Step 2: Examination of building heat and power demands

The heat and power profiles for an average day in each month can be viewed graphically as shown in Fig 6.2, and can be copied to another spreadsheet if required.

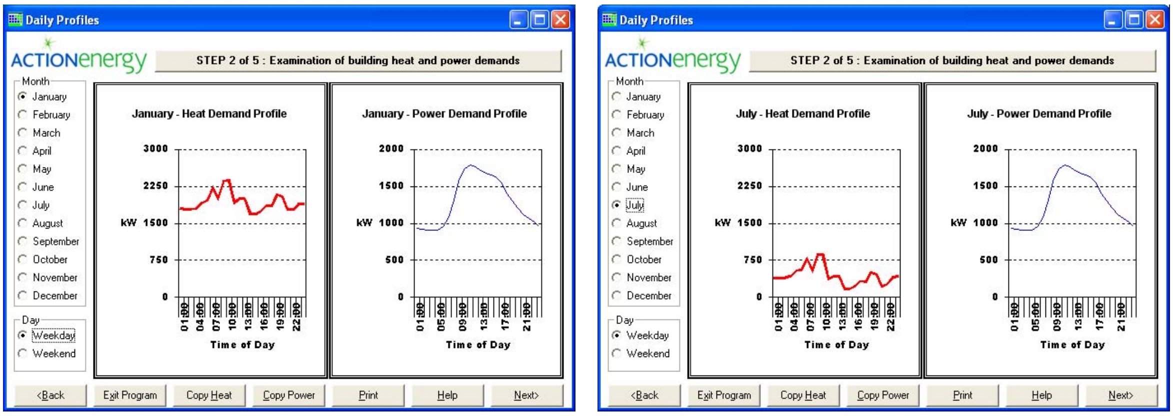
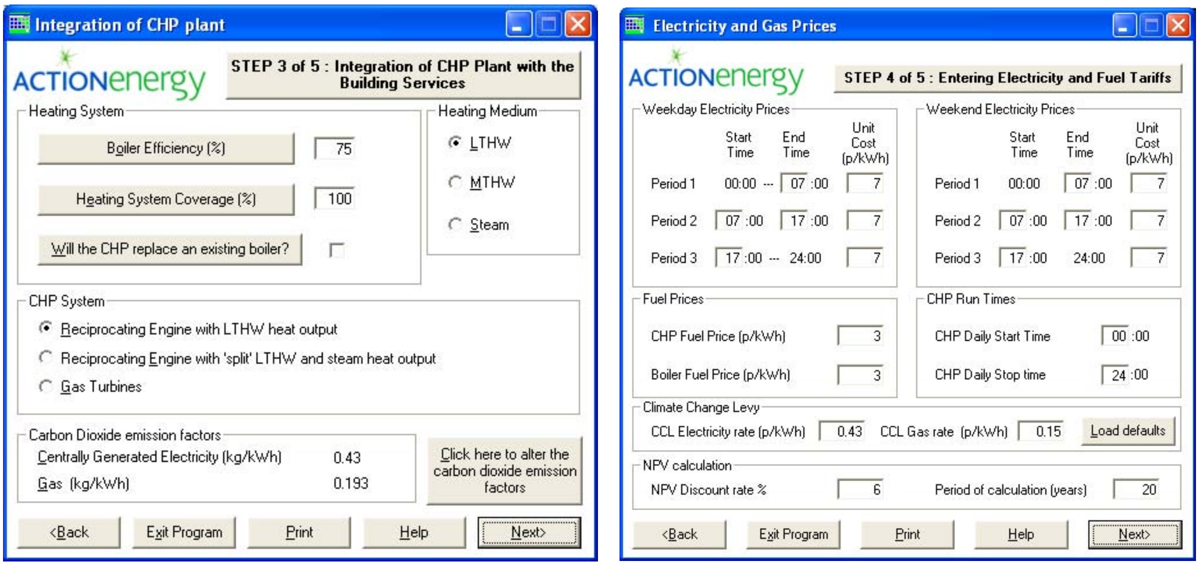


Fig 6.2. Examination of heat and power demands

Step 3: Integration of CHP Plant with the Building services

Basic information about the CHP system type and the heating system is entered, including the boiler efficiency and heating system coverage, as shown in Fig 6.3(a).



Heating System
Boiler Efficiency (%) 75
Heating System Coverage (%) 100
Will the CHP replace an existing boiler? ☐

Heating Medium
● LTHW
○ MTHW
○ Steam

CHP System
● Reciprocating Engine with LTHW heat output
○ Reciprocating Engine with 'split' LTHW and steam heat output
○ Gas Turbines

Carbon Dioxide emission factors
Centrally Generated Electricity (kg/kWh) 0.43
Gas (kg/kWh) 0.193

Weekday Electricity Prices

	Start Time	End Time	Unit Cost (p/kWh)
Period 1	00:00	07 :00	7
Period 2	07 :00	17 :00	7
Period 3	17 :00	24:00	7

Weekend Electricity Prices

	Start Time	End Time	Unit Cost (p/kWh)
Period 1	00:00	07 :00	7
Period 2	07 :00	17 :00	7
Period 3	17 :00	24:00	7

Fuel Prices
CHP Fuel Price (p/kWh) 3
Boiler Fuel Price (p/kWh) 3

CHP Run Times
CHP Daily Start Time 00 :00
CHP Daily Stop time 24 :00

Climate Change Levy
CCL Electricity rate (p/kWh) 0.43
CCL Gas rate (p/kWh) 0.15

NPV calculation
NPV Discount rate % 6
Period of calculation (years) 20

Fig 6.3. a) Integration of CHP plant b) Electricity and fuel tariffs

Step 4: Electricity and Fuel Tariffs

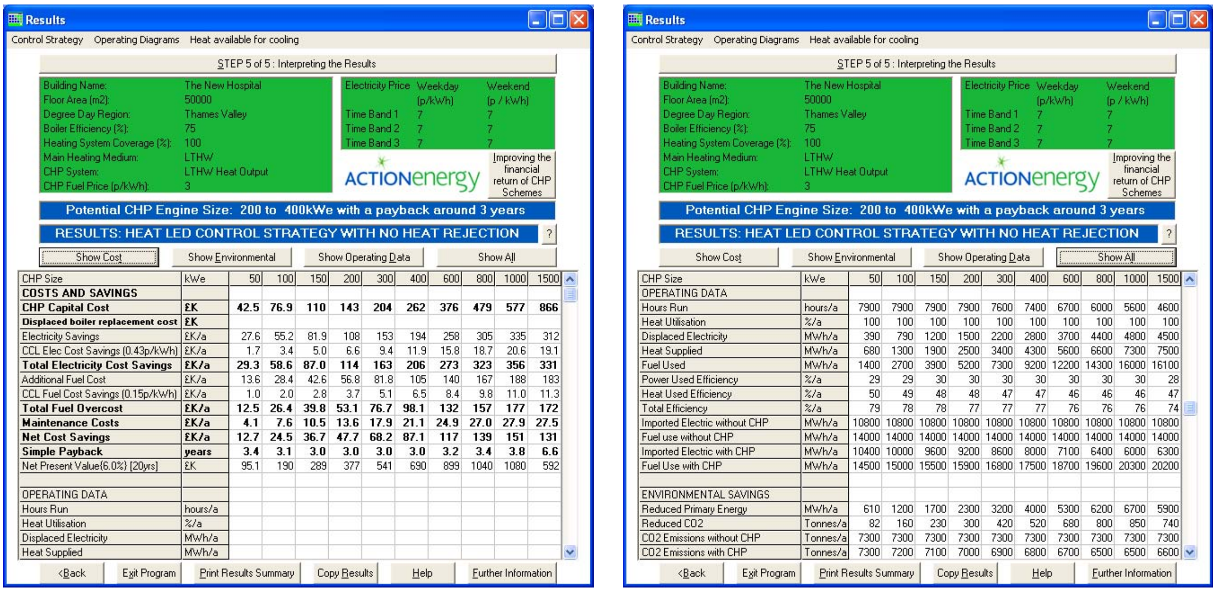
The cost of energy is entered, including electricity, gas and boiler fuel prices, as shown in Fig 6.3(b). This allows the impact of the Climate Change Levy (CCL) to be included, where the fuel cost for good-quality CHP is not subject to the levy, while the boiler fuel cost is subject to the levy. Complicated tariffs may be entered if required.

Step 5: Interpreting the results

The results produced include economic data, operating savings, and environmental data, and can be presented for either heat led or electric led control strategies. Information is provided for a range of CHP sizes, and a range of sizes with best payback is indicated, as shown in Fig 6.4 :

- Economic information includes capital cost, electricity savings, fuel cost, maintenance cost, and payback;
- Operational data includes hours run, heat utilisation, displaced electricity, heat supplied, fuel used, and electrical, heat and total efficiencies;
- Environmental information includes primary energy savings, and CO_2 emissions savings.

Operating diagrams for each control strategy can be viewed for a typical day in each month, and for a selected CHP size, as shown in Fig 6.5. In the case of electric led control, excess heat may be available and must either be dumped, or can be utilised for absorption cooling, as shown in Fig 6.6.



Building Name: The New Hospital
Floor Area (m2): 50000
Degree Day Region: Thames Valley
Boiler Efficiency (%): 75
Heating System Coverage (%): 100
Main Heating Medium: LTHW
CHP System: LTHW Heat Output
CHP Fuel Price (p/kWh): 3

Electricity Price	Weekday (p/kWh)	Weekend (p / kWh)
Time Band 1	7	7
Time Band 2	7	7
Time Band 3	7	7

Potential CHP Engine Size: 200 to 400kWe with a payback around 3 years

RESULTS: HEAT LED CONTROL STRATEGY WITH NO HEAT REJECTION

CHP Size	kWe	50	100	150	200	300	400	600	800	1000	1500
COSTS AND SAVINGS											
CHP Capital Cost	**£K**	**42.5**	**76.9**	**110**	**143**	**204**	**262**	**376**	**479**	**577**	**866**
Displaced boiler replacement cost	**£K**										
Electricity Savings	£K/a	27.6	55.2	81.9	108	153	194	258	305	335	312
CCL Elec Cost Savings (0.43p/kWh)	£K/a	1.7	3.4	5.0	6.6	9.4	11.9	15.8	18.7	20.6	19.1
Total Electricity Cost Savings	**£K/a**	**29.3**	**58.6**	**87.0**	**114**	**163**	**206**	**273**	**323**	**356**	**331**
Additional Fuel Cost	£K/a	13.6	28.4	42.6	56.8	81.8	105	140	167	188	183
CCL Fuel Cost Savings (0.15p/kWh)	£K/a	1.0	2.0	2.8	3.7	5.1	6.5	8.4	9.8	11.0	11.3
Total Fuel Overcost	**£K/a**	**12.5**	**26.4**	**39.8**	**53.1**	**76.7**	**98.1**	**132**	**157**	**177**	**172**
Maintenance Costs	**£K/a**	**4.1**	**7.6**	**10.5**	**13.6**	**17.9**	**21.1**	**24.9**	**27.0**	**27.9**	**27.5**
Net Cost Savings	**£K/a**	**12.7**	**24.5**	**36.7**	**47.7**	**68.2**	**87.1**	**117**	**139**	**151**	**131**
Simple Payback	**years**	**3.4**	**3.1**	**3.0**	**3.0**	**3.0**	**3.0**	**3.2**	**3.4**	**3.8**	**6.6**
Net Present Value(6.0%) [20yrs]	£K	95.1	190	289	377	541	690	899	1040	1080	592
OPERATING DATA											
Hours Run	hours/a										
Heat Utilisation	%/a										
Displaced Electricity	MWh/a										
Heat Supplied	MWh/a										

Building Name: The New Hospital
Floor Area (m2): 50000
Degree Day Region: Thames Valley
Boiler Efficiency (%): 75
Heating System Coverage (%): 100
Main Heating Medium: LTHW
CHP System: LTHW Heat Output
CHP Fuel Price (p/kWh): 3

Electricity Price	Weekday (p/kWh)	Weekend (p / kWh)
Time Band 1	7	7
Time Band 2	7	7
Time Band 3	7	7

Potential CHP Engine Size: 200 to 400kWe with a payback around 3 years

RESULTS: HEAT LED CONTROL STRATEGY WITH NO HEAT REJECTION

CHP Size	kWe	50	100	150	200	300	400	600	800	1000	1500
OPERATING DATA											
Hours Run	hours/a	7900	7900	7900	7900	7600	7400	6700	6000	5600	4600
Heat Utilisation	%/a	100	100	100	100	100	100	100	100	100	100
Displaced Electricity	MWh/a	390	790	1200	1500	2200	2800	3700	4400	4800	4500
Heat Supplied	MWh/a	680	1300	1900	2500	3400	4300	5600	6600	7300	7500
Fuel Used	MWh/a	1400	2700	3900	5200	7300	9200	12200	14300	16000	16100
Power Used Efficiency	%/a	29	29	30	30	30	30	30	30	30	28
Heat Used Efficiency	%/a	50	49	48	48	47	47	46	46	46	47
Total Efficiency	%/a	79	78	78	77	77	77	76	76	76	74
Imported Electric without CHP	MWh/a	10800	10800	10800	10800	10800	10800	10800	10800	10800	10800
Fuel use without CHP	MWh/a	14000	14000	14000	14000	14000	14000	14000	14000	14000	14000
Imported Electric with CHP	MWh/a	10400	10000	9600	9200	8600	8000	7100	6400	6000	6300
Fuel Use with CHP	MWh/a	14500	15000	15500	15900	16800	17500	18700	19600	20300	20200
ENVIRONMENTAL SAVINGS											
Reduced Primary Energy	MWh/a	610	1200	1700	2300	3200	4000	5300	6200	6700	5900
Reduced CO2	Tonnes/a	82	160	230	300	420	520	680	800	850	740
CO2 Emissions without CHP	Tonnes/a	7300	7300	7300	7300	7300	7300	7300	7300	7300	7300
CO2 Emissions with CHP	Tonnes/a	7300	7200	7100	7000	6900	6800	6700	6500	6500	6600

