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# Technology-Rich Modelling of Micro Combined Heat and Power for Economic, Environmental, and Policy Assessment

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Submitted for the degree of PhD

# Abstract

Micro combined heat and power (micro-CHP) is an emerging technology application that produces heat and some electricity for a single residential dwelling. It is designed to replace existing home heating systems such as boilers. This thesis deals with development of robust techno-economic modelling for micro-CHP, and its application to assess the ability of the technology to meet private investment and policy goals and the influence of key technical characteristics on its economic and environmental credentials. Lessons learned from this modelling are then applied to consider appropriate policy support.

Various methods for modelling micro-CHP are critically reviewed, and an alternative methodology utilising mixed integer linear programming is developed to address their shortcomings. This new modelling framework builds on existing efforts in that it provides sufficient technical detail to enable credible system design analysis whilst simultaneously optimising system operating schedule. This provides a feedback loop between operational strategy and system design, resulting in an arguably more useful assessment tool for this emerging technology.

The model is then applied to determine key market drivers for Stirling engine, internal combustion engine (ICE), and medium term fuel-cell based micro-CHP systems. The ability of these technologies to meet policy objectives is then assessed. Nine specific technical parameters are then examined in terms of impact on the economic and environmental performance of the systems. These parameters are; overall efficiency, part-load efficiency, thermal demand load factor, ramp rates, start-up cost, turndown ratio, minimum up-time, addition of thermal energy storage, and degradation for fuel cells. Results of this analysis give technology developers insight regarding where R&D should be focused for maximum benefit. Finally a critique of policy supporting microgeneration and energy efficiency in the UK is presented, leading to discussion of methods of policy support for micro-CHP in the context of modelling results.

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# Optimisation Nomenclature (for Chapter 4)

*Objective*

| | |
|---|---|
| Annual Cost | The operation and maintenance cost of meeting energy demand over one year of the project. |

*Decision Variables*

| | |
|---|---|
| $a_{2,t},\ldots,a_{L,t}$ | Piecewise electrical output ($kW_eh$) of micro-CHP in time period t. |
| $\alpha_{1,t},\ldots, \alpha_{L,t}$ | State of each segment of piecewise electrical output – 0 = not fully dispatched, 1 = fully dispatched for each time period t. |
| $S_{st,t}$ | Start up cost for micro-CHP in time period t. |
| $S_{sd,t}$ | Shutdown cost for micro-CHP in time period t. |
| $b_t$ | Thermal output ($kW_{th}h$) of supplementary heat-only unit in time period t. |
| $c_t$ | Electricity bought ($kW_eh$) from the grid in time period t. |
| $d_t$ | Electricity sold ($kW_eh$) to the grid in time period t. |
| $e_t$ | Electricity used to charge electricity storage ($kW_eh$) in time period t. |
| $f_t$ | Electricity discharged from electricity storage ($kW_eh$) in time period t. |
| $g_t$ | Thermal energy charge to thermal storage ($kW_{th}h$) in time period t. |
| $h_t$ | Thermal energy discharged from thermal storage ($kW_{th}h$) in time period t. |

*Constants*

| | |
|---|---|
| $CHP_{cap}$ | Nameplate capacity of micro-CHP ($kW_e$). |
| $B_{cap}$ | Nameplate capacity of supplementary heat-only unit ($kW_{th}$) |
| $ES_{cap}$ | Nameplate capacity of electricity storage unit ($kW_eh$) |
| $TES_{cap}$ | Nameplate capacity of thermal energy storage unit ($kW_{th}h$) |
| $\zeta$ | Binary variable indicating if a micro-CHP is present. |
| $\vartheta$ | Binary variable indicating if electricity storage is present. |
| $\mu$ | Binary variable indicating if thermal energy storage is present. |
| $D_1,\ldots,D_L$ | Breakpoints in micro-CHP piecewise linear generating cost function |
| $\eta_{CHP,1,\ldots}\ \eta_{CHP,L,}$ | Initial micro-CHP LHV electrical efficiency coefficients. |
| $\sigma_{CHP,1,\ldots}\ \sigma_{CHP,L,}$ | Micro-CHP LHV overall efficiency (heat + power) coefficients. |
| $\tau_d$ | Minimum down-time of micro-CHP (no. of time periods). |
| $\tau_u$ | Minimum up-time of micro-CHP (no. of time periods). |
| $\tau_s$ | Number of time periods in system start up cost function. |

| | |
|---|---|
| $s_{start,\tau}$ | Start-up cost of micro-CHP system if started after τ time periods off (£). |
| $s_{shutdown}$ | Shutdown cost of micro-CHP system (£). |
| $r_{up}$ | Maximum ramp up for micro-CHP ($kW_e$ per time period). |
| $r_{down}$ | Maximum ramp down for micro-CHP ($kW_e$ per time period). |
| $\kappa_\eta$ | Micro-CHP electrical efficiency degradation coefficient (%/$kW_e$h/$kW_{installed}$). |
| $\varphi_\eta$ | Micro-CHP electrical efficiency degradation coefficient (%/thermal cycle) |
| $\sigma_{SHU}$ | Supplementary heat-only unit LHV efficiency. |
| $u_{ch}$ | Electricity storage unit maximum charge rate ($kW_e$h per time period). |
| $u_{dis}$ | Electricity storage unit maximum discharge rate ($kW_e$h per time period). |
| $v_{ch}$ | Thermal energy storage unit maximum charge rate ($kW_{th}$h per time period). |
| $v_{dis}$ | Thermal energy storage unit maximum discharge rate ($kW_{th}$h per time period). |
| $\eta_{ch\text{-}es}$ | Electricity storage charge efficiency. |
| $\eta_{dis\text{-}es}$ | Electricity storage discharge efficiency. |
| $\eta_{ch\text{-}tes}$ | Thermal energy storage charge efficiency. |
| $\eta_{dis\text{-}tes}$ | Thermal energy storage charge efficiency. |
| | |
| $m_{CHP}$ | Micro-CHP maintenance cost per year (£/year). |
| $m_{SHU}$ | Supplementary heat-only unit maintenance cost (£/year). |
| $m_{ES}$ | Electricity storage maintenance cost (£/year). |
| $m_{TES}$ | Thermal energy storage maintenance cost (£/year). |
| $\varepsilon_t$ | Electricity price from grid (£/kWh) in time period t. |
| $\gamma_t$ | Gas price (£/kWh) in time period t. |
| $\beta_t$ | Electricity buyback price (£/kWh) in time period t. |
| $AM$ | Combined annual maintenance costs for all equipment (£/year). |
| $OP$ | Combined annual fuel and electricity cost minus revenue (£/year) |
| $\omega_z$ | Weighting for day-types in the problem, for each day-type z. |
| $EDem_t$ | Electricity demand in time period t |
| $HDem_t$ | Heat demand in time period t |
| | |
| T | Number of time periods in one sample day. |
| L | Number of piecewise linear elements for micro-CHP production cost. |
| Z | Number of representative sample days analysed in the problem. |

# Capacity Credit Nomenclature (for Chapter 7)

| | |
|---|---|
| *CC* | Capacity credit |
| *F* | Random variable for aggregate output from a number of large dispatchable plant ($kW_e$) |
| *mCHP* | Random variable for aggregate output from a large number of micro-CHP units ($kW_e$) |
| *D* | Random variable for aggregate national demand ($kW_e$) |
| *M* | Random variable for margin between supply and demand ($kW_e$) |
| $\mu_X$ | Mean of random variable identified by "X" |
| $\sigma_X$ | Standard deviation of random variable identified by "X" |
| $n_0$ | Number of large dispatchable (centralised) generators before addition of micro-CHP |
| *n* | Number of micro-CHP units after addition of micro-CHP |
| $c_F$ | Capacity of each large dispatchable generator ($kW_e$) |
| $c_{mCHP}$ | Capacity of each micro-CHP unit ($kW_e$) |
| *A* | Covariance between random variables D and mCHP |
| $\pi_i$ | Probability of micro-CHP operating at set-point *i* |
| $\pi_{Available}$ | Probability of a large dispatchable unit being available |

## Acknowledgements

I gratefully acknowledge the guidance of my supervisors Professor Matthew Leach and Professor Nigel Brandon. Without their support and consistent ability to employ me this work would not have been possible. I would also like to express my gratitude to the late Professor Dennis Anderson who provided feedback on the capacity credit mathematics presented herein. Finally thanks go to my brother Dr Evatt Hawkes who advised regarding approaches for linearisation of the fuel cell efficiency degradation function.

# Chapter 1: **Introduction**

Micro combined heat and power (micro-CHP) is an emerging class of technologies that have the potential to tackle a number of energy policy aims relating to the economics, environmental impacts, and energy security of supply. Perhaps foremost among the credentials of micro-CHP is the perceived ability to reduce greenhouse gas (GHG) emissions arising from residential energy consumption at low private and societal cost. This thesis develops and applies a modelling framework designed to assist micro-CHP technology developers in creating successful products, and to explore the potential of mature micro-CHP systems. The modelling framework and supporting analysis is used to assess the ability of the technologies to meet commercial and policy aims, and to assess the suitability and effectiveness of policy instruments in encouraging uptake where that uptake will aid in meeting policy objectives. This chapter notes broad concerns regarding climate change, the position of the United Kingdom, why the residential sector is an important consideration, and where micro-CHP may fit in addressing the issues. It then outlines the key research questions to be answered and the approach adopted in this thesis.

Anthropogenic production of greenhouse gases and resultant climate change has been recognised as a fundamental current issue. It's inherently global nature has highlighted the need for co-ordinated international action to mitigate effects and adapt to change where necessary. The international community has started to address the threat via emissions reduction agreements such as the Kyoto Protocol, which requires a set of developed countries to reduce their emissions in a 2008-2012 commitment period by 5.2% relative to 1990 levels. In order to meet the targets created by this (and other) agreements many governments are actively promoting mitigation actions and establishing their own domestic greenhouse gas reduction targets. In the United Kingdom there is a domestic goal to achieve 20% carbon dioxide emissions reduction by 2010 and 26% by 2020, relative to 1990 levels. The government has acknowledged it is likely to miss the 2010 target, and the 2020 target also appears increasingly challenging. However, difficulties the UK faces with these near to medium term targets did not deter the government from setting a longer term aspiration to reduce greenhouse gas emissions by 60% by 2050 in DTI (2003). This target was recently increased to 80% and set in law via HM Government (2008a); the Climate Change Act 2008. If these challenging short and long term greenhouse gas reduction targets are to be even approached, mitigation action in all sectors of the UK economy will

be required. The focus of this thesis is the residential sector, which currently contributes more than 25% of national greenhouse gas emissions, and is an area where significant reductions could be made at relatively low cost.

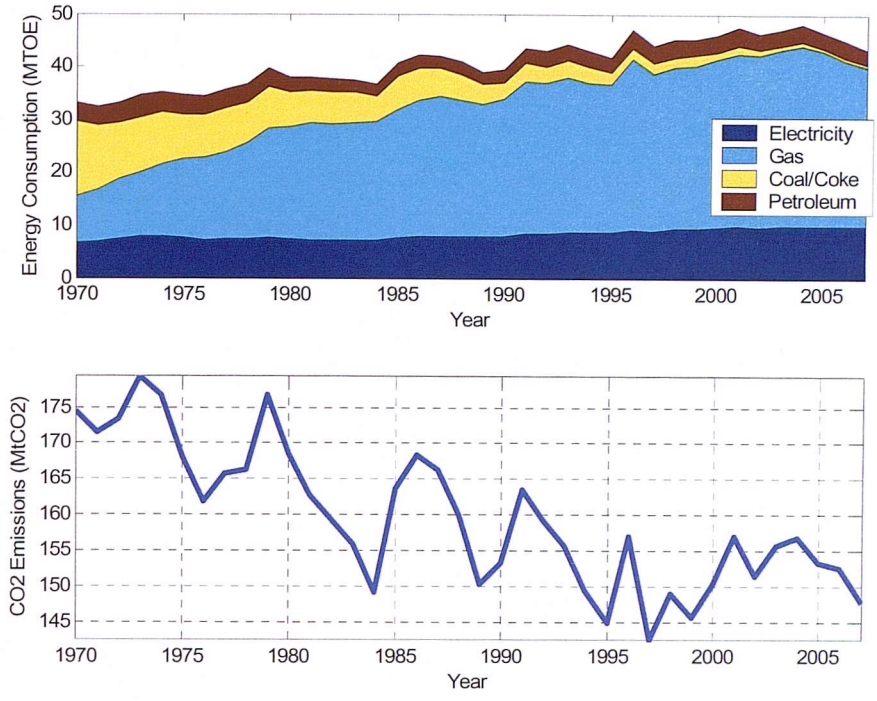



**Figure 1: Trends in Energy Consumption, Fuel Mix, and $CO_2$ Emissions for the UK Residential Sector adapted from BERR (2008a)**

Figure 1 shows the trend since 1970 for residential energy consumption, fuel mix, and corresponding $CO_2$ emissions. The generally downward $CO_2$ trend was caused by the "dash for gas" which led to rapid decarbonisation of centralised electricity supply in the 1990s and an overall steady switch to gas-fuelled systems for meeting dwelling thermal demand.[1] Since just before the turn of the century the downward trend appears to have slowed, predominantly due to slightly increased use of coal in centralised electricity generation combined with an increase in electricity consumption, and little further potential for residential heating fuel switching. Overall the net effect is that aggregate $CO_2$ emissions in 2007 for the sector are approximately the same as those of 1990. If the residential sector is to play a part in achieving a 60% or 80% reduction in greenhouse gas (GHG) emissions relative to 1990 levels, the broad downward emissions trend needs to be maintained. This is a primary motivation for the interest in low carbon technologies for the residential sector, including but not limited to the micro-CHP systems considered in this thesis.

[1] Perturbations in the $CO_2$ trend are predominantly related to annual average temperature variations, which bear mainly upon fuel consumption for space heating.

Looking into the future, existing projections for the residential sector published in BERR (2006) predict that energy consumption will remain stable until 2020, suggesting that low-carbon technologies to supply that demand, in addition to demand reduction, will be important. Looking further ahead Hinnells (2006) reported that the "Building Market Transformation" project has developed scenarios for the residential sector, with an "incremental change" scenario based on existing policy and technologies predicting little aggregate reduction in greenhouse gas emissions until 2050. This scenario was contrasted with "60% GHG reduction by 2050" scenario which noted that, among other measures, substantial adoption of zero and low carbon technologies for heat and electricity (i.e. microgeneration) will be required. More specifically for the case of micro-CHP, in the related "40% House" project, Boardman et al. (2005) developed a 60% GHG reduction scenario that predicted 21% of dwellings would adopt Stirling engine and 17% would adopt fuel cell micro-CHP technologies by 2050. Accounting for growth in the number of buildings, this translates to more than 12 million installed systems, implying that development of successful micro-CHP systems could be an important element in enabling the residential sector to play a role in achievement of national emissions targets.

In order to meet the perceived need for micro-CHP technologies, development of commercial micro-CHP products has been underway for some time, with Knight et al. (2005) reporting that over 50 companies worldwide are active in the area. Technical innovation, such as development of regenerative heat exchangers for Stirling engines and development of potentially viable fuel cell systems, is a strong driver for this commercial interest. Driven by this technical innovation, small scale CHP technologies are becoming economically attractive: According to Mariyappan (2004), the cost per $kW_e$ installed for small generation systems has become competitive with large-scale centralised generation systems, providing impetus for an increase in decentralised generation (DG). The economically-competitive availability of small generators is an important motivation for the interest in and development of micro-CHP systems.

Complementary incentive exists for commercial micro-CHP development in that a large potential market has been identified for the technologies: The Micro-Map (2002) project predicted that between 5 and 12 million micro-CHP installation could be in place in European Union countries by 2020, and SBGI (2006) predicted that with low levels of government support less than 1 million units would be installed in the UK alone by 2020, but this figure could rise to more than 12 million with high levels of support. These figures

serve to bolster the case for interest in micro-CHP technologies, indicating that a range of stakeholders see the technologies as commercially viable, providing a strong complement to GHG reduction and technology availability drivers. In light of these market size figures, technology development, and environmental credentials, a number of commercial arrangements aimed at eventually distributing micro-CHP have emerged. For example, agreements towards bringing Stirling engine and Solid Oxide Fuel Cell (SOFC) based micro-CHP systems to market in the UK have been announced in E.ON UK PLC (no date) and 'Ceres Power funding to develop manufacturing' (2007), respectively.

Energy policy development to support GHG reduction in the residential sector has also been underway for some time. Microgeneration, including micro-CHP has been integrated into aspects of these support mechanisms, particularly in providing value added tax (VAT) relief and more recent developments such as the Carbon Emissions Reduction Target (CERT). Also, cogeneration in general has been bolstered by a supporting EU directive (EU (2004)). Whilst these changes send a useful message to stakeholders, the lack of commercially available mass-market micro-CHP products has thus far made the policy measures redundant in a practical sense. For the UK, the primary incentive for policy support appears to be the potential for GHG reductions, but clear secondary drivers exist. Examples of these are the perception that promising micro-CHP developments are underway by UK companies, knock-on consumer engagement benefits, the possibilities the technologies offer to address fuel poverty, and the compatibility with general drives towards more decentralised generation (DG) and efficient energy systems. Indeed the majority of benefits associated with DG cited in Lovins et al. (2002) and OECD/IEA (2002) apply to micro-CHP. In addition to these, Jansen et al. (2003) concluded that systematic investment in DG has the potential to avoid undesirable boom-bust cycles seen in centralised generation investments, where electricity price collapse after the addition of a large power station significantly influences its economics, and smaller systems such as micro-CHP avoid this drawback.

Despite the set of drivers for its development discussed above, it is clear that micro-CHP is still an emerging class of technologies with uncertain economic or environmental performance credentials. No widely adopted precedent exists that generates electricity and heat in single residential dwellings, and currently available commercial products such as the BAXI DACHS system and the Honda ECOWILL system are more suitable to larger multi-residence buildings or not directly appropriate for the UK market, respectively. There

is also lack of clarity regarding regulatory, institutional and other potential barriers. As discussed in Voß and Fischer (2006), issues not directly related to the technology itself are likely to be important for successful introduction of micro-CHP. Examples include, a) how users might become acquainted with the operation of a power generator in their home, b) whether a skilled workforce of installers and further personnel is or could be in place to support the new market, c) to what extent existing electricity and gas networks might need to be reconfigured to absorb changing load patterns, and d) the details of regulatory changes required to enable a shift of balance from a few incumbent centralised generators to potentially millions of very small scale generators.

A number of field trials are underway around the world in an attempt to address these questions surrounding the technologies' performance and to gain learning-by-doing understanding of other barriers. In the UK, Carbon Trust (2007) reported relatively poor performance of Stirling engine micro-CHP in a recent field trial, but noted that the products are at an early stage of development. It noted that installer and user expertise are both very important factors in achieving good performance. It also found that potential future micro-CHP products such as fuel cells may perform better than the Stirling engines reported on in the trial, although no attempt was made to quantify their advantages. Given the relative immaturity of micro-CHP, and its perceived potential to help meet policy aims and provide commercial opportunities, it is timely to perform research that gives a better view of the future potential of micro-CHP products. Specifically, more robust evidence is required regarding the economic and environmental performance of micro-CHP systems. Without this base of evidence to inform system development and help shape policy, it is likely that related commercial developments will be disjointed and will fail to contribute effectively to overall policy aims. This thesis seeks to provide such evidence through robust techno-economic performance modelling, and consideration of modelling outcomes in policy and regulatory context. It pays less attention to institutional and other barriers for micro-CHP, which have benefitted from consideration in (for example) Allen et al. (2008), Watson (2004), Watson et al. (2008) and Pehnt et al. (2006).

The overarching aim of this thesis is therefore to provide understanding of the primary drivers of economic and policy-related performance (including greenhouse gas related performance) of micro-CHP, and then use these to help focus technology development and shape supporting policy and regulations. To achieve this aim, four key questions need to be answered. These are:

1. What are the key economic drivers for residential micro-CHP systems?
2. Where and why does each micro-CHP technology have the ability to meet the UK's energy policy aims, including greenhouse gas emissions reduction?
3. What are the key technical characteristics that differentiate performance of micro-CHP systems?
4. What is the potential of current, proposed and new policy instruments in terms of encouraging uptake, and will installations help to achieve energy policy aims?

In order to answer to these questions, a modelling methodology is required to enable exploration of unchartered system characteristics and consideration of multiple scenarios or parameter values. This methodology must be capable of probing the credentials of mature micro-CHP technology through consideration of high level technical parameters, which in itself can provide constructive information to system developers. The information gleaned from these analyses can then be used to carry out policy critique and development with the aim of understanding what incentive structures are appropriate to support uptake and operation to meet policy aims, and indeed what messages to send to system developers now to ensure creation of appropriate products. This thesis provides these modelling tools and analyses through a series of interconnected modular studies.

Chapter 2 covers the relevant general background information, including patterns and trends in UK residential energy demand, and description of the characteristics of each micro-CHP "prime mover" technology investigated. Chapter 3 then discusses specific issues of importance to the research including review of existing modelling methods, consideration of appropriate reference systems to compare micro-CHP against, and discussion of previous performance and related studies of the technologies. Chapter 4 presents the mathematical treatment for the optimisation model developed for the research, including justification for the applied performance and analysis metrics. Chapter 5 tests the reliability and repeatability of the developed model, focusing on the impact of some typical assumptions used in energy system modelling, and briefly comparing modelling results to the performance of systems in practice. This concludes the background and model development sections of the thesis, with the subsequent chapters focused on applying the model to answer relevant research questions.

Chapter 6 applies the developed model to consider key market drivers for micro-CHP, attempting to isolate the primary metrics that have bearing on the economic performance of the systems. This is achieved through sensitivity analysis across a range of parameters

relevant to the residential situation; annual electricity and thermal demand, system size, energy tariffs, and electricity buyback prices. Chapter 7 considers the ability of micro-CHP technologies to meet energy policy objectives, namely greenhouse gas emissions reduction, detailed consideration of capacity credit, and touching on issues relating to energy security. Chapter 8 then presents a scrutiny of the nine primary high-level technical characteristics influencing the performance of each type of micro-CHP system, providing system developers with information about the relative importance of aspects of their technologies, and enabling them to focus research and development attention on areas with the highest potential gain. Finally Chapter 9 considers the performance of technologies in the context of broader residential sector energy policy. Current and proposed support mechanisms are presented and discussed, and a critique of these measures is developed in light of the potential of mature micro-CHP systems. New methods of support for micro-CHP designed to address potential barriers are presented and discussed, highlighting their relative strengths and weaknesses.