Fig 6.4. Economic, operational, and environmental results

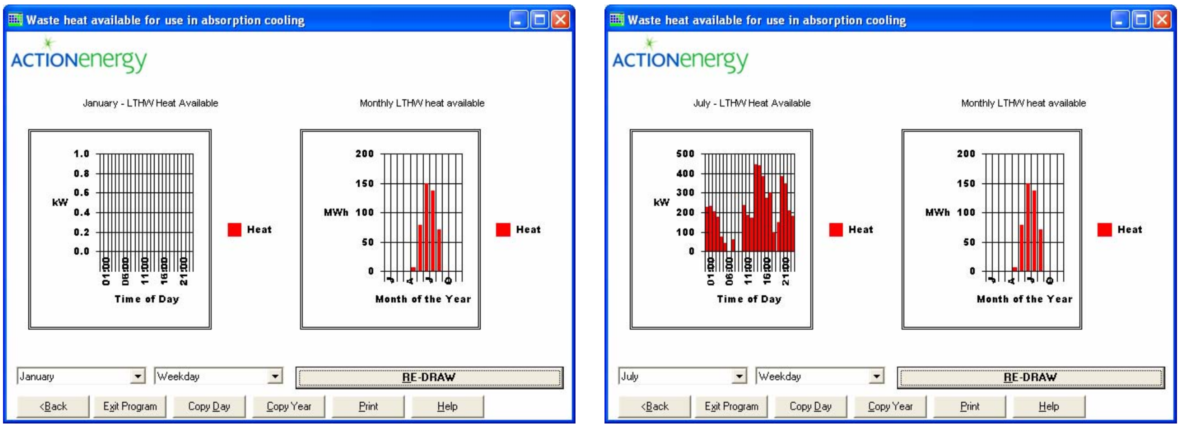


Fig 6.5. Heat dumped or available for absorption cooling (CHP 400kWe, electric led control strategy)

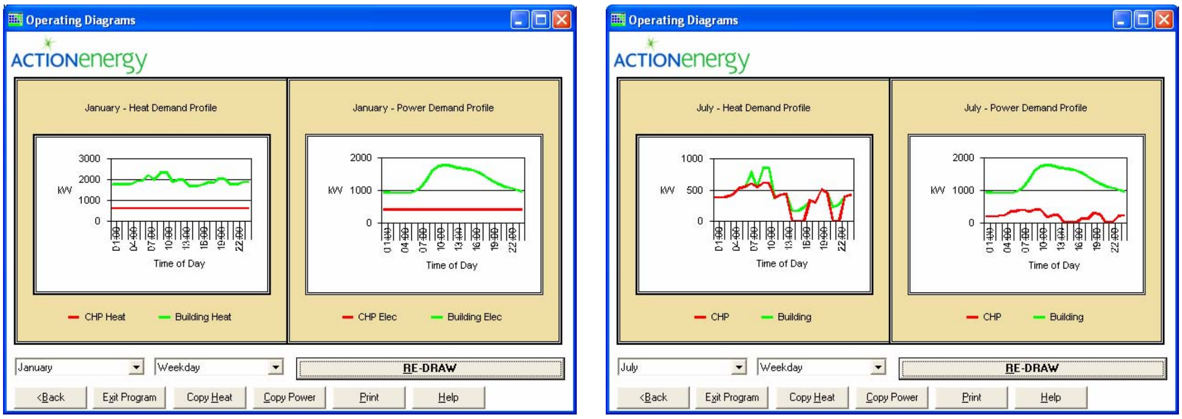


Fig 6.6. Operating diagrams (CHP size 400kWe, heat led control strategy)

6.5 BCHP Screening tool

The intended end-use of the BCHP Screening Tool is to evaluate whether or not a CHP system in a commercial building on a particular site in the USA is likely to be economically viable. Development of this tool clearly represents a large investment by US DOE. It is built upon the DOE 2.1e building loads calculation program for estimating building energy use for heating, cooling, lighting, and other electrical loads. The user has to specific building parameters, equipment, and the geographical location in the USA.

This tool includes cost and performance databases for a variety of components in CHP systems. It includes data libraries for generation equipment (including IC-engine driven generators, gas turbines, micro-turbines, and fuel cells), HVAC equipment, utility rates, and weather. It can be used for 14 building types; hospital, hotel (large and small), office building (high- and low-rise), school, nursing home, supermarket, restaurant (full service and quick-service), retail store, refrigerated warehouse, theatre, and ice-skating arena. Applications for hot (or chilled) water and space heating are included. The user selects meteorological data appropriate for the target system from a database for 239 sites in the USA.

The BCHP tool enables simulation of CHP systems in desired scenarios, and presents results of fuel used, emissions, etc. as required by the project. The attractive features are the databases, the derivation of hourly heat and power demand profiles using the DOE-2 simulation program, the simulation of CHP system operation (including control options), and the presentation of results for fuel used, emissions, and economics. The main features are:

- A building simulation programme is included, and heat and electricity profiles are generated from specified building types and Typical Meteorological Year (TMY2) weather information;
- A range of building types and weather data can be selected from the database of locations in the USA. The typical meteorological year (TMY2) database for the 239 sites is embedded in the code;
- The database includes an extensive range of CHP generator types (including fuel cells in Version 1.2);
- A wide range of parameters are produced by the simulation. Heat and power time-series profiles can be saved. However there is no facility provided to enter user-defined profiles.

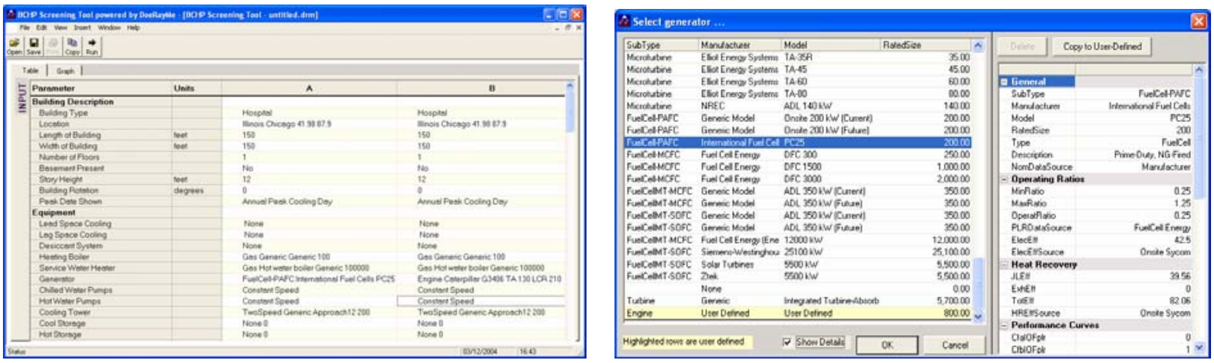
The BCHP tool allows investigation of a range of building types (creates heat & power profiles), application types (from district heating to industrial CHP), and using a range of CHP systems (including fuel cell). The BCHP tool is capable of simulating a wide range of complex systems. A detailed manual is provided with the software, however basic operation is simple:

Step 1: Selection of building and system parameters

When the BCHP screening tool is first started, the Table tab in the main screen should be selected. This offers a table in 3 main sections; Input, Result, and Help. The Input section contains parameters allowing the user to specify the building description (dimensions and location), the CHP and HVAC (Heating, Ventilating, And Air-conditioning) equipment and control strategies, the building constructional details, and building usage (equipment, occupation, zones), as shown in Fig 6.7(a). The Help area shows information about each row in the Input and Result areas when the row is selected. Some input lines contain pull-down lists of choices, for example data from the in-built database may be selected in the case of ‘building type’, ‘location’, and ‘generator type’, etc. The selection of generator type is shown in Fig 6.7(b). Several columns of data can be included, for example the first column can be the baseline or standard building and system design, while further columns can be used for alternative designs incorporating CHP or other options.

Step 2: Interpreting the results

The results of the simulation can be viewed in the Results section, including annual electricity and gas consumption, generation details, etc. A useful feature is that the hourly simulation results for an entire year for heating, cooling, and electrical loads can be saved. Selecting the Graph tab allows the presentation of data graphically, as shown in Fig 6.8. Displays include monthly, annual, and averaged 24 hours graphs for electricity and gas usage.



Parameter	Units	A	B
Building Description			
Building Type		Hospital	Hospital
Location		Illinois Chicago 41.98 87.9	Illinois Chicago 41.98 87.9
Length of Building	feet	150	150
Width of Building	feet	150	150
Number of Floors		1	1
Basement Present		No	No
Story Height	feet	12	12
Building Rotation	degrees	0	0
Peak Date Shown		Annual Peak Cooling Day	Annual Peak Cooling Day
Equipment			
Lead Space Cooling		None	None
Lag Space Cooling		None	None
Desiccant System		None	None
Heating Boiler		Gas Generic Generic 100	Gas Generic Generic 100
Service Water Heater		Gas Hot water boiler Generic 100000	Gas Hot water boiler Generic 100000
Generator		FuelCell-PAFC International Fuel Cells PC25	Engine Caterpillar G3406 TA 130 LCR 210
Chilled Water Pumps		Constant Speed	Constant Speed
Hot Water Pumps		Constant Speed	Constant Speed
Cooling Tower		TwoSpeed Generic Approach12 200	TwoSpeed Generic Approach12 200
Cool Storage		None 0	None 0
Hot Storage		None 0	None 0

SubType	Manufactuer	Model	RatedSize
Microturbine	Elliot Energy Systems	TA-35R	35.00
Microturbine	Elliot Energy Systems	TA-45	45.00
Microturbine	Elliot Energy Systems	TA-60	60.00
Microturbine	Elliot Energy Systems	TA-80	80.00
Microturbine	NREC	ADL 140 kW	140.00
FuelCell-PAFC	Generic Model	Onsite 200 kW (Current)	200.00
FuelCell-PAFC	Generic Model	Onsite 200 kW (Future)	200.00
FuelCell-PAFC	International Fuel Cell	PC25	200.00
FuelCell-MCFC	Fuel Cell Energy	DFC 300	250.00
FuelCell-MCFC	Fuel Cell Energy	DFC 1500	1,000.00
FuelCell-MCFC	Fuel Cell Energy	DFC 3000	2,000.00
FuelCellMT-MCFC	Generic Model	ADL 350 kW (Current)	350.00
FuelCellMT-MCFC	Generic Model	ADL 350 kW (Future)	350.00
FuelCellMT-SOFC	Generic Model	ADL 350 kW (Current)	350.00
FuelCellMT-SOFC	Generic Model	ADL 350 kW (Future)	350.00
FuelCellMT-MCFC	Fuel Cell Energy (Ene	12000 kW	12,000.00
FuelCellMT-SOFC	Siemens-Westinghou	25100 kW	25,100.00
FuelCellMT-SOFC	Solar Turbines	5500 kW	5,500.00
FuelCellMT-SOFC	Ztek	5500 kW	5,500.00
	None		0.00
Turbine	Generic	Integrated Turbine-Absorb	5,700.00
Engine	User Defined	User Defined	800.00

General	
SubType	FuelCell-PAFC
Manufacturer	International Fuel Cells
Model	PC25
RatedSize	200
Type	FuelCell
Description	Prime-Duty, NG-Fired
NomDataSource	Manufacturer
Operating Ratios	
MinRatio	0.25
MaxRatio	1.25
OperatRatio	0.25
PLRDataSource	FuelCell Energy
ElecEff	42.5
ElecEffSource	Onsite Sycom
Heat Recovery	
JLEff	39.56
ExhEff	0
TotEff	82.06
HREffSource	Onsite Sycom
Performance Curves	
CfalOFplr	0
CfblOFplr	1

Fig 6.7. a) Selection of building and system parameters b) Selection of generator type

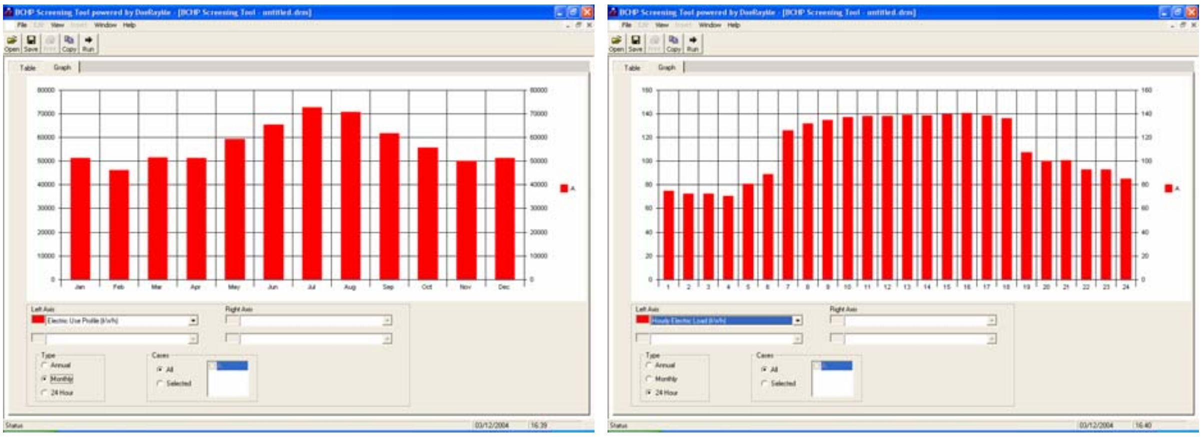


Fig 6.8. Monthly and hourly electricity use profiles

6.6 Utilisation of software tools

The availability of heat and power profile data (especially for individual domestic properties) is acknowledged as a problem. Some monitored data has been obtained in the UK by commercial organisations, but is not generally available; therefore it was necessary to simulate profiles.