Chapter 10 provides conclusions drawn from the research results, identifies areas where improvements could be made, and suggests themes for future studies.

# Chapter 2: **Background**

In order to begin investigation into techno-economic and policy-related performance of micro-CHP, it is necessary to understand the nature of technology under consideration and the setting in which they are likely to operate. This chapter addresses this requirement through consideration of trends in and characteristics of residential energy demand in the UK, leading to choice of a set of representative energy demands for use later in the thesis. It then discusses the technologies under consideration and presents the central estimates of technical parameters for the micro-CHP systems to be analysed.

As the thesis has been undertaken as a series of interconnected modular studies, relevant literature is discussed in more detail in each chapter, rather than in a dedicated literature review.

## 2.1 Patterns and Trends in UK Residential Energy Demand

This section presents selected information regarding energy demand in the United Kingdom residential sector, with the intention of creating context and justification for the energy demand profiles used for investigations presented later in this thesis. Trends in individual dwelling energy demand are presented, and the driving forces of these trends discussed. Distributions of dwelling annual demands are considered, and the unique characteristics of demand in single residential dwellings are examined. This leads to choice of a set of demand scenarios for use in the modelling work presented later.

### 2.1.1 Historical Trends in UK Residential Energy Demand

Residential energy consumption can be disaggregated according to final end use; space heating, domestic hot water (DHW), cooking, and lighting and appliances. A number of factors influence the requirement for each one of these energy services, including but not limited to external conditions (e.g. temperature, wind speed, ambient light, etc), level of energy efficiency refurbishment, and behavioural patterns of occupants. As presented in Figure 2 (based on data from the BREDEM model published in Utley and Shorrock (2006)), trends in total average energy demand per dwelling have been relatively stable in the past few decades. More specifically, space heating demands have been relatively constant (perturbations are closely correlated with mean external temperature in each year), and a slight decline in DHW demand has been offset by an increase in lighting and appliance

demand. Cooking-related energy demand has also been relatively constant (not shown in Figure 2).

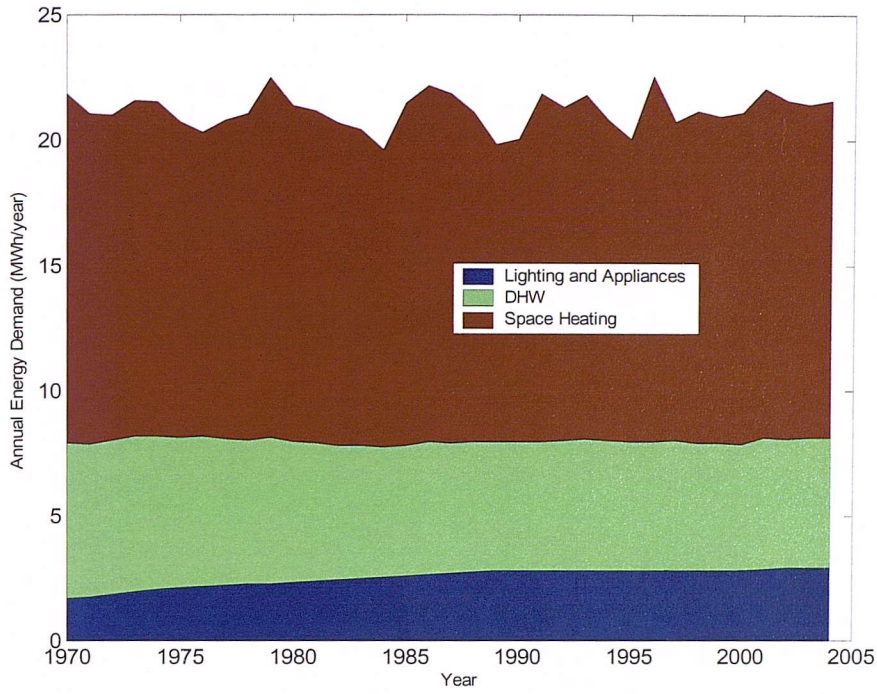



**Figure 2: Trend in UK Average Annual Residential Energy Demand per Dwelling from 1970 to 2004**

Whilst these trends appear to be relatively stable, the underlying factor that produces this result is a tension between increased efficiency and increased demand for energy services. Technical change simultaneously offers an improvement in efficiency of energy service provision and sometimes the ability to take more of that service. Likewise, efficiency gains can be offset by demands for new or replacement services. An example of this effect is the case where improvement in efficiency of heat production and delivery (e.g. condensing boilers and central heating systems) has been offset by demand for higher internal temperatures in dwellings as shown in Utley and Shorrock (2006). This and similar responses to technical improvement are often described via a concept known as the "rebound effect", where (in this case) "comfort taking" maintains energy consumption levels even though efficiency has been improved (this is analogous to the rebound effect concept whereby reduced energy prices can lead to higher energy consumption). A number of demographic factors also influence recent trends in residential energy consumption, including reduction in the number of persons per dwelling, and reduction in average dwelling floor area. As is apparent from Figure 2 (which shows slightly increasing electricity demand per dwelling), reduced number of occupants and reduced floor area combined with

improving energy efficiency have failed to counterweigh demand for new of improved services. As a result, lighting and appliance demand exhibits an average increase of only 0.5% per year.

A further point to note with regard to Figure 2 is the contribution made by the "lighting and appliances" category. Questions can be raised regarding the accuracy of this modelled demand because it does not tally with the government's measures data in BERR (2008b). Figure 2 indicates that in 2004, average lighting and appliance demand was approximately 3MWh per year. However, the UK governments energy statistics (BERR (2008b)) indicate average annual electricity demand of roughly 4.5MWh in 2007. The difference between these two figures should be accounted for by electric space and water heating methods, electric cooking (hobs and ovens) that are applied in some dwellings, and a small change over the 3 years between investigations, but the magnitude of the difference does not support this conclusion. In BERR (2008b) "ordinary meters" (as opposed to "economy 7" meters which are usually associated with overnight electric storage heating, which is not appropriate for micro-CHP installations) average consumption is just above 4MWh annually. Although this certainly still includes consumption related to cooking and some heating, it remains unlikely that this would account for the magnitude of the difference observed because according to Utley and Shorrock (2006) electric space heating is present in only 8% of centrally heated dwellings in Great Britain, and further dwellings utilise electric or partially electric DHW systems.

Despite these discrepancies, for the purposes of the arguments presented in this thesis, it is useful to make an assumption of the mean annual electricity demand for the existing housing stock in order to inform choice of demand profiles for analysis. Dwellings that choose to apply micro-CHP may or may not continue to include some forms of electric heating and cooking (e.g. ovens and hobs, a booster element for DHW or storage heating, or electric shower systems in applications where plumbing or other constraints require an independent system). Therefore, for electricity demand, the measured "ordinary meter" data presented in BERR (2008b) is assumed to represent the mean UK annual electricity demand of just above 4MWh per year, and a variety of other demand cases are defined including a "median 3MWh" case to account for the spread in observed annual demands (see section 2.1.3).

### 2.1.2 Future Trends for UK Residential Energy Demand

In order to gain an understanding of the demand profiles that micro-CHP will serve in the future, given the fact that the technology is not yet mature, it is valuable to consider possible developments in electricity and heat demand patterns.

As displayed in Figure 2 electricity demand per dwelling in the UK has been fairly stable historically, exhibiting only small average year-on-year increase. In general this trend could be expected to continue as increased energy efficiency is offset by demand for new or improved services, although this rebound effect is difficult to quantify and casts doubt on any future predictions. The rebound effect, in terms of increased ownership or increased usage of appliances/lighting, is now discussed in terms of influence on future energy demand.

In terms of ownership, according to Mansouri et al. (1996), whilst some appliance classes (e.g. clothes washing machines) have reached saturation levels, others may still achieve further penetration (e.g. dishwashers). Indeed those appliances that have reached saturation can go on to reach several units per dwelling as is the case for televisions, where 45% of dwellings had more than one unit according to the survey presented in Mansouri et al. As services improve (particularly those that relate to entertainment), existing classes of appliances will be used more commonly, and new hardware will emerge. These changes, which usually serve to increase electricity demand, will be at least partially offset by improved efficiency and appliance consolidation, delivered via minimum standards regulation and/or appliance labelling motivating energy-efficient consumer choice. Overall, these competing factors make detailed prediction of future residential electricity demand in individual dwellings problematic. Given that the factors discussed here have all had an influence historically, the most defensible approach is to assume that per-dwelling electricity demand will not change significantly into the future[2]. As it is recognised that this is an assumption with attached uncertainty, a wide range of annual electricity demand scenarios are investigated in the analysis section of this thesis (see Table 1 for annual electricity demand values).

Similar issues apply to thermal demand, where increased thermal efficiency of dwellings is offset by "comfort taking" where the occupier demands higher internal temperatures and greater use of domestic hot water. According to Utley and Shorrock (2006) internal

[2] Note that it is beyond the scope of this thesis to carry out a detailed investigation of the possible evolution of demand in the future – trends are presented and discussed leading to broad conclusions regarding possible developments.

temperatures have been consistently rising in step with uptake of central heating systems over the past few decades. By 2004 average internal temperatures were approaching 19°C, a rise of more than 6°C since 1970. This temperature is perceived to be generally sufficient for the purposes of health and comfort, suggesting that further comfort taking is less likely and further efficiency improvements should result in per-dwelling demand reductions. However, it is possible that occupiers may demand yet higher temperatures, up to between 21°C and 25°C, with a consequent impact on thermal demand.

If one takes the view that saturation internal temperatures have been reached and further comfort taking is unlikely, it is informative to consider the potential for thermal efficiency improvements in the housing stock into the future. Increased thermal efficiency of dwellings relates primarily to the presence of insulation and rates of air turnover, and there is still substantial opportunity for further improvements in this regard in the existing housing stock. According to Utley and Shorrock (2006) approximately 37% of dwellings in Great Britain that could potentially install cavity wall insulation had done so by 2004, making the remaining majority candidates for this improvement. Loft insulation and double-glazing had achieved higher penetrations, but potential still exists for both of these measures. New build housing will be substantially more energy efficient than the existing stock, with year-on-year improvement in the building regulations and a government target to make all new homes zero carbon post 2016 in CLG (2007a).

Whilst questions remain regarding the "comfort taking" rebound effect, it appears likely that thermal energy demand will decrease on a per-dwelling basis in the future, driven by government policies and regulations incentivising (or mandating) uptake of insulating measures and improvements in air-tightness. The success of such approaches varies from dwelling to dwelling, and is strongly dependent on the age and construction type of the dwelling, so a large distribution of thermal demands could still be expected even as mean thermal demand declines.

### 2.1.3 Distributions of Annual Energy Consumption

Choosing a representative set of dwellings for analysis requires knowledge of the spread of annual electricity and thermal demands. Figure 3 is an estimated probability density function for annual electricity demand for a set of energy-efficiency houses in the Milton Keynes Energy Park, and Figure 4 is a histogram of annual thermal demand in the UK adapted from Mariyappan (2004). Whilst it is not expected that Figure 3 or Figure 4 are

representative of the entire UK housing stock, they are informative with regard to understanding distributions of annual demand.

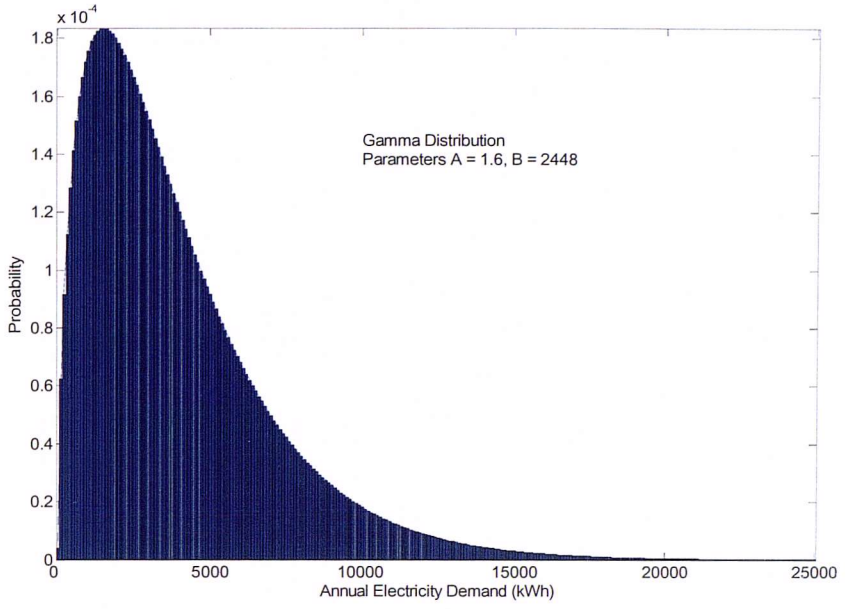



**Figure 3: Estimated Probability Density Function for Annual Electricity Demand in England Based on Data from Milton Keynes Energy Park**

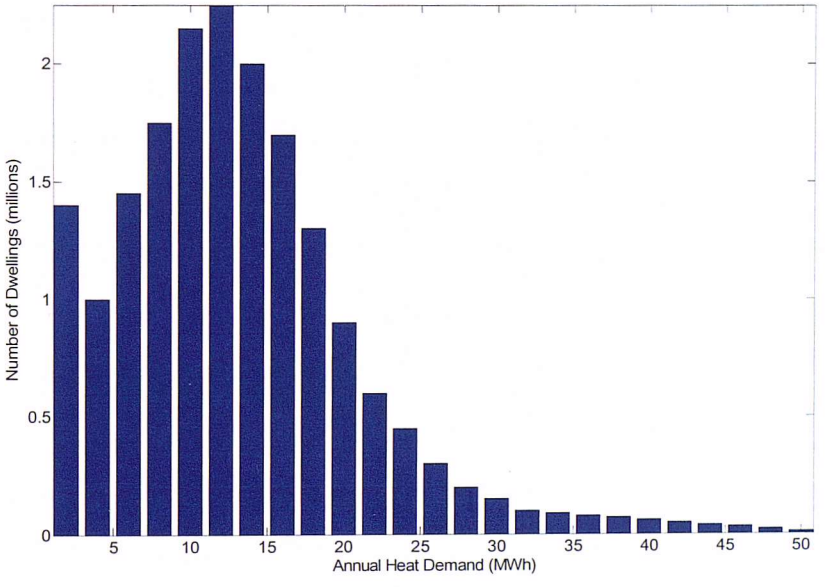



**Figure 4: Distribution of Annual Heat Demand in the UK Based on Mariyappan (2004)**

Both distributions of annual demand in Figure 3 and Figure 4 show a density of dwellings around the median demand, and clear long tail to the right. This spread and skew of the distributions suggests that use of a single specific demand profile may produce overly deterministic results regarding the broad performance of the technologies because a) the

distributions are not centred around the mean, and b) the spread of the distributions is significant. This implies that analysis of a single dwelling has limited relevance where the intention is to assess performance of a significant penetration of the technology, and a selection of dwelling variants with a variety of annual demand characteristics should be drawn upon instead. A representative selection of dwellings would reflect the spread of demands, including very low, median, mean, and a range of higher demand scenarios to capture the skew towards larger values. This is the approach adopted in this thesis to characterise demand.

### 2.1.4 Volatility of Demand in Single Residential Dwellings

A further consideration in order to characterise energy demand relates to how rapidly it can change from minute-to-minute. The observed time-dependence of energy demand in single residential dwellings is significantly different to patterns of aggregate energy demand. Aggregate electricity demand profiles are typically smooth, with relatively predictable changes between time periods, days, seasons, etc. Electricity demand in a single residential dwelling is volatile, with frequent brief peaks overlaying slightly more predictable cyclic loads. The volatility of the electricity load is due to use of appliances such as kettles, toasters, hobs and washing machines which have significant (i.e. several $kW_e$) demand occurring over relatively brief periods. Dwelling occupants operation of these appliances is discretionary, indicating that instantaneous load in a single dwelling is difficult to predict. According to Peacock and Newborough (2007), the daily load factor[3] of an aggregation of 50 residential demand profiles is roughly 0.4 whilst the annual load factor of a single residence is much lower at approximately 0.1, reflecting the "peaky" nature of individual dwelling residential demand, and the smoothing effect of load aggregation.

[3] Daily load factor is defined as the mean load divided by the peak load, over one day.

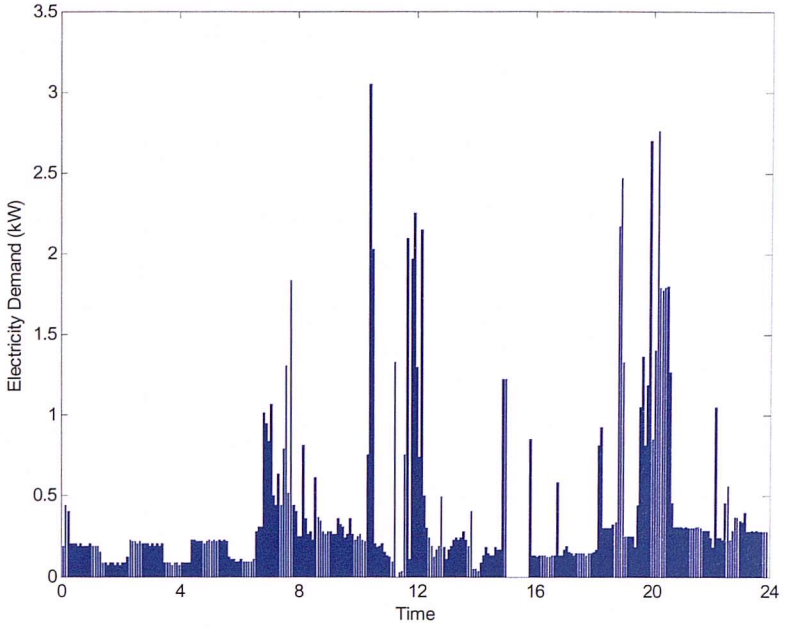



**Figure 5: Example Electricity Demand Profile for One Day in a Single Residential Dwelling in the UK**

Figure 5 shows a typical electricity demand profile for a residential dwelling, based on 5-minute resolution data produced by a field trial of domestic photovoltaic systems (details of the trial were published in DTI (2006a)). This demonstrates the volatility of residential demand and suggests that a fine time resolution is necessary to capture its characteristics. The impact of choosing various time resolutions for economic and environmental studies is analysed later in this thesis in section 5.1.

### 2.1.5 Building Variants and Demand Profiles Chosen for Analysis

In order to perform the desired investigations regarding micro-CHP is it necessary to choose relevant demand situations for analysis. Ideally each dwelling in the entire housing stock would be represented explicitly, but this is neither practical in terms of data gathering nor computationally tractable. Therefore the information presented above in sections 2.1.1 to 2.1.4 above, which explored important characteristics and trends in demand in individual dwellings, the spread in distributions of annual demand, and the volatile nature of that demand act as a guide for identifying demand situations for analysis.

Spread of annual thermal demand suggests that a range of demand scenarios should be investigated, and could relate to existing, refurbished and new building stock given significant impact of varying levels of insulation. The spread of annual electricity consumptions also suggest that a range of demand profiles (as opposed to consideration of

the average dwelling only) is necessary. Finally, the volatility of demand suggests that fine temporal resolution may be required to properly reflect the physical situation.

As such, five basic building variants based on construction type are chosen for analysis, with further variants with respect to the potential for refurbishment, and the characteristics of new-build dwellings. The building variants represent a range of thermal and electrical demands commensurate with annual demand distributions in Figure 3 and Figure 4, and demand data at 5-minute time-steps is sourced to represent electrical and thermal demands. The vital statistics of the chosen building variants are presented in Table 1. The building variants chosen are based on the census categories for construction type because they have reasonable correlation with floor area which in turn has strong correlation with annual space heating demand. Additionally significant time-series exist for their numbers in Great Britain, making interpretation of results in terms of market size and future potential plausible (although such analysis is beyond the scope of this thesis). Whilst precise figures for improvement in insulation U-values due to refurbishment and for new dwellings are debatable as compliance with the building regulations is uncertain, the chosen changes in heat loss coefficients represent observed trends reported by Utley and Shorrock (2006) reasonably well.