The basic requirements of modelling are:

a) Simulation of heat and power profiles;

b) Simulation of operation of a specific CHP system (type/size/control) to satisfy the heat and power demand;

c) Analysis of energy, economic, and emission factors; and presentation of results

The CHP Sizer and BCHP tools have been designed to address the most important CHP applications. The simulation of heat and power profiles in the two tools is quite different; the CHP Sizer simulation is based on actual energy profile data collected from UK buildings, while the BCHP Screening Tool uses the well-established US DOE-2 building simulation tool. Neither the CHP Sizer nor the BCHP software tool on its own is ideally suited to the needs of the study, and the best aspects of each tool have been used, together with measured data, and specialised software. Basically the BCHP tool was used for simulation of heat and power profiles, which were saved and then post-processed as necessary, and the profiles were entered into the CHP Sizer program for simulation of CHP systems and presentation of results.

The analysis procedure, which used the BCHP and CHP Sizer tools, as well as customised Matlab programs, followed the following steps:

a) The total heating and electricity energy demands per annum for individual building types were estimated;

b) The heat and power profiles for individual building types were produced using the building simulation part of the DCHP software tool. A location (Seattle) with weather which is closest to the UK situation was selected from the database. Domestic buildings required special treatment (see Chapter 7 for further details). The heat and power profiles were then saved;

c) The heat profiles for each building type were post-processed for UK weather conditions using degree-day data;

d) The heat and power profiles for each building type were scaled to give the desired total energy per annum;

e) The profiles for the building types were combined into a single composite community heat and power demand. A factor was applied to account for the heat distribution loss;

f) The composite heat and power profiles were processed into time-steps as required for profile entry into the CHP Sizer tool (i.e. electricity demand profile: one year of half-hourly electricity data; heat demand profile: average heat demand in time bands on typical days in each month);

g) The composite heat and power profiles, and CHP system details, were entered into the CHP Sizer program, and the simulation program was run to obtain CHP operational results for one year.

The next chapter 7 (Chapter 7, Case Studies), contains full details of how this procedure was applied for a range of specific building types in a community development.

6.7 Conclusions

Two existing CHP software tools were selected and obtained, and effectively used to satisfy the requirements for computer modelling. The building simulation part of the BCHP screening tool was used to generate heat and power profiles, which were then post-processed to produce profiles for UK applications. These heat and power profiles were then input to the CHP Sizer program, which was used to produce results for fuel usage and associated emissions.

7. CASE STUDIES

7.1 Introduction

In evaluating performance criteria for buildings with CHP, primary energy savings result from local generation of power. Therefore comparisons of CHP and other systems providing heat and power should include analysis of primary energy and cost savings.

The economic benefit of installing CHP compared with using conventional supply is usually the driver, and is subject to the prevailing energy prices, in particular the ‘spark spread’ of electricity and gas prices, defined as the difference between the price of electricity and the price of the fuel used to generate it, in equivalent units[9]. The economic benefit of installing CHP, with a hardware cost considerably higher than using heat from a conventional boiler and electricity from the utility, also relies on an overall higher efficiency of fuel use, and the period during which the CHP system operates. A usual generalisation is that the CHP system should be sized such that it operates at full load for at least 50% of time over the whole year, with the remaining shortfall of heat and electricity demand provided by conventional boilers and the electrical utility respectively. In the case of fuel cell CHP, hardware is currently at an early stage of development and commercialisation. Therefore the costs of fuel cell systems are high compared with conventional CHP, and future price trends are difficult to predict with any degree of certainty.

Therefore the analysis is mainly concerned with identifying the benefit in terms of CO_2 reduction during operation of the plant, rather than an economic evaluation.

Detailed demand profiles, usually hourly for a period of one year, are required to permit analysis of CHP. Monitored data is generally not available for existing buildings, and this certainly presents an obstacle to analysis of the potential. Indeed it is believed that property owners do not often have time-series records better than annual consumption, and the first stage required in the assessment is a detailed monitoring exercise. While it is known that the domestic demand has been monitored for commercial purposes by companies developing and marketing domestic scale CHP, this data is not freely available. Therefore to analyse the overall potential it is necessary to rely on data from national energy statistics (for the whole installed housing stock) as well as existing studies of typical buildings using models. Notably two other Tyndall projects (IT1.33: Microgrids – distributed on-site generation; and T2.23: The 40% house) have modelled domestic heat and power demands, and useful discussions have taken place with the project investigators, who have made technical papers and results available.

The following sections first discuss the annual average delivered energy (section 7.2), and the annual average energy demand for average UK dwellings (section 7.3), then review several reports to determine the annual average demand for typical dwelling types (section 7.4). Finally a method of determining the profile of energy demand is described (section 7.5).

A case study is then described (section 7.7), and estimates for energy demand for other properties other than domestic dwellings are presented, together with simulation results for the energy demand profiles. (Note : The LCA methodology developed in Chapter 4 was also applied to this detailed case study – see section 4.7 for the detailed findings). Finally, the composite energy demand of a mixed group of properties is derived, and CHP simulation results are presented.

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[9] The spread is calculated by multiplying the price of gas by the heat rate and then subtracting the electricity price, where the heat rate is the ratio of fuel energy consumed to electricity produced (or the inverse of the electrical generation conversion efficiency).

7.2 UK historical domestic energy demand

7.2.1 Total domestic energy demand

The Digest of UK Energy Statistics (DUKES, 2004, chart 1.1.5) presents domestic energy consumption by final use, 1970 to 2001. Total domestic energy consumption has historically been rising steadily at the rate of 0.8% per annum during the period 1970 to 2003, while the fuel mix has changed significantly away from coal to natural gas, see Fig. 7.1(a). Domestic electricity consumption has risen at an average rate of 1.2% per annum during the period 1970 to 2003, and was around 21% of the total domestic energy consumption in 2003. The energy unit used in the DUKES data is Mtoe, and the data in Fig. 7.1(a) have been converted to TWh (1Mtoe = 11.63TWh) for consistency with later discussion of electricity consumption.

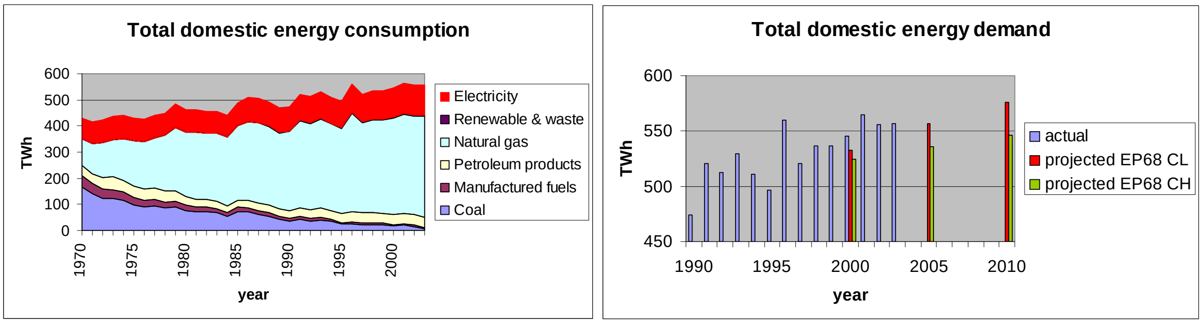


Fig. 7.1. Total domestic energy consumption in Terawatt-hour [TWh]

Fig. 7.1(a) historical 1970-2003 *(Dukes, 2004)*

Fig. 7.1(b) projected to 2010 *(Energy Paper 68, 2000)*

Energy projections for the UK to 2010 (Energy Paper 68, 2000) focussed on two core scenarios, Central GDP Growth and Low Energy Prices (CL), and Central GDP Growth and High Energy Prices (CH). Total domestic energy demand is projected to rise at around 0.8% pa (CL scenario) and around 0.4% pa (CH scenario) up to 2010.

The two scenarios refer to Central GDP Growth of 2.5% (2000-2005) and 2.25% (2006-2020), and a High or Low Energy Price of 20 US$ or 10 US$ per barrel (1999 prices) from 2005 onwards. However given the rise of the oil price to 30 US$ in 2000 and to in excess of 50 US$ per barrel in 2004, it appears that there is considerable uncertainty (and unpredictability) in predicted oil prices and resulting energy consumption. It is widely accepted that there is a close relationship between gas and oil prices. Consequently, the uncertainty in long-term oil prices will have an impact on future domestic energy demand predictions.

Energy Paper EP68 assumed that household numbers will grow by approximately 8% over the period 2000 to 2010, or approximately 0.8% pa. This growth rate is consistent with data presented in ECI Country Pictures Report (Griffin and Fawcett, 2000) which shows the number of households rising from 24.484 million in 1999, to 26.419 million in 2010, equivalent to 0.7% pa. Data in BRE Domestic energy fact file 2003, Table 6 (Shorrock, 2003), shows historic data for the number of households rising from 22.392 million in 1991 to 24.422 million in 2001, a growth rate of 0.87 % pa.

The projected growth rates (Energy Paper 68, 2000) seem to be credible in the short term when shown against actual growth data (DUKES, 2004) as shown in Fig. 7.1(b), although the actual values are higher overall.

Shorrock (2003) has derived an empirical formula to predict housing stock energy use:

$$Q = N * \left[97.81 + \left(2.12 * \left(year - 1970\right)\right) - \left(3.30 * Te\right) - \left(0.26 * DH\right) - \left(1.49 * DE\%\right)\right]$$

Where	Q	is the housing stock consumption (PJ)
	N	is the number of households (millions)
	Te	is the mean winter external temperature (degC)
	DH	is the improvement in average dwelling heat loss relative to 1970
	$DE\%$	is the improvement in average heating efficiency relative to 1970

This formula is based on underlying trends in the data from 1970 to 2001 and the predictions agree well for this period. In principle the formula could be used to predict future energy use over timescales up to 10 years, although the reliability of the estimates obtained are unknown.

7.2.2 Total domestic energy end use

A breakdown of domestic energy by end use has been estimated by Building Research Establishment (BRE) (Shorrock, 2003). The estimates have been obtained for each fuel using data from DUKES and then totalled, first making estimates for lighting and appliances, cooking, and water heating, and then assuming that space heating makes up the total. The data, also presented in Chart E11.14 of UK Energy Sector Indicators (DTI, 2004), is shown in Fig. 7.2. The estimates indicate that energy for lights and appliances (which in 1997 was around 62.7 % of electricity consumption, ECI Country Pictures, 2000) has risen considerably, while energy for water heating has remained fairly constant, and energy for cooking has dropped. Around 85% of energy is used for space or water heating, and is susceptible to weather and, in particular, external temperature conditions, and the effect of the cold winters of 1979, 1985, 1986, 1987, and 1996 can be clearly seen. Since 1970 energy use has risen by 36% for space heating, and by 12% for water heating, and by 28.3% (equivalent compound rate 0.81% pa) for heating overall. However, when put in the context of an increase in the number of households from 1970 to 2001 of 36%, energy use per household for space heating has remained fairly constant, and has fallen slightly for heating overall.

The breakdown by fuel type and end use is implicit in these estimates, and the energy for each end use is not exclusively provided by a particular fuel, for example 66.1% of gas consumption is used for space heating, while 16.3% of electricity consumption is used for space heating (ECI Country Pictures, 2000).