The data presented in Table 1[4] were sourced as follows: Electrical demand profiles are from the DTI (now BERR) Domestic Photovoltaic Field Trials, consisting of approximately 70 dwellings monitored at 5-minute time resolution over a period of 3 years. A selection of these dwellings has been identified based on data quality, and the considerations with respect to characterisation of residential demand as discussed above. Space heating demands were drawn from research related to Hawkes et al. (2007) which generated profiles using TAS building simulation software (EDSL (2004)), assuming building heat loss coefficients and typical building layouts. Domestic hot water (DHW) demand profiles are sourced from the International Energy Agency Annex 26 on HVAC systems (DHW profiles were developed within the scope of the Solar Heating and Cooling Program of the International Energy Agency (IEA SHC), Task 26: Solar Combisystems), which produced a DHW profile generator. This generator creates a profile by bottom-up superposition of draws on hot water based on a probabilistic representation of occupant behaviour and type

[4] Note that Table 1 also presents data regarding an expected annual thermal consumption if internal temperatures were 25°C. These profiles are not used in the analysis presented in later chapters, but the interested reader could deduce micro-CHP performance for a high internal temperature scenario using this information combined with results presented in Chapters 5, 6, 7, and 8.

of draw required. The generator is designed to create profiles based on estimated daily DHW usage, measured in litres. The DHW information presented in Table 1 correspond to 100 litre/day, 200 litre/day and 300 litre/day profiles, with corresponding energy demands calculated via assumption of DHW-to-inlet temperature difference and the specific heat of water.

| | Terraced House | Semi-Detached House | Detached House | Bungalow | Flat |
|---|---|---|---|---|---|
| Number of Properties (thousands) in 2001 | 6,766 | 6,936 | 3,956 | 2,051 | **4,639** |
| Annual Electricity Demand (kWh) | Mean<br>4,300 | Above Mean<br>5,400 | Large<br>8,300 | Median<br>3,000 | **Small**<br>**1,100** |
| Annual Domestic Hot Water Demand (kWh) | 3,360 | 6,430 | 6,470 | 1,930 | **1,970** |
| Existing Dwellings | | | | | |
| Heat Loss (W/ºC) Shorrock and Utley (2003) | 243 | 276 | 365 | 229 | **182** |
| Annual Space Heating Demand with 20ºC Internal Winter Temperature (kWh) | 14,600 | 16,600 | 22,000 | 13,100 | **11,000** |
| Annual Space Heating Demand with 25ºC Internal Winter Temperature (kWh) | 19,900 | 22,600 | 30,000 | 18,800 | **15,000** |
| Annual CO2 Emissions for Electricity and Heat Use (at 20°C) | 5,040 | 5,480 | 6,680 | 4,860 | **4,240** |
| Refurbished Dwellings | | | | | |
| Heat Loss (W/ºC) | 176 | 199 | 311 | 147 | **117** |
| Annual Space Heating Demand with 20ºC Internal Winter Temperature (kWh) | 10,600 | 12,000 | 18,700 | 8,900 | **7,000** |
| Annual Space Heating Demand with 25ºC Internal Winter Temperature (kWh) | 14,400 | 16,300 | 25,500 | 12,000 | **9,600** |
| Annual CO2 Emissions for Electricity and Heat Use (at 20°C) | 4,160 | 4,470 | 5,950 | 3,780 | **3,360** |
| New Dwellings | | | | | |
| Heat Loss (W/ºC) | 107 | 121 | 189 | 88 | **70** |
| Annual Space Heating Demand with 20ºC Internal Winter Temperature (kWh) | 6,400 | 7,300 | 11,300 | 5,300 | **4,200** |
| Annual Space Heating Demand with 25ºC Internal Winter Temperature (kWh) | 8,800 | 9,900 | 15,500 | 7,200 | **5,700** |
| Annual CO2 Emissions for Electricity and Heat Use (at 20°C) | **3,230** | **3,430** | **4,310** | **2,990** | **2,740** |

**Table 1: Space Heating Demand for by Dwelling Type for Current Stock, Refurbished Stock, and New Stock in Great Britain (Office for National Statistics (2004), Shorrock and Utley (2003))[5]**

[5] Heat loss coefficients for refurbished and new dwellings based on assumed U-values. Refurbished dwellings U-values: Roof = 0.35W/m²ºC, Floor = 0.45W/m²ºC, Walls = 0.6W/m²ºC, Windows = 3.0W/m²ºC. New dwellings U-values: Roof = 0.16W/m²ºC, Floor = 0.25W/m²ºC, Walls = 0.35W/m²ºC, Windows = 2.1W/m²ºC (approx 2002 Building Regulations).

## 2.2 Micro-CHP Technologies

This section presents a brief technical description, characteristics and recent developments for each of the micro-CHP prime mover technologies investigated in this thesis; Stirling engines, internal combustion engines (ICE), and two fuel cell based systems (Polymer Electrolyte Membrane Fuel Cells (PEMFC), and Solid Oxide Fuel Cells (SOFC)). Other micro-CHP technologies, such an organic Rankine cycle, Ericson cycle and other fuel cell based systems have been proposed, but as they are not a focus of commercial attention they are not included in this research.

For the purposes of this thesis micro-CHP is defined as a cogeneration system designed for relatively simple installation in a residential dwelling according to current standards and regulations. As per HM Government (2002), a statutory instrument that includes connection regulations, a micro-CHP system should not exceed 16 amps per phase if it is to be connected without prior consent of the Distribution Network Operator (DNO) and be eligible for aggregate rather than half-hourly metering. This corresponds to a maximum capacity of just under $4kW_e$ for a single-phase 230 Volt connection. Therefore the maximum capacity of prime mover considered in this thesis is set at $4kW_e$. The system is installed on the customer side of the meter, and is complemented by a "bi-directional" meter (which has, at least, the ability to meter both import and export of electricity for the premises). The micro-CHP system consists of a prime mover (i.e. engine or fuel cell) and balance of plant (BOP). The BOP would typically include a supplementary thermal system to meet heat demand not met by the prime mover CHP unit. For example, this supplementary thermal system may be an integrated condensing boiler, or a tail-gas burner designed for this supplementary use. BOP also includes all other components required to deliver heat and power to the dwelling/grid, such as heat exchangers, manifold arrangements, insulation, pumps, blowers, compressors, control systems, power conditioning and inverters where necessary. This thesis focuses on the characteristics of the prime mover technologies, with relatively broad assumptions regarding the performance of the BOP, although some results do bear upon these components.

All micro-CHP systems modelled in this thesis are assumed to have an operating lifetime of 10 years; approximately equivalent to the average working life of competing boiler systems. This assumption is realistic for near term engine-based systems and near-to-medium term fuel cell based systems.

### 2.2.1 Stirling Engine Based Systems

Stirling engine micro-CHP is based on the closed-cycle piston heat engine concept developed by Robert and James Stirling around 1816. It operates via a temperature difference between two ends of a closed cylinder with internal piston. The working fluid cycles between hot and cold ends of the cylinder via a regenerative heat exchanger. The thermodynamic cycle consists of an isothermal expansion, a constant-volume heat removal, an isothermal compression, and a constant volume heat addition. External combustion – for example of natural gas – is typically the heat source for hot end of the cylinder, but many other fuels may also be used.

Stirling engine based micro-CHP systems are arguably close to entering the commercial market, with demonstration projects underway in the UK and elsewhere. An example of Stirling engine micro-CHP is the $1kW_e$ WhisperGen system developed by Whisper Tech and described in Whisper Tech Ltd (2006). The UK energy supplier E.ON UK announced a distribution agreement for the WhisperGen system, with an initial arrangement to install 80,000 systems (Whisper Tech Ltd (2004)) at an installed cost of £3000 each, although this project appears to be on hold at present.

Stirling engine electrical efficiency in recent field trial results published by the Carbon Trust (2007) was low at around 6-8%, with average thermal efficiency around 68-72%. This trial also concluded that the units could provide $CO_2$ emissions reductions in residential dwellings where thermal demand was large and consistent. Units can start rapidly, and may be controlled to operate at a variety of set-points, although emerging early-market technologies generally exhibit only on/off operation.

Beausoleil-Morrison et al. (2007) and Arndt et al. (2007) carried out modelling of a variety of micro-CHP technologies, including Stirling engines, where models where calibrated to the performance of real systems. In general these models report similar performance characteristics to that of the UK field trials. Part-load performance data for small $1kW_e$ Stirling engine systems is not widely available, and as such approximations based on Arndt et al. (2007), Beausoleil-Morrison et al. (2007) are used as central estimates of mature system performance in this research. The central estimates of key performance parameters for a $1kW_e$ Stirling engine system are shown in Table 2.

| Parameter | Central Estimate | Information Source/s |
|---|---|---|
| **LHV electrical efficiency (part load, full load)** | 0.2kW$_e$ – 0.5kW$_e$: 6%<br>0.5kW$_e$ – 1.0 kW$_e$: 10% | Carbon Trust (2007), Kuhn et al. (2008), Peacock and Newborough (2005) |
| **LHV prime mover overall efficiency (part load, full load)** | 0.2kW$_e$ – 0.5kW$_e$: 80%<br>0.5kW$_e$ – 1.0 kW$_e$: 90% | Carbon Trust (2007), Kuhn et al. (2008) |
| **Integrated supplementary thermal system LHV efficiency** | 86% | Carbon Trust (2007) |
| **Minimum set-point (i.e. max turndown)** | 0.2kW$_e$ | Estimate based on Whisper Tech Ltd (2006) |
| **Maximum Ramp Constraints** | None (i.e. load following possible) | Kuhn et al. (2008) |
| **Start-up Energy Consumption** | 10W$_e$h electricity, 500W$_{th}$h gas | Arndt et al. (2007), Carbon Trust (2007) |
| **Shutdown Energy Consumption** | 25 W$_e$h electricity | Arndt et al. (2007), Carbon Trust (2007) |
| **Minimum Up-time, Minimum Downtime** | 10 minutes, 10 minutes | Carbon Trust (2007) |

**Table 2: Central Estimates of Performance of 1kWe Stirling Engine Micro-CHP System**

### 2.2.2 Internal Combustion Engine Based Systems

Internal combustion engine (ICE) technology is well understood and frequently applied, with a long history in transport and stationary energy applications. ICE-based micro-CHP technology is currently available, and can claim to be the most commercially successful class of micro-CHP to date. In the UK and Germany the Baxi/Senertec DACHS system is a 5kW$_e$ CHP generator suitable for very large residential or multi-family dwellings. This system has been reasonably successful in Europe, particularly Germany, with more than 12,000 installations. In the USA and Japan, Honda is supplying ICE-based micro-CHP in the 1.0 and 1.2kW$_e$ range through various partnerships. In Japan Tokyo Gas Co (2005) identified a target market of 15,000 installations per year of ECOWILL (based on the Honda ICE technology) systems, with each system costing approximately £3,500 installed. Honda Motor Co (2007) reported that more than 50,000 of these units had been sold by July 2007. Most ICE installations to date are outside dwellings or in basement/utility rooms, raising questions regarding their suitability to the UK market where wall-hung units suitable for kitchen installation may form an important part of the market. Electrical efficiency reported for the ECOWILL system in Osaka Gas Co et al. (2004) was 20% LHV, with overall efficiency around 85% LHV. Furthermore, a steady state efficiency curve for a 6kW$_e$ ICE micro-CHP system has been reported by Arndt et al. (2007) and is reproduced in Figure 6.