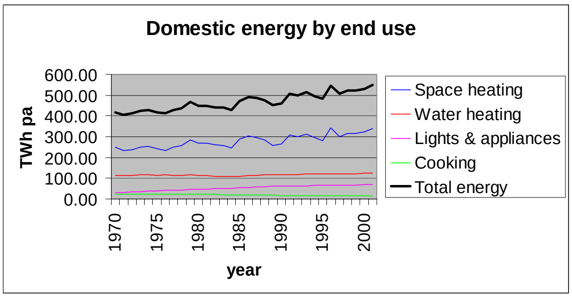


Fig. 7.2. Domestic energy by end use
[from Shorrock, 2003)]

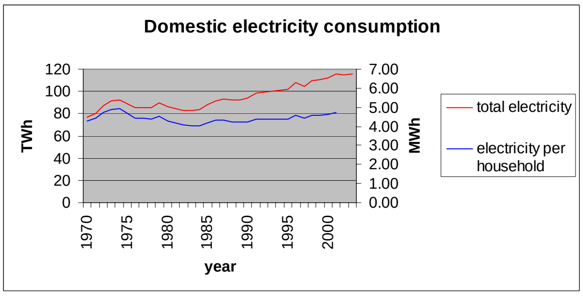


Fig. 7.3. Domestic electricity consumption
[from DUKES, 2004]

7.3 Average domestic heat and power demand per household

Although the total domestic electricity consumption has been rising steadily, see Fig. 7.3, the consumption per household has been rising more slowly, at the rate of 0.75 % pa from 1991 to 2001. The domestic electricity consumption per household of 4.72 MWh pa in 2001 is equivalent to an annual average power demand of 0.54 kW. The increased total consumption is primarily due to increased numbers of appliances, while the slower rise in consumption per household is due to improved insulation, and reduced numbers of population per household.

When considering the application of CHP to the domestic sector (individual homes, or community heating schemes), it would be useful to group the indicative end use data provided by the Domestic Energy Fact File (Shorrock, 2003) such that energy for lighting, appliances, and cooking would be supplied by electricity, and space heating and water heating would be supplied by heat from the CHP system. Analysis of data from Table 25 in the report (Shorrock, 2003) shows an annual delivered energy demand of around 19MWh/yr for heat (of which 13.90MWh is for space heating and 5.10MWh is for water heating, in proportions 73% and 27%) and 3.5MWh/yr (end-use: lights, appliances, cooking) for the current housing stock, as shown in Fig. 7.4(a).

It is interesting to note that while heat and electricity demands in total and per person (Fig. 7.4(b)) are rising, the energy consumption per household (Fig. 7.4(a)) is fairly constant at around 19 MWh pa for heat, and 3.5 MWh pa for electricity. It should be remembered that the figures for heat are in terms of delivered energy (i.e. fossil fuel delivered) therefore the actual useful heat is subject to the average space heating efficiency for central heating systems, which was 72% in 2001 (Shorrock, 2003). This indicates an average domestic heat demand of around 13.68MWh pa in 2001.

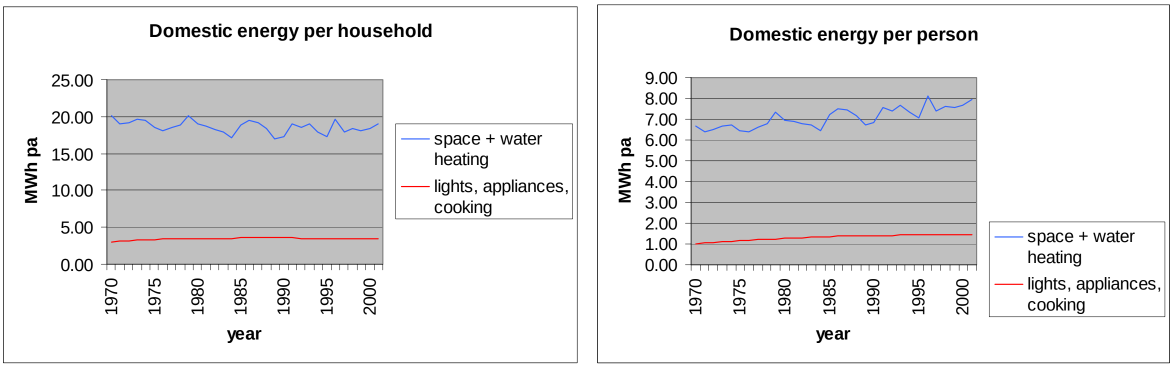


Fig. 7.4. Delivered domestic energy
Fig. 7.4(a) per household Fig. 7.4(b) per person
[derived from data in Domestic Energy Fact File, (Shorrock, 2003)]

The ECI Country Pictures Report Table 15.4 (Griffin and Fawcett, 2000; original source DTI, 1997) presents a breakdown of domestic fuel consumption (%) by fuel type and end use. Including DUKES data for the delivered energy for the fuel mix, gives a breakdown of delivered energy by mix of fuels and end use in 1997, see Fig. 7.5.

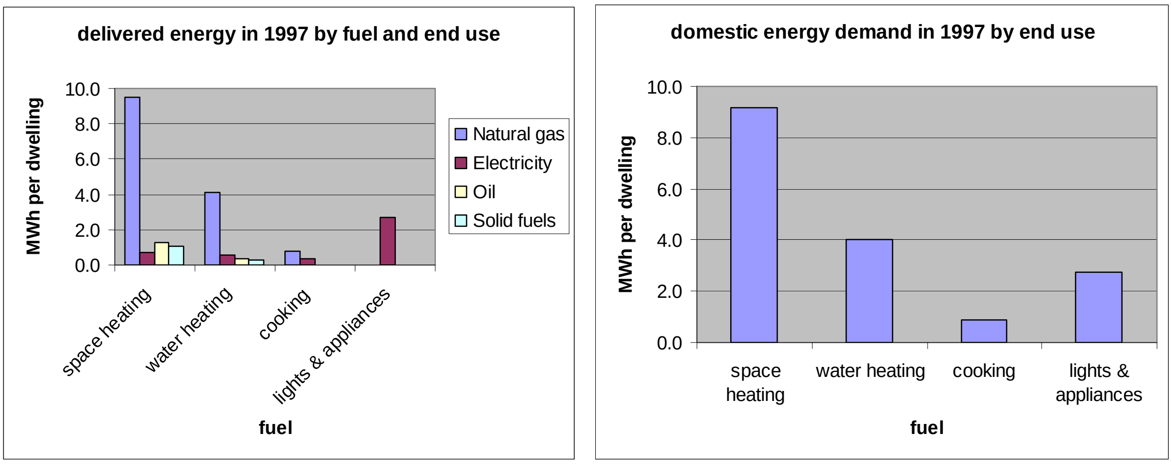


Fig. 7.5 Domestic energy in 1997
(a) delivered energy by fuel and end use (b) energy demand by end use
[derived from data in DUKES, and Country Pictures(2000), and assuming 72% boiler efficiency.]

The fuels have different efficiencies in terms of supplying useful heat, while electricity is 100% efficient at the point of use. Taking the mix of fuel types into account, and assuming an average fossil-fuel boiler efficiency of 72% (Shorrock, 2003) or 65% (Wiltshire, 2003), gives estimates of 13.2MWh or 11.9MWh respectively, for the heating demand at point of use for the current housing stock. The Country Pictures Report states that in 1997 lights and appliances accounted for 62.7%, and cooking accounted for 7.4% of domestic electricity consumption. Electricity supplied all the demand for lights and appliances, and around 50% of the demand for cooking. Assuming the same proportion of the total energy of 4.72MWh pa per household in 2001, would result in an estimate of 3.6MWh pa per household for total energy for lights and appliances and all cooking.

7.4 Domestic energy for different dwellings

Data presented in four reports for average delivered energy per annum in various dwelling types has been reviewed. Several of these reports used the BREDEM model (Anderson et al, 2001).

a) Good Practice Guide 234 presents indicative figures for the total heating demand for hot water and space heating of 22MWh/yr (detached), 17MWh/yr (semi-detached), 13MWh/yr (terraced), and 9MWh/yr, for well-insulated double-glazed homes. These figures may be assumed to be lower than for the present housing stock, and higher than for new build. This is equivalent to an average annual heating demand of 15.6MWh/yr for all house types, assuming a mix of house types as reported in the 2001 Census.

b) Webster (1999) presents typical energy consumption figures per dwelling for houses constructed to 1990 building regulations, which were produced using the BREDEM model. The data, summarised in Table 7.1, indicates an average demand of 11.8MWh/yr (heating), and 2.0 MWh/yr (electricity), assuming a fixed mix of house types (2001 census).

	4-bed detached	3-bed semi-detached	2-bed terrace	2-bed flat	Average per dwelling
Floor area [sq m]	111	86	59	49	76
Total heating [kWh pa]	18100	13600	9300	6200	11861
Total heating per area [kWh/sq m pa]	163.1	158.1	157.6	126.5	152.7
Electricity [kWh pa]	2860	2250	1580	1350	2011
Electricity per area [kWh/sq m pa]	25.8	26.2	26.8	27.6	26.5
Heat/Power ratio	6.3	6.0	5.9	4.6	5.8
% of dwelling types (2001 Census)	21%	31%	28%	20%	

Table 7.1 Typical energy consumption figures for houses constructed to 1990 building regulations *[Webster, 1999]*

c) Wiltshire (2003) produced energy performance indicators using the BREDEM model for typical dwellings with current levels of insulation. The data, summarised in Table 7.2, indicates a delivered energy demand of 18MWh (space heating and hot water), and 3MWh (electricity). The boiler efficiency assumed was 65%, giving an estimated average heating demand of 11.7MWh for space heating and hot water.

[kWh/dwelling pa]	Detached	Semi-detached	Terraced	Flats (purpose built)	Flats (converted)	Average per dwelling
Fossil fuel use, for space heating and hot water	25875	19210	16929	9086	10140	17988
space heating and hot water demand (boiler efficiency = 65%)	16819	12487	11004	5906	6591	11692
Electricity use, for lights, appliances, cooking	3910	3145	2916	1947	2340	3018
% of dwelling types (2001 Census)	21%	31%	28%	16%	4%	

Table 7.2 Energy performance indicators for typical current dwellings *[Wiltshire,2003]*

d) An Element Energy report (Element Energy, 2004) provides average data for 3-bed dwellings, for both typical existing buildings and new buildings to building regulations and incorporating energy saving measures, as shown in Table 7.3. A range of values is quoted for electricity demand, and the space heating is quoted per floor area. A further calculation for the total energy consumption for heating (water plus space heating) assumes the typical floor area 86 m^2 (Webster, 1999). Assuming boiler efficiency figures of 85% and 65% for new and existing buildings respectively, shows that the estimated heat demand for new dwellings may be reduced to around 70% of that for typical existing dwellings.

	new build: good practice	typical
Electricity [kWh]	<3000	3000-5000
space heat [kWh/sqm]	59	140
water heating [kWh]	3900	5140
total energy for heating [kWh]	8974	17180
boiler efficiency	85%	65%
heat demand [kWh]	7628	11167

Table 7.3 Average annual energy consumption for a 3-bed dwelling *[Element Energy, 2004]*, and estimated heat demand

7.4.1 Assumptions for annual heat and power demand

The heat and power figures presented in the various reports mentioned are not all in good agreement. However two reports (Webster, 1999; and Wiltshire, 2003) show a similar profile by house type, as shown in Fig. 7.6.

In the case of heating (space + hot water), the figures by Wiltshire for 18MWh pa average delivered heating energy per dwelling are in good agreement with most other estimates, including that by Shorrock (2003). Therefore these figures and profile per dwelling type were taken as the best estimate. The average heating demand per dwelling

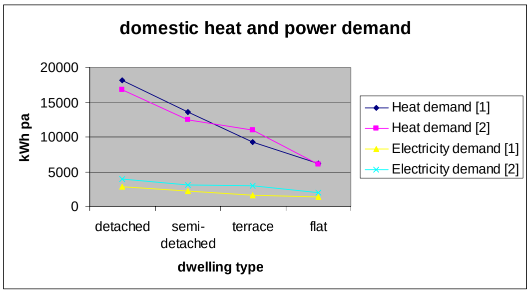


Fig. 7.6. Domestic heat and power demands for typical dwelling types
[1] *Webster (1999)*, [2] *Wiltshire (2003)*

can be calculated by applying a factor of 65% for the heating boiler efficiency for the existing housing stock, as was assumed by Wiltshire, to the delivered energy figures.

Therefore the figures assumed for the **heat demand** for the existing housing stock are 11.7 MWh total useful heating (of which 8.54 MWh is for space heating, and 3.16 MWh is for water heating, in the proportions 73% and 27% of total heating), see Table 7.4.

New dwellings built to the latest building regulations have much better insulation for floors, walls, roofs and windows, and can be expected to show very marked reduction in space heat demand, compared with existing dwellings. A reduction in heating demand of 20% has been assumed for new build, which may be pessimistic compared to the reduction of around 30% suggested by figures in the report by Element Energy (Element Energy, 2003). However it is difficult to see how hot water demand will reduce from present levels. Improvements in boiler efficiency also reduce fossil used for heating. The Sedbuk boiler efficiency database lists the seasonal efficiency of typical boilers, and old boilers may have efficiencies ranging from 55% to 65%, while new boilers may have efficiencies ranging from 78% (typical non-condensing) to 88% (typical condensing). Assuming a figure of 85% for new boilers shows that new buildings using new boilers could use around 60% of fossil fuel used by the average housing stock. This overall improvement is possible due to building insulation improvements (20% energy reduction) and boiler improvements (25% energy reduction).