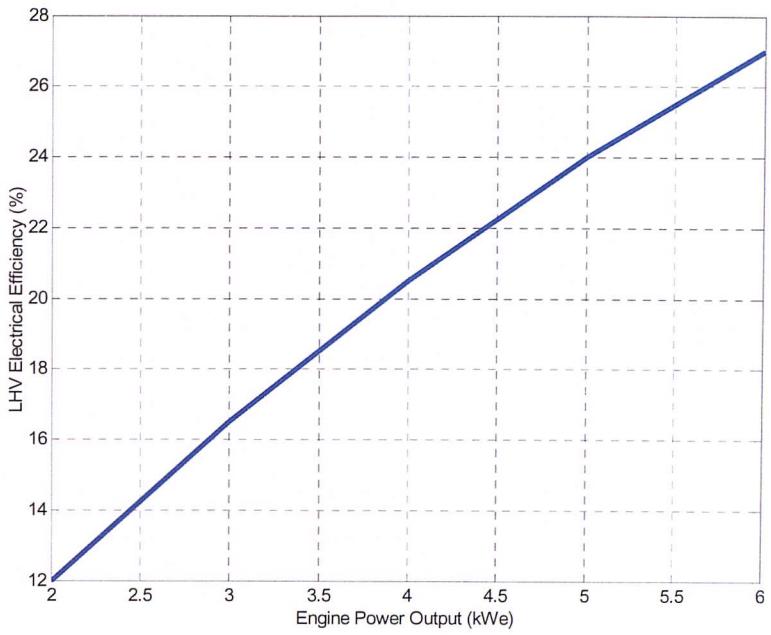



**Figure 6: Steady State Part-load LHV Electrical Efficiency of a 6kWe ICE-based Micro-CHP System as reported in Arndt et al. (2007)**

Detailed experimental investigations of small 1kW$_e$ ICE-based micro-CHP systems are not present in the literature, but larger system (such as the BAXI unit mentioned above) have been examined in Arndt et al. (2007). The central estimates of the performance of a 1kW$_e$ ICE-based micro-CHP system presented in Table 3 have been synthesised from basic data referenced above regarding the ECOWILL system and more detailed performance data for larger systems available in Arndt et al. (2007) and Carbon Trust (2007).

| Parameter | Central Estimate | Information Source |
|---|---|---|
| **LHV electrical efficiency (part load, full load)** | 0.2kW$_e$ – 0.5kW$_e$: 10%<br>0.5kW$_e$ – 1.0 kW$_e$: 20% | Estimate based on Arndt et al. (2007), Honda Motor Co (2007) |
| **LHV prime mover overall efficiency (part load, full load)** | 0.2kW$_e$ – 0.5kW$_e$: 80%<br>0.5kW$_e$ – 1.0 kW$_e$: 85% | Estimate based on Arndt et al. (2007), Honda Motor Co (2007) |
| **Integrated supplementary thermal system LHV efficiency** | 86% | Carbon Trust (2007) |
| **Minimum set-point (i.e. max turndown)** | 0.2kW$_e$ | Estimate based on Arndt et al. (2007) |
| **Maximum Ramp Constraints** | None (i.e. load following possible) | Estimate based on Arndt et al. (2007) |
| **Start-up Energy Consumption** | 10W$_e$h electricity, 500W$_{th}$h gas | Estimate based on Arndt et al. (2007) |
| **Shutdown Energy Consumption** | 25 W$_e$h electricity | Estimate based on Arndt et al. (2007) |
| **Minimum Up-time, Minimum Downtime** | 10 minutes, 10 minutes | Estimate based on Arndt et al. (2007) |

**Table 3: Central Estimates of Performance of a 1kWe ICE-based Micro-CHP System**

### 2.2.3 Fuel Cell Based Systems

Fuel cells are an emerging technology that is fundamentally different to the engine-based systems discussed above. The fuel cell concept was first conceived in 1839 by Sir William Robert Grove, who realized that reversing the process of electrolysis (splitting water to form hydrogen and oxygen using electricity) results in a process that would create electricity. Although there are several different types of fuel cells, they all operate on the same basic concept of electrochemical reaction of fuel and oxygen to produce water (and other products depending on the fuel), direct current electricity, and heat. In general fuel cells benefit from high part-load efficiency and modular compact design, but are challenged with regard to a number of materials issues leading to degradation (i.e. gradual demise of performance characteristics), use of exotic or expensive materials, and intolerance to fuel impurities.

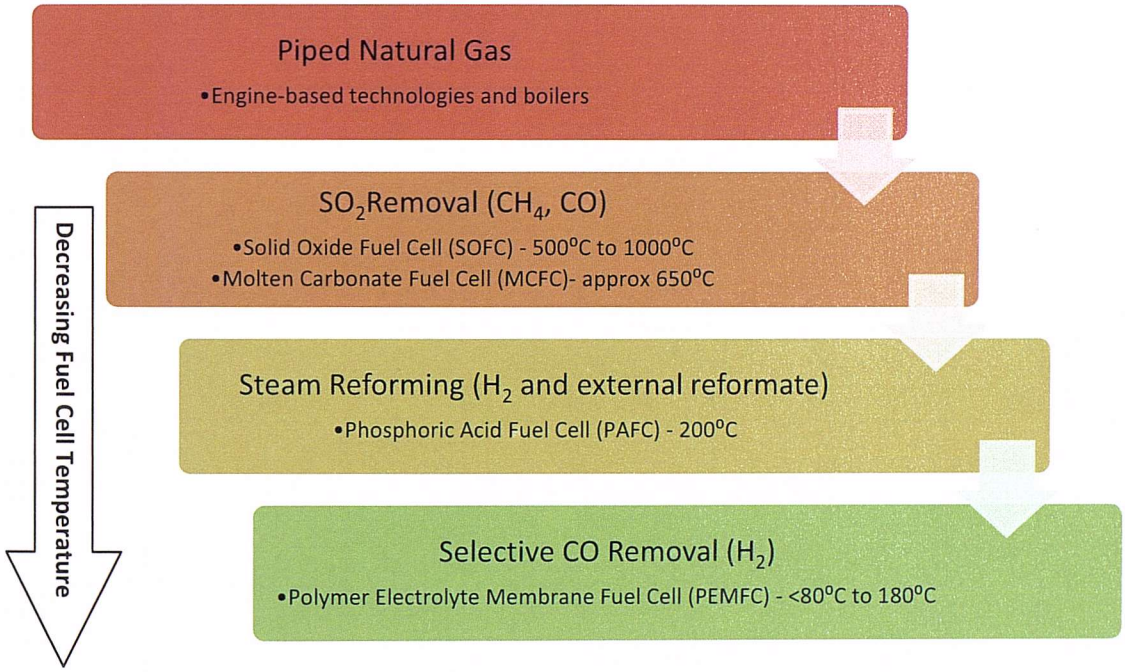



**Figure 7: Fuel Processing Requirements for Fuel Cell Systems and Engine/Boiler Systems (and Relationship with Fuel Cell Operation Temperature)**

Figure 7 shows the relationship between fuel processing requirements based on UK piped natural gas and the types of fuel cells (with engine and boiler systems included for comparison) that correspond to each level of fuel purity. High temperature systems such as solid oxide fuel cells (SOFC) are able to "reform"[6] the hydrocarbon fuel internally due to high temperature of operation, removing the need for further fuel processing steps. Lower

[6] Reforming refers to the process whereby heavy hydrocarbons and organic molecules are broken down into simpler molecules through breaking of carbon-carbon bonds.

temperature systems, such as polymer electrolyte membrane (PEMFC) systems require almost pure hydrogen necessitating the inclusion of a fuel reformer[7], with associated efficiency losses, in hydrocarbon fuelled systems. However the relatively lower temperature of operation of PEMFC (approx 80°C for low temperature systems, up to 180°C for "high temperature" systems) entails simpler balance of plant in that components are not required to withstand significant temperature gradients. The engine-based systems and conventional boiler systems require no fuel processing and typical combustion reactions produce temperatures around 900°C.

The ideal efficiency curve for a fuel cell is significantly different to that of an engine. Engine efficiency is theoretically limited by the Carnot efficiency where the ideal value is related to the temperature difference between two reservoirs. Fuel cells produce electricity through an electrochemical reaction, and are therefore not limited by the combustion-related Carnot efficiency. Theoretical fuel cell efficiency is limited by the Gibbs Free Energy and Nernst potential, predicting very efficient operation. However, comparing ideal efficiencies is not a good indicator of performance that can be achieved in practice. Practical fuel cell efficiency is limited by reaction kinetics (activation losses), ohmic losses related to resistance in components, and mass transport losses related to reactant depletion at reaction sites. When a fuel cell stack is integrated into a micro-CHP system further losses occur due to inefficiencies of balance of plant (BOP). These losses are somewhat similar across micro-CHP technologies (e.g. losses associated with pumping to deliver space and water heating, fan assisted flue, control electronics) but fuel cell based systems require additional components (e.g. DC-AC convertors and fuel processing related BOP) with corresponding additional losses.

Two types of fuel cell electricity generators have the focus of commercial attention for micro-CHP systems; solid oxide fuel cells (SOFC) and polymer electrolyte membrane fuel cells (PEMFC). Developments and characteristics of these two types of fuel cell are briefly discussed below. EG&G Technical Services Inc (2004) provides a more comprehensive technical description of issues related to these technologies in the Fuel Cell Handbook, but the following provides sufficient background for the purposes of this research.

[7] A fuel reformer (required with some fuel cells as discussed) is an additional hardware component which reacts hydrocarbons with water vapour at high temperature to produce a gas that contains hydrogen. Its presence entails additional efficiency losses for the system as a whole. PEMFCs require a fuel reformer, whilst SOFCs do not.

### *2.2.3.1 Solid Oxide Fuel Cell Based Systems*

Solid Oxide Fuel Cells (SOFCs) are high temperature fuel cells that use a solid electrolyte to conduct oxygen ions. The two geometries of SOFCs that are being developed are (a) tubular and (b) planar types. The tubular configuration is exclusive for SOFCs while planar configuration is used in all other types of fuel cells. SOFCs under development may also be classified by temperature of operation. The two general temperature ranges are intermediate temperature (approximately 550 – 800°C) and high temperature (approx 800-1000°C). These temperature ranges offer very high quality waste heat streams, implying relatively simple integration with existing dwelling heat delivery systems. As discussed above, SOFC stacks benefit from the ability to "reform" a hydrocarbon fuel on the anode, thereby creating hydrogen and carbon monoxide inside the system without the need for a separate fuel reformer to produce hydrogen.

Substantial research and development of SOFC-based micro-CHP systems is underway. For example, planar anode-supported high temperature systems are under development at Ceramic Fuel Cells Limited ( 'CFCL wins Euro approval for microgen system' (2008)), and planar metal-supported intermediate temperature systems are being developed at Ceres Power ( 'Ceres Power funding to develop manufacturing' (2007)). Both of these companies claim to be close to market. Centrica (a large residential energy Supplier trading under the name "British Gas") announced a development deal with Ceres Power aimed at bringing the technology to market within the next few years ( 'Ceres Power funding to develop manufacturing' (2007)), and CFCL has a development and distribution deal with E.ON ( 'CFCL selects UK partner for m-CHP project' (2007)).

As this technology is the focus of research and development, it would not be prudent to use performance data from existing prototype systems to estimate the capabilities of near to medium term systems. As such, modelling efforts are relied upon to create a picture of more mature SOFC-based micro-CHP system performance. Aguiar et al. (2004) presented a steady-state model of an anode-supported SOFC-stack. This representation was combined with balance of plant to create a steady-state efficiency performance map of a medium-term SOFC-based system in Hawkes et al. (2006) and refined in Hawkes et al. (2007). This efficiency characterisation, displayed in Figure 8, is used to inform the present study.

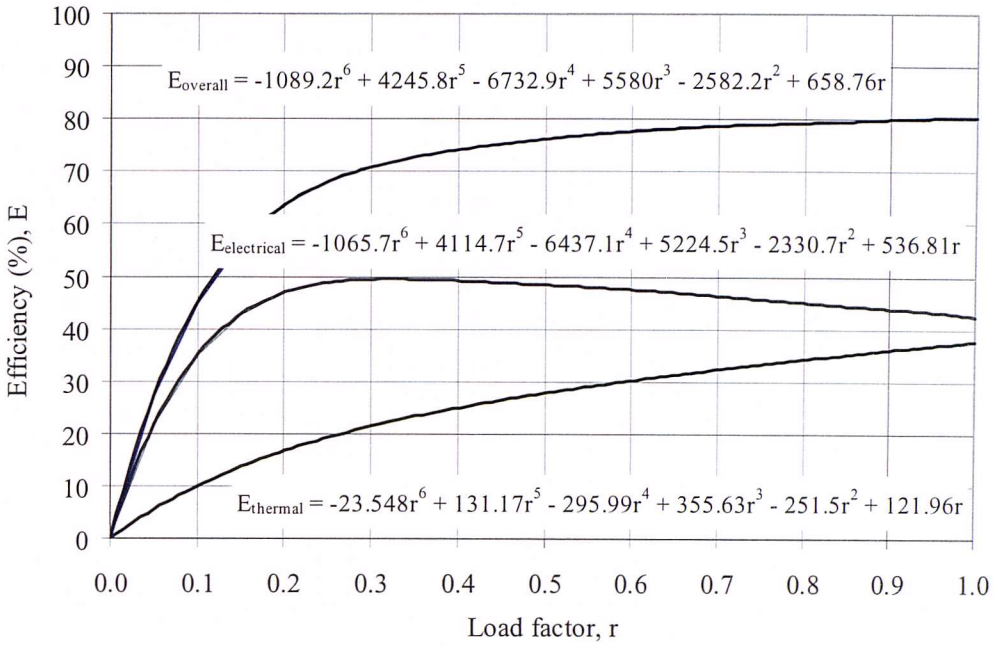



**Figure 8: SOFC system electrical, thermal and overall efficiencies versus load factor and corresponding fit functions as reported in Hawkes et al. (2007)**

This modelled performance is combined with start-up and shutdown data from experimental field trials in Arndt et al. (2007) to arrive at central estimates of mature system performance for a 1kW$_e$ SOFC-based micro-CHP system used in this research. These are displayed in Table 4.

| Parameter | Central Estimate | Information Source |
|---|---|---|
| **LHV electrical efficiency (part load, full load)** | 0.2kWe – 0.5kWe: 45%<br>0.5kWe – 1.0kWe: 40% | Hawkes et al. (2007) and Arndt et al. (2007) |
| **LHV prime mover overall efficiency (part load, full load)** | 0.2kWe – 0.5kWe: 75%<br>0.5kWe – 1.0kWe: 80% | Hawkes et al. (2007) and Arndt et al. (2007) |
| **Integrated supplementary thermal system LHV efficiency** | 86% | Carbon Trust (2007) |
| **Minimum set-point (i.e. max turndown)** | 0.2kW$_e$ | Author's estimate |
| **Maximum Ramp Constraints** | None (i.e. load following possible) | Estimate based on Aguiar et al. (2004) |
| **Start-up Energy Consumption** | 25W$_e$h electricity, 2000W$_{th}$h gas | Estimate based on Arndt et al. (2007) |
| **Shutdown Energy Consumption** | 25W$_e$h electricity | Estimate based on Arndt et al. (2007) |
| **Minimum Up-time, minimum downtime** | 60 minutes, 60 minutes | Author's estimate |

**Table 4: Central Estimates of Performance of a 1kWe SOFC-based Micro-CHP System**

There is no established capital cost of SOFC-based micro-CHP systems, although a variety of targets exist with relation to system research and development, and in the academic literature. The Solid State Energy Conversion Alliance (SECA) has set a cost target of US$400/kW$_e$ for mass-manufactured stacks, although this includes no balance of plant.

Further details of SECA are available in National Energy Technology Laboratory (2008). In the UK it has been suggested that SOFC-based micro-CHP should begin to become competitive at around £500/$kW_e$ marginal price (i.e. the price between the SOFC-based system and a competing conventional reference system) in Hawkes and Leach (2005a), which also noted significant sensitivity of this result to a variety of factors. Staffell et al. (2008) reported cost targets for SOFC micro-CHP of 740€/$kW_e$.

### *2.2.3.2 Polymer Electrolyte Membrane Fuel Cell Based Systems*

Polymer Electrolyte Membrane Fuel Cells (PEMFC) exhibit low temperature operation, and use a solid polymer such as Nafion from DuPont as the electrolyte. For micro-CHP applications the fact that PEMFCs operate at around 80°C presents challenges for delivering space heating and hot water requirements, which generally require slightly higher system outlet temperatures. To circumvent this issue (and other fuel purity requirement issues) high temperature PEMFC systems are under development, operating at temperatures up to approximately 180°C. PEMFCs require hydrogen fuel, and as such a fuel reformer is included in systems fuelled by hydrocarbons such as natural gas, as is the case examined in this thesis.

Commercial activity regarding development of PEMFC for micro-CHP is also apparent in a number of companies/collaborations: Ballard (undated) is marketing low temperature PEMFC for integration into micro-CHP, and is further developing the technology in Japan through joint venture Ebara Ballard. Also, as announced in 'EC funds transatlantic collaboration between Plug Power, Vaillant' (2007) high temperature PEMFC technology is also under development. The present capital cost of PEMFC systems is high, and does not assist its cause in the stationary power generation market. However, mass-manufacturing techniques are expected to bring down those costs and may enable PEMFC to compete with conventional generators and other fuel cells in the medium term.

Similarly to SOFC-based systems, PEMFC technology is the subject of research and development, and as such it would not be prudent to use results of experimental investigations into prototype systems to depict mature technology. Therefore modelling studies are relied upon to characterise a medium-term PEMFC, with estimates taken from experimental studies where deemed appropriate. Central estimates of PEMFC micro-CHP operating characteristics used in this thesis are based on steady-state modelled systems presented in Wallmark and Alvfors (2003) and experimental results presented in Arndt et al. (2007). A part-load LHV efficiency profile adapted from Wallmark and Alvfors (2003) is

presented in Figure 9, and central estimates of key techno-economic parameters for a 1kW$_e$ PEMFC-based micro-CHP system are displayed in Table 5.

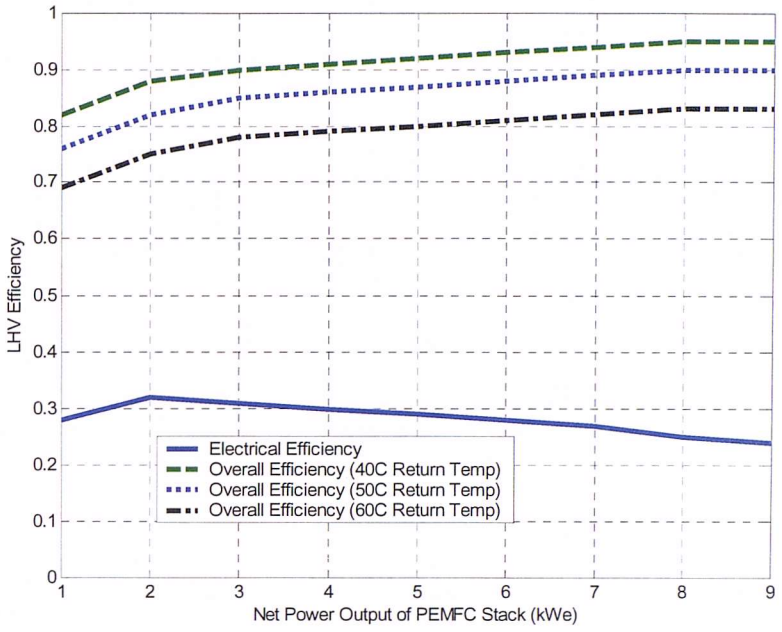



**Figure 9: Steady State Part-load Efficiency Profile for PEMFC Micro-CHP System Adapted from Wallmark and Alvfors (2003)**

| Parameter | Central Estimate | Information Source |
|---|---|---|
| **LHV electrical efficiency (part load, full load)** | 0.2kWe – 0.5kWe: 30%<br>0.5kWe – 1.0kWe: 26% | Wallmark and Alvfors (2003), Arndt et al. (2007) |
| **LHV prime mover overall efficiency (part load, full load)** | 0.2kWe – 0.5kWe: 75%<br>0.5kWe – 1.0kWe: 85% | Wallmark and Alvfors (2003), Arndt et al. (2007) |
| **Integrated supplementary thermal system LHV efficiency** | 86% | Carbon Trust (2007) |
| **Minimum set-point (i.e. max turndown)** | 0.2kW$_e$ | Author's estimate |
| **Maximum Ramp Constraints** | None (i.e. load following possible) | Wallmark and Alvfors (2003) |
| **Start-up Energy Consumption** | 25W$_e$h electricity, 1500W$_{th}$h gas | Arndt et al. (2007) |
| **Shutdown Energy Consumption** | 25W$_e$h electricity | Arndt et al. (2007) |
| **Minimum Up-time, minimum downtime** | 60 minutes, 60 minutes | Author's estimate |

**Table 5: Central Estimates of Performance of a 1kWe PEMFC-based Micro-CHP System**

# Chapter 3: **Review of Modelling Approaches and Results**

Building upon broader background presented in Chapter 2, it is necessary to appreciate the studies that precede this one to establish currently accepted modelling approaches, review the results they have contributed, and understand the potential market for micro-CHP products. This chapter serves to address these concerns, and as such provides more specific context for modelling and analyses presented in later chapters.

A review of selected micro-CHP modelling approaches is presented, followed by a discussion of importance and choice of "reference" systems investigated, and finally a review of performance and market studies to date.

## 3.1 Micro-CHP Modelling Approaches in the Literature

Conventional power system models are rarely appropriate for analysing onsite generation in the residential sector. This is because they do not adequately capture the dynamics of residential energy demand, and rarely consider a sufficiently diverse cross section of demand scenarios. To address their shortcomings, models designed to analyse the economic and environmental performance of residential generation technologies such as micro-CHP are becoming more common in the literature. Whilst the aims, assumptions and structures of these models vary greatly, they can generally be classified as either simulation or optimisation approaches. Simulation models performance over time using a set of (potentially temporally interdependent) physical relationships. Optimisation models performance (potentially over time) where some variables are not fixed and the system can adapt according to some objective. Either broad modelling approach can be very simplistic or extremely sophisticated.

Optimisation approaches can be further classified into those regarding system design, and those regarding system operation. Conversely, simulation approaches exist in a variety of forms and consider many different boundaries for analysis. The approaches and typical assumptions of each broad modelling approach are discussed below.

### 3.1.1 Optimisation of System Operation (Unit Commitment)

Optimisation of system operation is a frequently tackled area of research considering what is termed the "unit commitment" problem. Unit commitment is usually concerned with minimising cost or maximising profit for operation of a large power plant or set of energy

resources, subject to a variety of operational or other constraints. Decision variables are typically the generator's set-points in each time period over a defined horizon. A review of unit commitment methodologies is available in Padhy (2004). There are relatively few examples of application of unit commitment mathematics to combined heat and power systems, and even fewer considering unit commitment of micro-CHP systems. Micro-CHP systems are typically assumed to be heat-led and requiring only very basic control, but recent analysis in Hawkes and Leach (2007) has indicated that this assumption may lead to poor economic and environmental performance of systems. Indeed much more complex control approaches have been investigated in the literature, ranging from a fuzzy logic based study by Entchev (2003), to complex computational intelligence control algorithms in Matics and Krost (2008) and virtual power plant[8] strategies in van Dam et al. (2008).