[kWh pa]	housing type	Detached	Semi-detached	Terrace	Flat	Average per dwelling
Fossil fuel for heating (65% efficient)	existing	25875	19210	16929	9297	17988
Heating demand	existing	16819	12487	11004	6043	11692
Heating demand	new build (80%)	13455	9989	8803	4834	9354
Fossil fuel for heating (85% efficient)	new build	15829	11752	10357	5687	11005
Electricity demand	existing	4535	3648	3382	2349	3500
Electricity demand	new build (90%)	4081	3283	3044	2114	3150
Heat/Power ratio	existing	3.7	3.4	3.3	2.6	3.3
	new build	3.3	3.0	2.9	2.3	3.0
% of dwelling types (2001 Census)		21%	31%	28%	20%	

Table 7.4 Assumptions for annual heat and power demands for domestic buildings

In the case of **electricity demand**, it is assumed that the most accurate estimate of annual electricity demand for the existing stock, is that estimated by Shorrock (2003), i.e. average 3.5MWh pa. The profile derived by Wiltshire (2003), who estimated annual demand to be rather lower at 3MWh pa, is then used to estimate the demand for four house types. The historical electricity demand per dwelling for the whole housing stock appears to be fairly level, however new houses are likely to include the latest energy saving lights and appliances, which are all showing improved efficiencies. Demand reduction obtained through the use of more efficient appliances is offset by the trend towards increased numbers of appliances, and the possible demand reduction is under detailed investigation in the Tyndall 40% house project. The electricity demand for new build shown in Table 7.4 is assumed to be 90% of the demand for existing housing stock.

The heat power ratio varies from 2.3 to 3.7, however this is the average throughout the year and considerable deviation from these values can be expected from hour to hour. It is worth noting that the heat / power ratio is expected to reduce by 10% for new build.

No account has been taken here of the trend towards increased numbers of households, with fewer population per household, resulting in a change in the house type profile.

7.5 Domestic heat and power profiles

The previous section described how the assumed annual heat and electricity demands were derived. The next step is to obtain realistic heat and power time-series profiles for use in the CHP system analysis software.

7.5.1 Domestic electricity profiles

Half-hourly data for a one-year period from 1-April-1996 to 31-March-1997 was obtained from the load research at the Electricity Association (represented by three separate trade bodies since 30th September 2003). The data was processed into diurnal data for monthly averages to view the profiles, normalised by the annual average demand of 0.438 kW for electricity domestic end use, excluding Economy 7 heating. Fig 7.7 shows profiles for January and July.

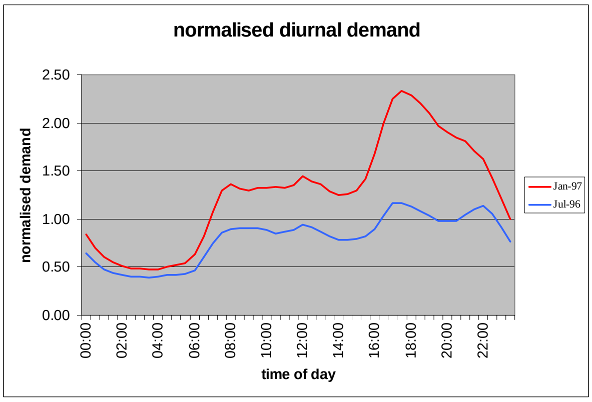


Fig. 7.7 Average diurnal electricity demand for each month of the year for domestic buildings (Electricity Association, 1996 to 1997)

This profile represents the average demand for domestic properties on unrestricted tariff, and therefore excludes electricity heating demand provided by storage heaters on Economy 7 tariff. However some space and hot water heating may be assumed to be included in the unrestricted tariff. We assume that the average domestic electricity demand for lights, appliances, and cooking, and excluding all heating, is 3.5 MWh pa (Shorrock, 2003). This is equivalent to an average power demand of 0.4 kW per household.

It may be assumed that the shape of this diurnal profile will not change substantially, however the average annual demand may change, depending on the expected growth in the number of electrical appliances. It should be remembered that this profile represents the average over all domestic properties, and is therefore smoothed by diversity. The actual profile for a single property is actually quite different, and is characterised by high peaks greatly exceeding the mean, typically caused by intermittent use of high current appliances such as cookers and electric kettles, and the regular on-off switching of water heaters and refrigerators.

7.5.2 Domestic heat demand profiles

The domestic heat demand consists of several components, for space heating, water heating and cooking. These vary greatly for individual homes according to several factors, including comfort requirements, personal perceptions of comfort, resource availability (ability or willingness to pay), as well as the specific heat loss of the building and the energy-saving improvements, see for example Agar and Newborough (1998). Two basic types of heating profile have been identified from collected demand data, viz. Type A where the residence is unoccupied for several hours per day, and Type B where some members of the household remain in the building throughout the day. Most households exhibit Type B profile during the weekend. These profiles may be regarded as average or typical, but do not indicate the wide variation between homes.

It was found that heat demand profiles, obtained by careful measurement and simulation, are presented in various technical papers, but it was not possible to obtain the actual source data. Therefore the building simulation software within the BCHP Screening Tool was used to produce heat profiles for domestic (and other buildings). As already noted, although the building simulation part of the software tool is very detailed, it was designed for USA applications, typical building specifications and weather conditions, and is not ideally suitable for UK use. Despite this, it was decided that profiles obtained using the simulation tool could be used, with post-processing to adapt to UK weather conditions, and annual heating demand.

The process of using the BCHP software to generate a heating profile can be simply described. First a location with a climate approximately matching that of the UK was chosen, for example Seattle. The BCHP building simulation was then used to produce an hourly heating (space heating and hot water) profile for 1 year. The space heating profile was then post-processed using monthly UK degree day data, and the estimated total annual demand was used to scale the annual profile. The hot water profile was then added to give the total heating profile. Typical results are shown in Fig 7.8, comparing the profile using the BCHP building simulation tool with typical assumed occupancy patterns, similar to those presented by Agar and Newborough (1998). This process was used to produce heat demand profiles for a wide variety of buildings, using the 14 building types provided within the BCHP tool. Domestic buildings required special attention; the heat profile for domestic buildings were obtained using the closest building type (small hotel).

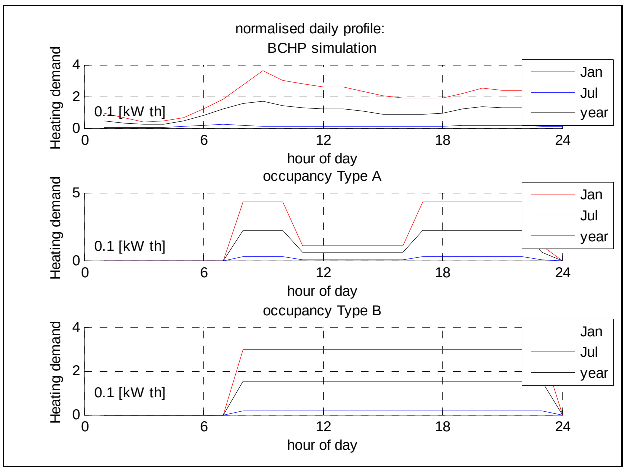


Fig. 7.8 Daily heat demand profiles, using the BCHP simulation tool, and assumed occupancy patterns Type A and Type B

7.6 Case studies

CHP is currently used in a wide range of sizes from large industrial to small individual domestic. This study targets the application for small-scale CHP (less than 1 MWe), where penetration currently rather low (3.5% of total installed CHP capacity), and operational data is rather sparse. Therefore case studies will be set up for typical defined systems, rather than actual urban areas. The base case is the use of the standard reciprocating engine (ICE), and operation will be compared with PAFC and SOFC fuel cells. System optimisation will be in terms of minimum usage of primary fuel, which is natural gas in all cases considered.

The focus of the study is community heating schemes, where a central heat generator (which may be a CHP system) is used to supply a group of dwellings or buildings.

7.6.1 Community heating

A community heating scheme consists of a central heat generator, a heat distribution network, and installations in the end-use buildings, which can include housing, community centres, shops and retail premises, and industrial premises. Even using conventional boilers, better overall efficiencies and security of supply can be achieved. However the best solutions use CHP plant, which has environmental benefits through reduced emissions, and cost savings through improved efficiency and better plant utilisation, and there is a choice of a wide variety of fuels. There are also social benefits, particularly where homes are properly heated and are taken out of fuel poverty.

Implementation of community heating schemes in the UK lags behind that in many other countries, and the proportion of the total domestic heating market is 1%, compared with Denmark (54%), Finland (50%) and Germany (12%) (Community Heating – a guide, 2004). Recognising the need for incentives, the UK government launched ‘Community Energy’ in 2001, a £50m programme awarding grants to encourage refurbishment of existing schemes and development of new ones. The programme has kick-started around £200m of total investment in the last 3 years.

Generally community heating may include CHP in new developments, CHP for refurbishment of heating systems in existing buildings, and CHP for combinations of closely located buildings. System feasibility has to be investigated on a case by case basis. Retrofit of existing buildings may be considered where the existing heating system will soon need replacing or is inefficient. Extending this to include other neighbouring buildings is less likely, however it could be useful to investigate the possibilities of combining the demand from different building types would make the overall demand profiles more closely match the output of CHP systems.

7.6.2 New community housing developments

Community heating schemes may be considered for new community housing developments, in which groupings of buildings would be designed according to usual guidelines, to include a primary school, health centre, and local shops. This pre-defines the profiles, and the challenge is to supply the heat and power demand in the lowest carbon way (usually corresponding to the lowest fossil fuel usage), and the most cost-effective way (which includes investment in plant, maintenance cost, and fuel costs).

An example of a new community housing development is described in the Vale of White Horse Local Plan, 2004. The plan designates an area of approximately 137 hectares to the west of Grove (population around 9000) and North West of Wantage, to accommodate around 2500 houses. Development will start after April 2006, and is envisaged to occur in three phases of 750, 1000, and 750 dwellings, from 2006 to 2021. The average net density of the 2500 dwellings will be 40 dwellings per hectare, and 50% of the dwellings will have 1 or 2 bedrooms. Affordable housing will be distributed across the site, and will account for 50% of the dwellings, while housing for special needs groups such as the elderly and disabled may be required but is not yet specified. Buildings should be generally two storeys, and the planning system will play a role in the location and orientation of buildings to maximise passive solar gain and light, and in the use of solar heat and photovoltaic panels.

At the heart of the development will be a local centre, with a range of services including:

- Multi-purpose community centre (at least 1400m^2);
- Indoor sports hall, which may be dual use associated with the secondary school
- Library, to serve the new community and Grove;
- Shopping facilities and retail service, limited to uses within Class A, including a small supermarket, and further small premises including at least a pharmacy, post office, café or wine bar (not less than 1000m^2 total);
- Pre-school, crèche, and day-care facilities;
- Small business premises and live-work units (commercial units linked to 1st floor dwellings), limited to uses within Class B1, such as offices and research.

There will be two primary schools, one at the centre, and one on the edge of the new development. A secondary school serving both the new community and the existing village of Grove may be included, and located on the edge of the new centre. The potential for dual use of the secondary school will be considered.

The Local Plan also describes a development to the West of Didcot, to accommodate about 3200 dwellings, together with a district centre including a range of services similar in range and proportion to those for the Grove development.

7.6.3 Analysis of Grove development

The 2001 Census showed that for the Vale of White Horse, the average household size was 2.46 persons per dwelling, and the number of children aged 0 to 15 years was 20.5% of the population. The existing statistics leads to estimates of a total population for the new Grove development of 6150, of which there would be 1260 children aged 0-15. The number of pupils attending the new schools would be approximately 150 (pre-school), 450 (primary) and 1100 (secondary, including Grove). Grove lacks many of the services and facilities that could be expected, and it may be that other services provided in the new local centre should be sized to serve both communities.

The breakdown of housing type for detached houses, semi-detached houses, terraced houses, and flats in this development is assumed to be 21%, 31%, 28% 20% respectively, the same as the entire UK housing stock as reported in the 2001 census.

The annual energy demands for domestic dwellings were estimated as described in Section 7.3.1, where the heat demand derived from modelling was used. Modern boilers are available with efficiencies in the range 80-90% and an average efficiency of 85% was used to derive the fossil fuel used for heating. The energy demands for other buildings were estimated using data from several sources for fossil fuel used, for example Energy Consumption Guides and Good Practice Guides, as detailed in Table 7.5. These figures are indicated of the fuel used with typical boiler installations. The efficiency of a typical heating boiler in leisure centres is indicated as 80% in Energy Consumption Guide 51, and this efficiency is used to derive the heat demand for all buildings (other than domestic). The total annual energy demand for the whole development as shown in Table 7.5 is around 34GWh.

	Energy consumption estimate for new community housing development at Grove											
					MWh pa per unit					**Total MWh per annum**		
Building type	floor area per person [sq m]	occupants	floor area [sq m]	number of units	Fossil fuel (heating)	boiler eff.	Heat demand	Electricity		Fossil fuel (heating)	Heat demand	Electricity
Dwellings												
Detached house (21%)				525	15.83	85%	13.46	4.08		8310	7064	2143
Semi-detached house (31%)				775	11.75	85%	9.99	3.28		9108	7741	2544
Terraced house (28%)				700	10.36	85%	8.80	3.04		7250	6162	2131
Flat (20%)				500	5.69	85%	4.83	2.11		2844	2417	1055
				2500	11.00		9.35	3.15	sub-total	27511	23384	7873
	Note 1. fossil fuel and electricity estimated from several sources											
					KWh per sq metre							
					Fossil fuel (heating)	boiler eff.	Heat demand	Electricity				
Community centre			1400	1	150	80%	120	50		210	168	70
	Note 2. 'Targets' from Energy Consumption Guide 54											
Dry sports hall			1000	1	215	80%	172	75		215	172	75
	Note 3. 'Good' figures from Energy Consumption Guide 51											
Library			200	1	150	80%	120	50		30	24	10
	Note 4. 'Target' figures from Energy Consumption Guide 54											
Shopping facilities												
supermarket			300	1	40	80%	32	900		12	10	270
café, wine bar			100	2	60	80%	48	200		12	10	40
pharmacy, post office, newsagent, etc			100	5	80	80%	64	50		40	32	25
			1000						sub-total	64	51	335
	Note 5: Estimated from Good Practice Guide 190											
Business premises			100	10	79	80%	63	33		79	63	33
(naturally ventilated offices)	Note 6: 'Good practice' from Energy Consumption Guide 19											
Schools												
Pre-school	6	150	950	1	126	80%	101	20		120	96	19
Primary school	6	225	1282	2	126	80%	101	20		323	258	51
Secondary school	9	1100	9986	1	136	80%	109	24		1358	1086	240
	Note 7: 'Good practice' from Energy Consumption Guide 73								sub-total	1801	1441	310
	Note 8. School gross building areas estimated from: Area guidelines for schools, draft BB98 & BB99 (supercede BB82) DFES, available from www.teachernet.gov.UK								Total	29910	25304	8706

Table 7.5. Energy demand estimates for new community housing development at Grove

The total annual energy demand is dominated by the demand by dwellings which is 92% of the total for the whole development, as shown in Fig. 7.9. The total delivered energy is 38.6 GWh, assuming typical boiler efficiencies. The average heat/power ratio at the point of use for the whole development is 2.9, while the heat/power ratio for the shopping facilities is particularly low at 0.2 due to the large electricity demand for refrigeration, lighting, and air-conditioning in the supermarket.

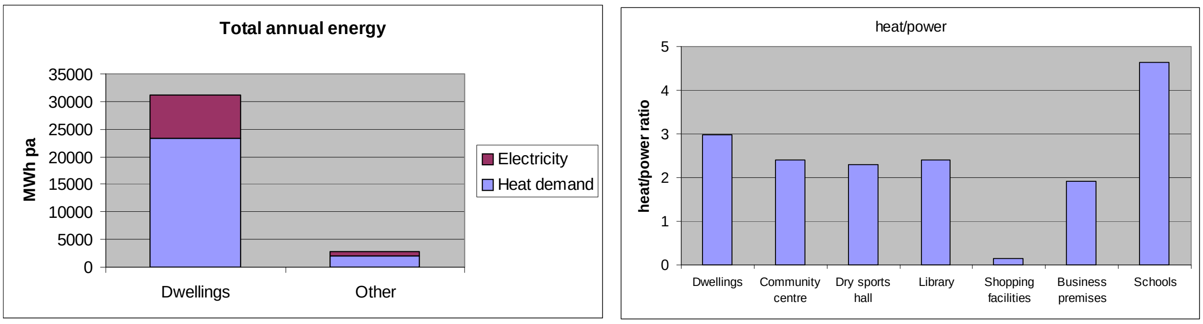


Fig. 7.9. Total annual energy demand and heat to power ratio at the point of use, for categories of buildings

The annual heat demand at the point of use is 25.3 MWh th. The heat distribution system has losses which are a function of the operating temperature, and the network design and complexity. A figure of 73% for heat distribution efficiency is quoted in the Energy Savings Trust report (IPA Energy Consulting, 2003) page 33 table 4. The EST report states this is based on published data, and a sample of Community Energy grant applications. An analysis of the heat losses in distribution systems has not been made in this project, and the efficiency figure of 73% has been assumed to be typical. Allowing for the heat distribution losses results in a heat demand at the CHP generator of 34.6 MWh. Therefore the heat/power ratio at the central CHP generator is 3.98 overall.

Community heating schemes are likely to be appropriate where the density of housing is high, for example in high-rise buildings. The density of the mainly housing development over 137 hectares (density of 18 dwellings per hectare) is relatively low, which suggests that heat losses in the dispersed distribution system may be even higher than average, and therefore two or more CHP systems strategically sited could be considered. The development would be constructed in 3 phases, and this would need to be taken into account when planning the heating system. Improved efficiency (but not necessarily improved economics) may be possible by installing two or more generators at each generation site, with scheduled operation to optimise the amount of heat and power provided by CHP, and to reduce the overall CO_2 emissions. If two systems were used, each would supply a demand at the point-of-use of 12.8 GWh th and 4.35 GWh e. The electrical demand is assumed to be provided through a distribution network with low losses.

The hourly profiles for heat and power were simulated using the tools as described in Chapter 6, and then scaled to the appropriate annual totals. In the case of domestic buildings, the published domestic profile (Electricity Association) was used, together with building simulation for the heat profile. A similar technique was used to generate hourly heat and power profiles for other buildings. The heat and power time-series for all the building types in the Grove development were then combined into a composite profile. The underlying time-series profiles are clearly complex, and an example of averaged data is shown in Fig. 7.10.

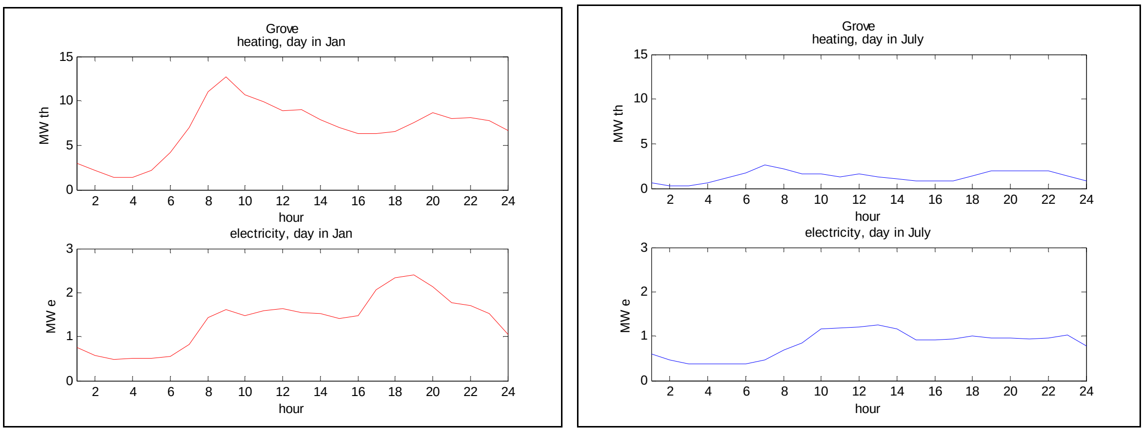


Fig. 7.10. Daily heat and power profiles for the Grove development, averaged for January and July.

Two basic control strategies are possible, heat or electricity demand led, where the choice of operating strategy is normally an economic decision.

1. Heat led without heat rejection is generally used, where the CHP unit is operated at full load where possible, and is controlled to modulate down its heat output as the heat demand drops below the CHP full load heat output. If the heat demand falls below the heat output of the engine at 50% of electrical output, the CHP system is shut down. Any shortfall of heating is provided by a conventional boiler.

2. Electricity demand led, with heat rejection. The CHP system is controlled to modulate down its output as the electrical demand of the building drops below the CHP full load electrical output. If the heat demand is below the heat output of the engine, then surplus heat is dumped.

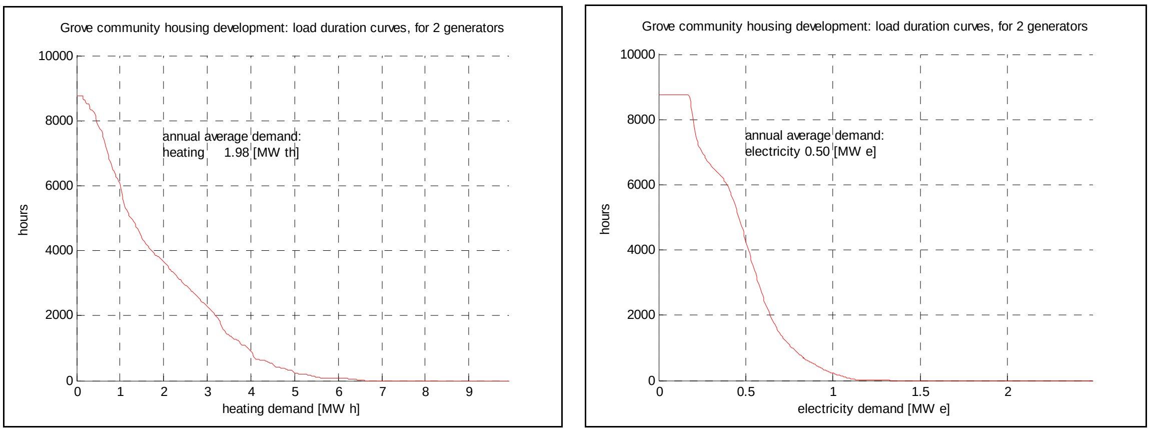


Fig. 7.11. Load duration curves for heat and power for 50% of the Grove development.

CHP systems are generally most attractive when the CHP system can operate for long periods at full load, and the heat and power loads coincide. Load duration curves, which show the cumulative time at various loads, are a useful tool to roughly assess the likely potential of various sizes of CHP system. The load duration curves for the Grove development, Fig. 7.11, show that a CHP of around 2MWt (heat power) could operate at full load for 4000 hours per year (heat led strategy), and a CHP of around 0.5MWe (electric power) could operate at full load for around 4000 hours per year (electricity led strategy). The curves also illustrate how a generator with heat/power ratio of around 4 (as previously calculated) could be useful; however this does not take into account the coincidence of the heat and power loads, which is clearly important.

Conventional CHP uses an internal combustion engine, where the overall efficiency is around 80%, and the heat/power ratio is around 1.5. In the case of the Grove development, the heat/power ratio is around 4, and therefore a considerable proportion of the heat should be provided by a conventional heating boiler. The information presented in Fig.7.12 is from the database of engine type CHP systems in the CHP Sizer database.

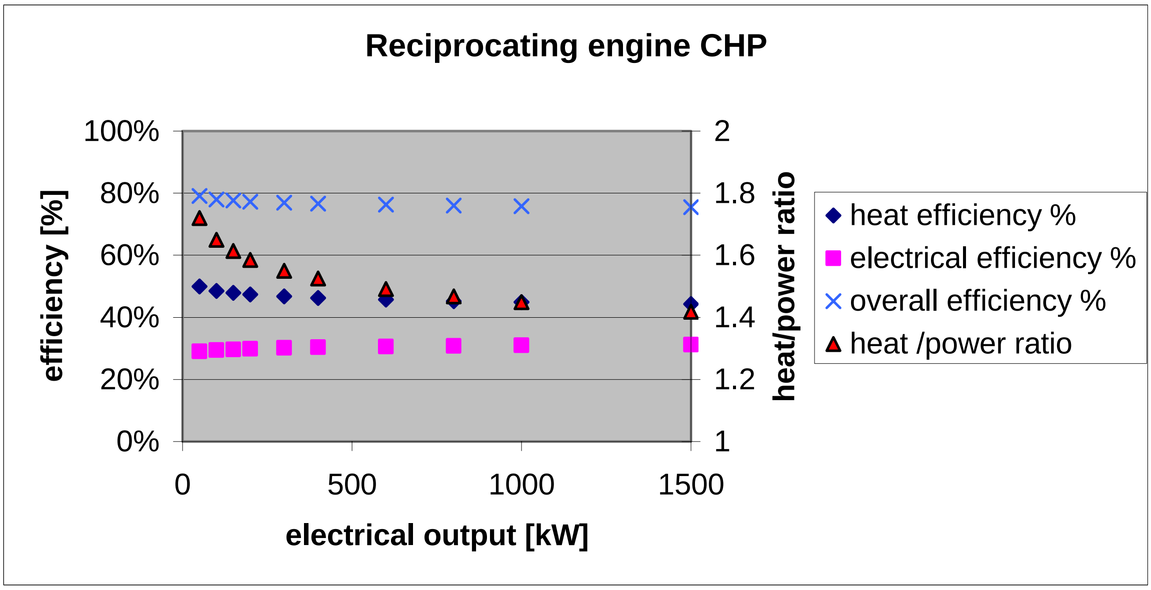


Fig. 7.12. Efficiency and heat/power ratio at full-load for a range of reciprocating engine CHP systems (data from CHP Sizer v2 database)

Basic data for two examples of fuel cell CHP systems are shown in Table 7.6. The data for the Siemens Westinghouse system was reported by Pehnt (reference in Chapter 4), and was used in the Lifecycle assessment. A demonstration version of this system was operated by EDB/Elsam for over 16,000 hours, operating at an electrical efficiency of 46%. The UTC Power system is the PureCell 200 power system (formerly known as the PC25 system) and is a well established product, with over 250 systems installed around the world.

manufacturer	Siemens Westinghouse	UTC Power
type	SOFC	PAFC
electric power output [kW]	100	200
electrical efficiency	41%	37%
heat efficiency	37%	50%
overall efficiency	78%	87%
heat/power ratio	0.90	1.35

Table 7.6. Basic available full-load data for fuel-cell CHP systems

Simulations of the operation of various types of CHP systems were conducted using the CHP Sizer programme to assess the primary energy and carbon dioxide savings. The programme assumes that modulation down to 50% of full load is possible, and the CHP system shuts down at low load demands where operation would be inefficient. As yet there are no manufacturers offering fuel cell CHP systems with a full range of rated power outputs, and therefore for the purposes of comparing operation, the two systems with efficiencies tabulated in Table 7.6 were scaled to give a range of CHP sizes with equivalent efficiencies. Detailed part-load performance data was not available; however from the literature it is clear that a key advantage of fuel cells is that they maintain higher levels of overall efficiency at part load than reciprocating engines. The effect of part-load performance was not analysed in the simulations, however a more detailed simulation could be expected to show a further advantage for fuel cells. The results are shown in Fig. 7.13 (heat led operation) and Fig. 7.14 (electric led operation), where the three CHP systems (engine, SOFC, PAFC) all show primary energy savings, and CO_2 emissions, compared with the base case of using a conventional heating boiler, and importing centrally generated electricity. Electric led operation shows the highest CO_2 savings, reflecting the fact that savings results from avoidance of use of centrally generated electricity, rather than reducing the heat supplied by conventional heating boilers. The assumed primary energy requirement for grid electricity is assumed to be 2.7 kWh / kWhe, and the CO_2 emission factors are 0.43 kg CO_2 / kWhe for centrally generated electricity, and 0.193 kg CO_2 / kWh for natural gas. The

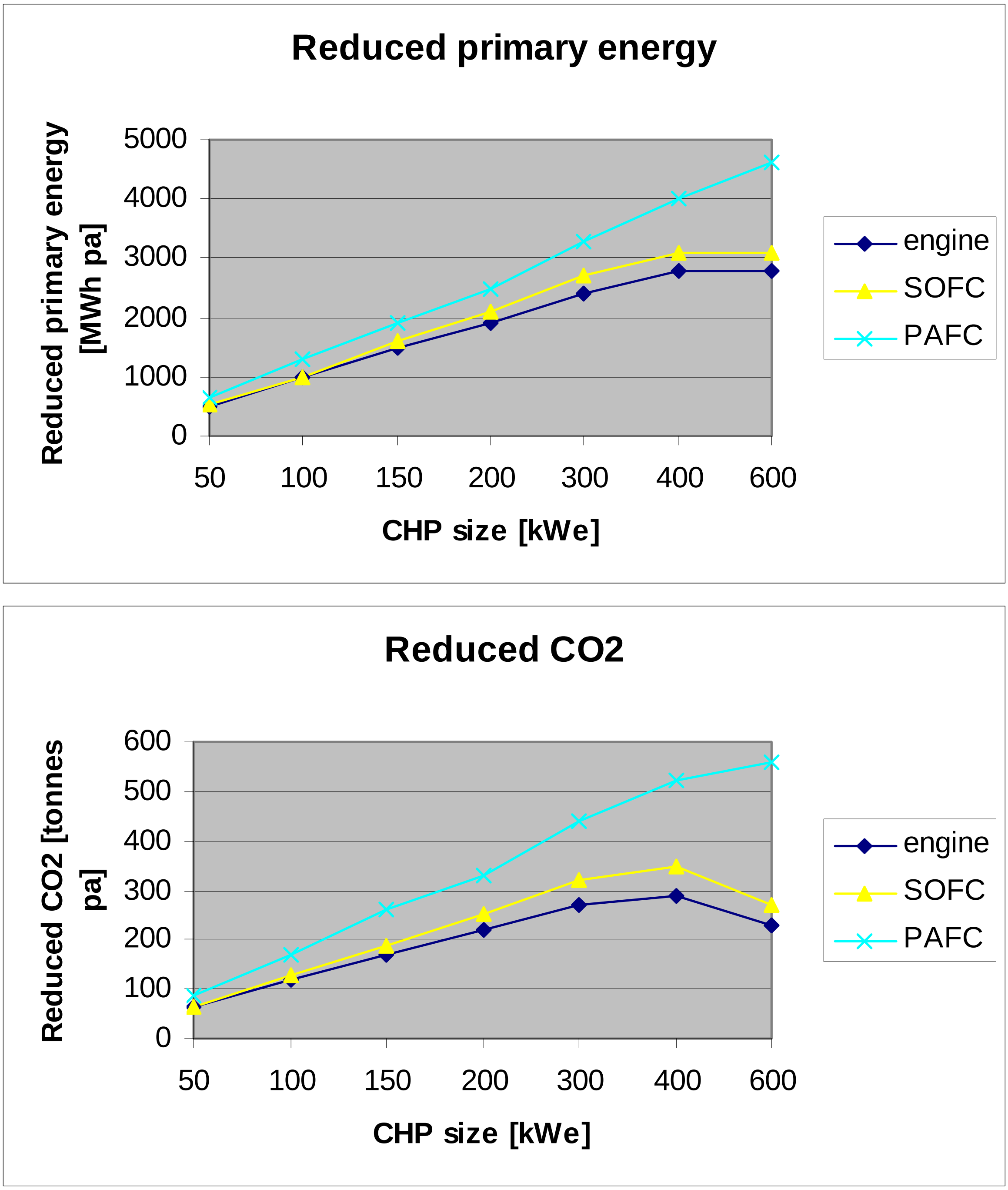
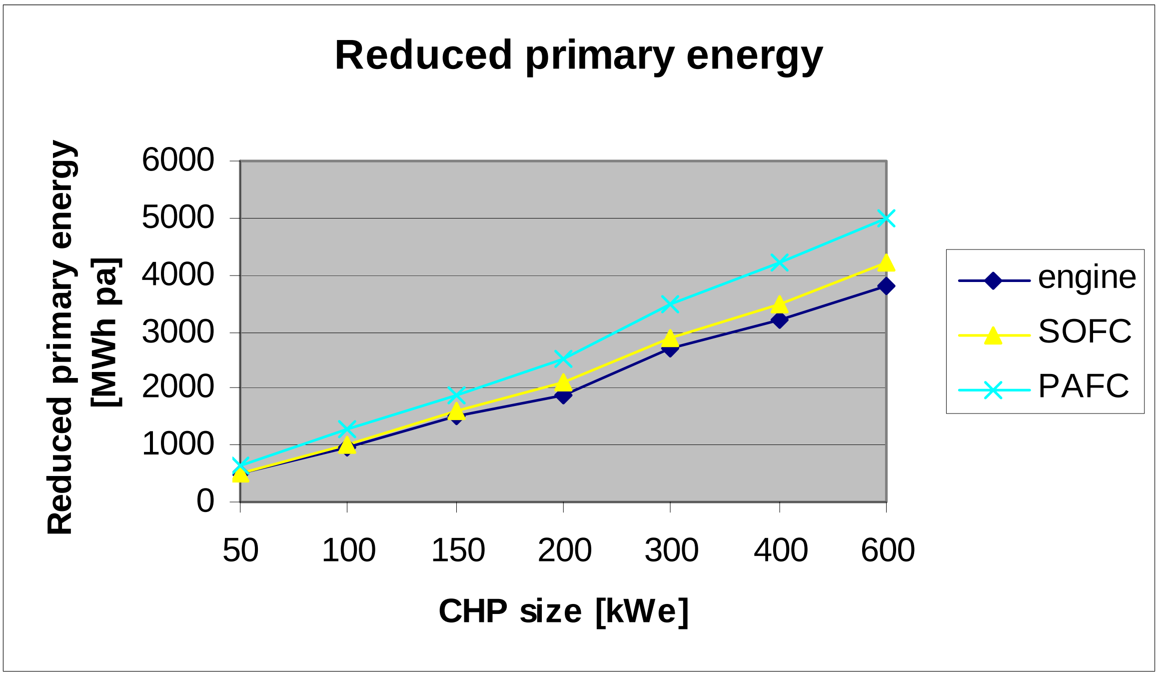


Fig. 7.13 Primary energy and CO_2 savings for the Grove development, heat led operation

PAFC system has the highest overall efficiency and shows the best environmental performance in terms of CO_2 emissions, particularly at higher power levels.



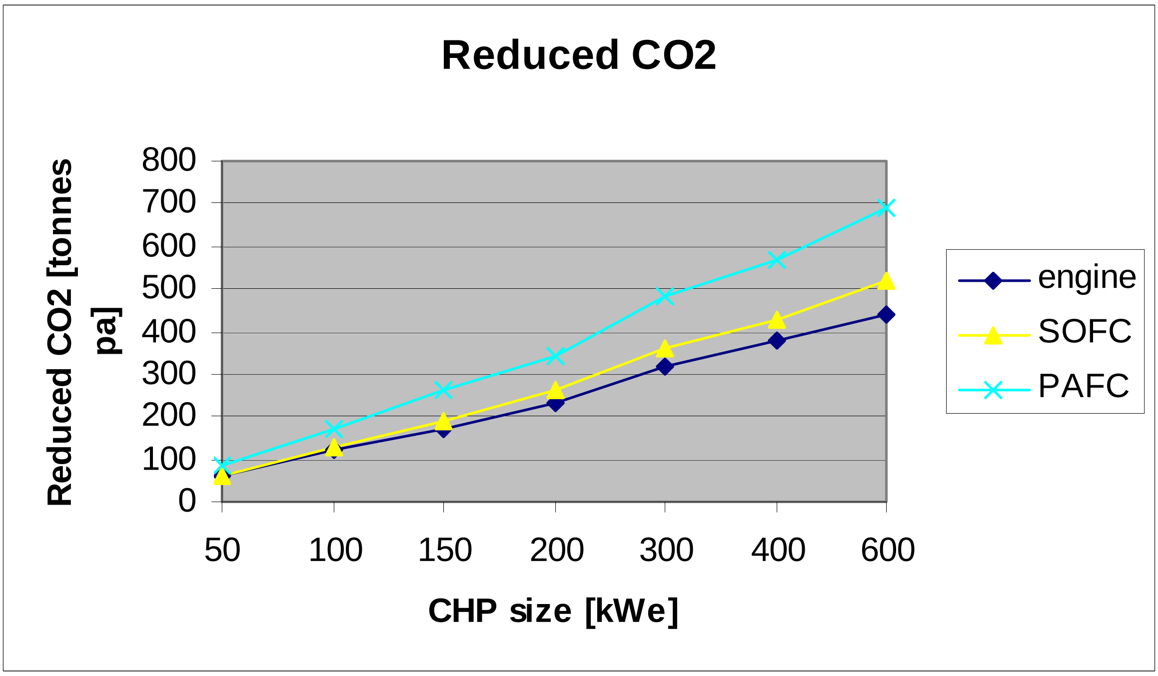
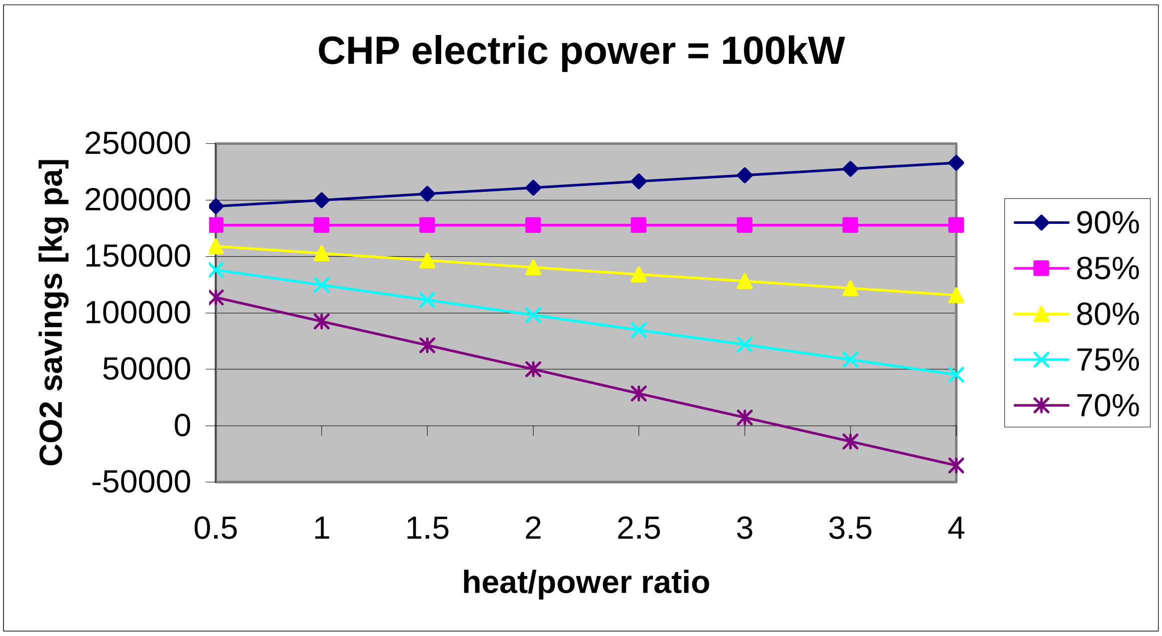


Fig. 7.14 Primary energy and CO_2 savings for the Grove development, electric led operation

The theoretical CO_2 savings for a range of CHP generator heat/power ratios and overall efficiencies is shown in Fig. 7.15. In the first case the CHP size is for a constant rated power, and in the second case the CHP size is for a fixed total power. The boiler efficiency in both cases is 85%. To simplify the investigation, operation at constant full power is assumed, which may be possible if the CHP size is under-rated. Normally the CHP system would have to modulate down its output (when operating in heat-led or electric-led control strategies) according to the demand profiles and system sizing.

The graphs confirm that the environmental benefits, in terms of CO_2 reduction, are best achieved by a CHP system with low heat/power ratio. The benefits mainly result from displacing centrally generated electricity production, while utilisation of the 'waste' heat ensures that the overall thermal efficiency is high. However it should be noted that the provision of heat merely displaces that which could be supplied by a conventional high efficiency boiler.



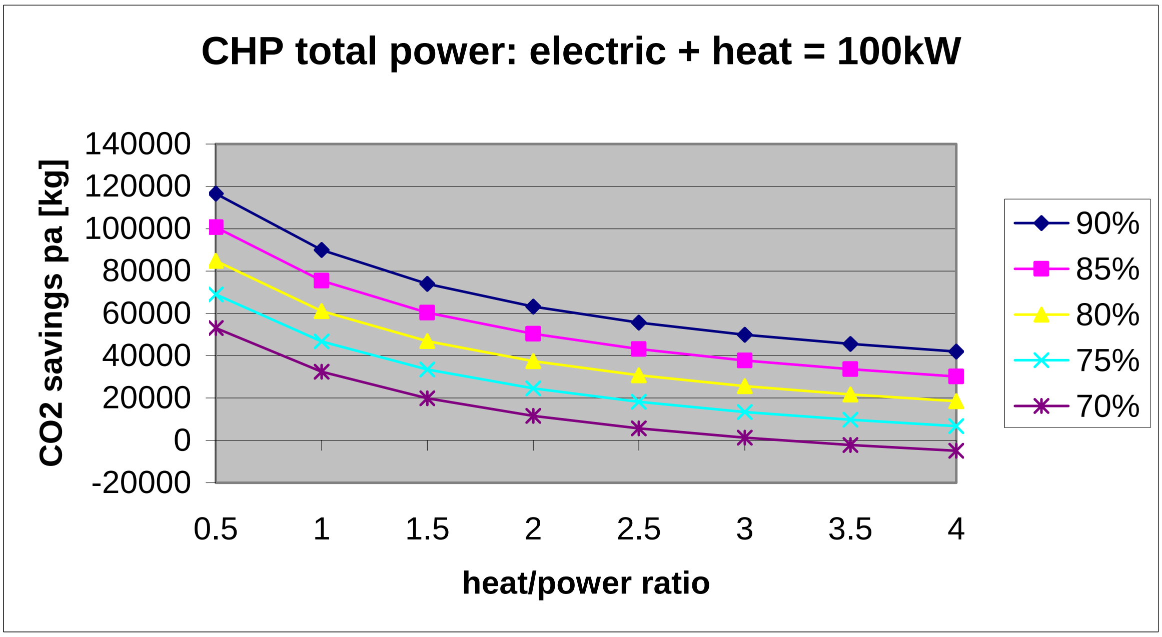


Fig. 7.15. Carbon dioxide savings for a range of CHP generator heat/power ratios and overall efficiencies, for full power operation.

7.6.4 Conclusions and future work

The preliminary analysis the Grove development has demonstrated the potential environmental benefits of using a community heating system with CHP as the central heat source. However, the Grove case study was also used as an input for the LCA methodology described in Chapter 4. The results of this analysis indicate that despite its potential importance as a future energy provider, stationary fuel cell CHP does not compare favourably with conventional CHP in terms of overall lifetime emissions – in part due, to those occurring during the manufacture of the fuel cells. (For more details, please refer to the text, tables and graphs in section 4.7).

Fuel cells are becoming available with high overall and electrical efficiencies, and application to CHP systems can result in reduced CO_2 emissions. Other benefits are the reduction of other emissions (CO etc), and quiet operation. However fuel cells are in the early stages of commercialisation, and are currently expensive. There are likely to be future cost reductions, however it is not clear when they will be competitive with conventional generators in this application.

The density of housing in this development is rather low (on average around 18 dwellings/hectare), and therefore the heat distribution system may be relatively expensive and inefficient. There are likely to be many more economically attractive opportunities for community heating schemes, and one estimate suggests there is potential for application to between around 200,000 to 5.5m homes in the UK, depending on the assumed discount rate (Community Heating – a guide, 2004).

Community heating is likely to be attractive where the density is greater than around 50 dwellings/hectare, while micro-CHP (aka domestic CHP) is likely to be more attractive for low density housing.

The work in this project has highlighted several topics worthy of further research, which could improve the environmental and economic benefits of community CHP:

- The scheduling of multiple CHP generators, with modifications to the usual ‘heat led’ or ‘electric led’ control strategies;
- Improved utilisation of CHP plant (including micro-CHP) by operating at full load for longer periods, achieved by the inclusion of heat or electricity storage to smooth the demand;
- A comparison of the benefits of micro-CHP in each dwelling, and community heating, for various housing densities. This would include investigation of the effect of heat loss in the distribution system.

8. CONCLUSIONS

This collaborative project has brought together the complimentary skills and expertise of two well-established research groups to examine the potential of fuel cell CHP systems. The study has not only examined the status of the current technology; but also considered the policy implications, the economic aspects, the environmental costs and benefits, and the practical options for introducing fuel cell CHP into building developments.

To highlight the findings and achievements of each part of the study in turn:

Technology Review :
This has summarised the current state of CHP in the UK, and described the latest types and characteristics of fuel cells, before examining the status of fuel cell CHP. Whilst there is currently only one demonstration fuel cell CHP system operational in the UK (at Woking), it is clear that there is considerable commercial and Governmental interest in developing micro-CHP (aka domestic) fuel cell systems. Indeed ambitious predictions have been made that there will be four million micro-CHP systems installed worldwide by 2010.

Social Cost Benefit Analysis and Lifecycle Assessment :
The study has reviewed the current cost of fuel cell CHP systems and the predicted reductions in cost. It found that whilst there is agreement that such systems can not currently compete with conventional systems and that price reductions are expected, there is considerable uncertainty about how quickly costs will fall, and to what extent price reductions can be accelerated by investment in research and development. It also noted that, to some extent, the competitiveness of fuel cell CHP will be influenced by the increase in cost of conventional energy technologies. Notwithstanding the current concerns about cost, one recent (2004) review suggested that fuel cell CHP might be commercially available (without subsidy) by 2009.

The study recognised that there was a need to evaluate the environmental cost/benefits of the systems. The published results of other studies into the economic values attributable to a range of atmospheric pollutants were reviewed. This has enabled a financial benefit to be ascribed to the reduced pollution resulting from a change to fuel cell CHP systems.

The study also carried out a lifecycle assessment on both the general case and a specific case study. The lifecycle assessment of fuel cell CHP in the case study was based on the operational results obtained from system modelling, and demonstrates how important results have been achieved by the integrated assessment of these multi-disciplinary work packages. These two assessments have provided a useful insight into the environmental impacts arising from alternative methods of providing heat and power to a housing development. The main findings are as follows:

- The introduction of gas fired CHP reduces emissions substantially compared with grid electricity and gas-fired central heating.
- Producing excess energy has positive results for all scenarios when it displaces more polluting sources, particularly when the displaced energy is less efficiently generated. (For example when CHP electricity displaces grid electricity produced by less efficient coal-fired plant.) However there may be significant financial penalties to producing oversized CHP plant, particularly for fuel cells.
- Despite its potential importance as a future energy provider, stationary fuel cell CHP does not compare favourably with conventional CHP for most emissions. This is mostly due to the manufacturing impacts of fuel cells.
- A lifecycle approach is important, as the manufacturing stage has significant impacts particularly the manufacture of precious metals for the fuel cells. Moreover this impact will vary with the different types of fuel cell.

- A lifecycle approach is also important as it is necessary to take into consideration the heat and power balance achieved by using conventional CHP and fuel cell CHP.

Identification of Barriers and Solutions :
Detailed stakeholder interviews were undertaken to determine the key drivers and barriers to the development of fuel cell CHP. It was found that both at a technical and non-technical level there is still a long way to go before fuel cells become an established, mainstream technology. The participants recognised the need to extend the knowledge base for fuel cell technologies, to improve their efficiencies, reliability, lifetime and material performances; as well as a significant number of non-technical aspects that need to be addressed.

Four main conclusions were drawn from the interviews:

- Stationary fuel cells offer a significant way forward towards sustainable energy, but the carbon implications are uncertain and will be influenced by the source of, and storage of, the hydrogen to power the fuel cell.
- Fuel cells cannot be considered in isolation, a lifecycle approach is needed.
- It was felt that a significant change of attitude, and associated pro-active action, was required within the government. Whilst reforms within the new electricity trading regulations BETTA (British Electricity Trading and Transmission Arrangements) will address some of the regulatory barriers, it was suggested that further action was required.
- The scarcity of demonstration models in the UK was seen as extremely detrimental to their development. It was suggested that financial support for the integration of fuel cell CHP into new housing developments would provide an ideal opportunity, particularly if they are combined with other integrated forms of renewable energy.

System Modelling and Case Studies:
A key objective of the study has been to evaluate the economic and environmental benefits of using fuel cell CHP. The results of the lifecycle assessment have already been described. However, the study has also undertaken a systems analysis for typical applications. This has been carried out by integrating the best features of two well-established CHP software simulation tools with purpose-written processing software.

The resulting procedure, which uses detailed heat and power profiles, has been used to study the same case study as previously used (a proposed community housing development in Oxfordshire). This has demonstrated the potential environmental benefits of using a community heating system with CHP as the central heat source.

The density of housing in this case study is rather low (on average around 18 dwellings/hectare), and consequently the heat distribution system is likely to be relatively expensive and inefficient. Community heating is likely to be more attractive where the density is greater than around 50 dwellings/hectare, while micro-CHP (also known as domestic CHP) is likely to be more attractive for low density housing. It was noted that there are likely to be many economically attractive opportunities for community heating schemes; indeed one reported estimate suggested that there is potential for application to between around 200,000 to 5.5M homes in the UK, depending on the assumed discount rate.

In summary : This study has found that:

- Fuel cell CHP systems may be commercially available and in some cases economically viable by 2009.
- In high density developments (for example around 50 dwellings per hectare) community heating is likely to be economically viable and efficient, while in lower density developments (for example less than 25 dwellings per hectare) micro CHP is likely to be economically attractive.
- Conventional and fuel cell CHP economics are highly sensitive to the ‘spark spread’ of electricity and gas prices, defined as the difference between the price of electricity sold by a generator and the

price of the fuel used to generate it (there are many other factors including specific negotiated tariffs, the electricity trading arrangements, the capital and running costs, Climate Change Levy Exemption certificates – LECs, as well as the Distribution Use of System Costs – DUoS).

- Fuel cells are becoming available with high overall and electrical efficiencies, and when combined with CHP systems they can result in reduced CO_2 emissions. However the greenhouse gas reductions are not clear cut. Although the fuel cell scenario that meets the thermal demand produces the lowest net greenhouse gas emissions, where the electricity demand is met the net benefits are not so clear. The conventional CHP scenarios have similar or lower greenhouse gas emissions.
- There may be significant environmental costs associated with the manufacture of the fuel cells, the magnitude varying with the type of fuel cell. It is therefore critically important to carry out a full lifecycle assessment of the different schemes in order to minimise overall environmental costs.

Further research : It is suggested that further research is required to :

- Explore the application of fuel cells plus the use of renewable energy for hydrogen production, and the consequent change in life cycle cost and emissions;
- Explore alternative fuel cell technologies (especially those which have lower emissions in the manufacturing stage);
- Determine the optimum scheduling of multiple fuel cell CHP systems, with modifications to the usual ‘heat led’ or ‘electric led’ control strategies;
- Improve utilisation of CHP plant (including micro-CHP) by operating at full load for longer periods, achieved by the inclusion of heat or electricity storage to smooth the demand;
- Compare the benefits of micro-CHP in each dwelling, and community heating, for various housing densities. This would include investigation of the effect of heat loss in the distribution system.

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