Of particular interest to this research are studies that have applied unit commitment methodologies to the case of combined heat and power. Thorin et al. (2005) presented a mixed integer linear programming approach to maximise the profit of a large district heating CHP system trading on an electricity spot market and serving one of two possible heating networks. El-Sharkh et al. (2005) developed a unit commitment approach for fuel cell power plants based on mixed integer linear programming where evolutionary programming based solution methodology was adopted. This model was applied to perform cost-related sensitivity for optimal operation of a PEMFC power plant in El-Sharkh et al. (2006a), and to investigate the impact of recovered thermal energy management on the economics of operation of a PEMFC power plant in El-Sharkh et al. (2007). The systems investigated by Thorin were in the region of 100$MW_e$ and those considered by El-Sharkh were 250$kW_e$. Whilst model structures are largely similar to that developed in this study, it is clear that these relatively large systems are not subject to the same operating environment or technical challenges as a micro-CHP system, and differing constraints have been applied. Whilst El-Sharkh et al. (2006a) has investigated CHP performance sensitivity with respect to energy price and selected thermal management options for the United States situation, they have not investigated sensitivities to important technical design parameters (such as overall efficiency, turndown ratio, etc, investigated in this research) or compared performance with that of a reference system. None of the reviewed studies considered fuel cell degradation in the context of a unit commitment formulation.

[8] A virtual power plant (VPP) is a set of decentralised energy resources operating co-operatively. Aims of a VPP may include trading in an electricity market, or providing network ancillary services.

### 3.1.2 Engineering Design Optimisation

Optimisation of system design is also an active area of research, particularly with respect to fuel cell systems. Pinch design[9] of small fuel cell CHP systems has been undertaken by Wallmark and Alvfors (2002), Wallmark (2004) , Colella (2002) and Colella (2003), and the economics of such systems was analysed in Wallmark and Alvfors (2003). Maréchal et al. (2005) and Palazzi et al. (2007) also utilised pinch design and developed an approach where system efficiency is maximised, and installed cost is minimised using a relatively detailed technical system representation and multi-objective optimisation. These techniques are critical to technology development and specifically for design of balance of plant for maximisation of system overall efficiency. However, they do not provide a feedback loop between the optimisation of design and the operational strategy for the prime-mover. Nor do they explicitly consider design in terms of performance in comparison with a competing conventional "reference system".

### 3.1.3 System Simulation

Simulation is by far the most common approach adopted for performance assessment of micro-CHP. These models vary from technology characterisations based on single-figure efficiency values through to complete 1st principles engineering system and building representations. The treatment of dynamic system aspects also varies greatly between simulation studies. These issues relating to technical characterisation and system dynamics are discussed below.

A number of studies use a single-figure efficiency value to characterise a micro-CHP system (for example, Boait et al. (2006), De Paepe et al. (2006)). Efficiency characterisation can also consider part-load operation, where an efficiency curve is defined piece-wise or continuously over the range of power output of the prime mover. Studies such as Maclay et al. (2006) and Ferguson and Ismet Ugursal (2004) use part-load efficiency characterisation based on experimental systems. Alternatively part-load efficiency characterisation can be synthesised from more complex engineering models as demonstrated in Wallmark and Alvfors (2003). In order to simulate operation the efficiency characterisation is typically combined with a pre-defined operating strategy, ranging from (for example) simple strategies such as "continuous full load operation" in Pehnt (2001) to variants including "on/off operation" in Cockroft and Kelly (2006) or part-load operation

[9] Pinch design (or pinch analysis or pinch technology) is an analysis method designed to guarantee minimum energy levels in a heat exchanger network, and maximising heat exchange efficiency at minimum capital cost.

such as "follow heat demand" in Lilien et al. (2004) or "follow electricity demand" which was one of the strategies investigated in Hawkes and Leach (2007). Simulation studies can use unit commitment approaches to decide an operating strategy, and then simulate it, or can attempt to "optimise" operation based on comparing a small set of possible strategies and choosing the one with the best outcome. These result in optimised unit commitment to an extent commensurate with the quality of the adopted approach.

Representation of thermal demand, the dynamics of the modelled system, and boundaries of analysis also form an important distinctions between model types. Definition of system boundary varies from the prime-mover itself (or small parts of the prime mover) out to entire building simulation. For example, Aguiar et al. (2005) developed detailed technical characterisation of intermediate temperature solid oxide fuel cell technology and assessed performance considering only the fuel cell stack (i.e. prime mover). This model boundary was extended to consider balance of plant components in Hawkes et al. (2007) in addition to the stack, based on a derived a steady-state efficiency model. Boundaries of analysis may be further extended to consider the interaction of the building itself with the micro-CHP system. In these case building thermal demand is often represented by a fixed demand profile (for example, Peacock and Newborough (2005), Staffell et al. (2008)). An alternative to these fixed thermal demand profiles is use of building simulation programs, which typically are able to dynamically calculate thermal loads on the heat delivery system based on a complex variety of factors relating to (for example) heat transfer and ventilation. Building simulation models have been developed and applied to assess the performance of micro-CHP in the International Energy Agency Annex 42 on Residential Cogeneration (for example, Beausoleil-Morrison et al. (2007)), with micro-CHP system models calibrated to results from experimental systems. One primary advantage of building simulation models is that they are able to calculate a hydronic system's return temperatures, and therefore estimate when condensing operation is occurring. However, results generated for a dwelling are specific to that dwelling, and changes to insulation levels, ventilation, and relationships between internal spaces can all influence estimated micro-CHP performance. Additionally, micro-CHP control strategy in building simulation programs has to date been simplistic, reflecting the difficulty in making broad assumptions regarding the best control strategy for a particular dwelling. A useful comparison of the capabilities of various building simulation programs is available in Crawley et al. (2005).

### 3.1.4 Comparison of Micro-CHP Modelling Approaches

Based on the discussion in sections 3.1.1 to 3.1.3 it is apparent that a wide array of modelling approaches exists for micro-CHP. At the broadest level, performance assessment can be split into optimisation and simulation approaches. Unit commitment optimisation is useful for analysing systems under research and development, because it can reflect changes in system constraints back onto the optimal operating strategy and optimal system design. This is opposed to simulation modelling which can consider the impact of a changed constraint for a particular operating strategy, but cannot suggest an operating strategy that better accounts for that constraint. Engineering design optimisation focuses on maximising efficiency, and us usually less techno-economic in nature. The relative merits of optimisation and simulation are listed in Table 6.

| | Unit Commitment Optimisation | Engineering Design Optimisation | Simulation |
|---|---|---|---|
| Operating Strategy | Can choose the best strategy, based on objective function and estimates or knowledge of future demand | Usually steady-state at rated power | Operation according to a pre-defined strategy. Emulates "real system" operating strategy |
| Dynamic Behaviour | Can approximate dynamics, but usually relies on steady-state technology representation | Can represent system (but not building) dynamics and transients explicitly. | Can represent dynamics and transients explicitly, but usually relies on steady-state technology representation |
| System Design | Reflects system constraints onto objective function, resulting in defensible analysis of design | Chooses best configuration and specification of system components | Can analyse system design by "brute force" (by simulating every possibility) |

**Table 6: Qualitative Comparison of Optimisation and Simulation Modelling Approaches Applied for Micro-CHP**

Perhaps the biggest advantage of unit commitment optimisation is that it is able to adapt various parameters (i.e. decision variables) to changing system constraints. This provides a feed-back loop between constraints and operating strategy, and thereby simplifies sensitivity analyses. Engineering design optimisation is the obvious choice to aid technical design where desirable system characteristics are known, but it is less grounded in the techno-economic realities of operation. The biggest advantage of simulation is that it is able to accurately represent the response of a real system, and is able to better represent thermal interactions within a building and between the micro-CHP system and the building. Where a technology is emerging, the first advantage is diminished because the modeller will have difficulty choosing a control strategy, because they do not yet know which

strategy will result in the best performance. Better representation of thermal interactions by simulation programmes therefore remains their primary advantage.

For this research, a unit commitment optimisation model based on steady-state efficiency characterisation has been chosen to assess the performance of micro-CHP. No such model currently exists in the literature (except for the author's publications). The dynamic performance of the micro-CHP is emulated via a set of operational constraints, adding elements of system and building transients into the formulation. Given that micro-CHP is an emerging technology, this optimisation approach will provide the most useful information regarding the best system design and control, and can thereby also create the understanding of the performance potential of mature technology required for this research. This is an improvement over simulation models that are best suited to assessing the performance of existing systems, or assessing the performance of a system in relation to a particular building configuration or heat delivery system. The superior thermal demand modelling of credible building simulation models is drawn upon to create fixed thermal demand profiles for use in this research, and whilst this is recognised as a limitation, it is not expected to cause appreciable deviation of results (indeed a number of thermal profiles are investigated, providing some sensitivity analysis to the influence of this assumption). Further research could attempt to incorporate the complex thermal modelling of building simulation approaches into an optimisation framework for technology assessment, which would theoretically improve the model presented herein.

## 3.2 Reference or "Baseline" Systems Investigated

It has been noted in Dorer et al. (2005) and others that if the service provided by a new technology (for example, electricity, heat, etc) is a necessity and/or already provided by a conventional or incumbent technology, meaningful analysis must make comparison of the new or "disruptive" technology with the incumbent. In the literature the incumbent conventional technology is often referred to as the reference or baseline case. For example, in the United Kingdom the reference case when considering micro-CHP is typically the scenario where a dwelling's electricity demands are met via grid electricity, and it's heat demands are met by burning natural gas in a boiler (for example, Harrison (2001), Hawkes and Leach (2007), Peacock and Newborough (2008)). However, the costs, $CO_2$ emissions rates, and energy use of the reference system are a point of significant and justified controversy. The following two subsections consider typical reference electricity and heating systems in the context of the published literature.

### 3.2.1 The Reference Electricity System

The reference electricity system is typically the centralised generation, transmission and distribution system, which produces and delivers grid electricity. In the literature a wide variety of interpretations of the reference system exist. These range from extremely pessimistic cases where the interaction of a microgenerator with the electricity system is entirely ignored (for example, Oxera (2003)) through to optimistic cases where the microgenerator is assumed to displace generators with large $CO_2$ emissions per kWh delivered, such as coal-fired generation. Neither of these approaches can be easily justified, and the majority of studies use average or marginal costs and emissions rates to characterise the incumbent electricity system, although precise methods to achieve this vary. For example, Peacock and Newborough (2005) perform direct calculation of operating emissions based on a simulation model whilst Pehnt (2008) performs a life cycle analysis method where thermal energy produced is considered to be a by-product of electricity and its influence is credited during performance assessment.

The average cost per kWh of electricity delivered is relatively easy to observe; it is simply the average residential electricity tariff. This tariff includes the cost of generation, transmission, distribution, retail and administration, and profit margins at all of these echelons of the supply chain (Cost breakdown between echelons estimated by Williams and Strbac (2001) is displayed in Figure 10). The average carbon and energy content of grid electricity is also relatively easy to observe through annual output, efficiency, and fuel type of each generator participating in the market. However, use of these grid-average parameters has important drawbacks in that it does not account for the marginal nature of the economic impact on the micro-CHP investor or the marginal nature of delivered carbon dioxide emissions reductions.

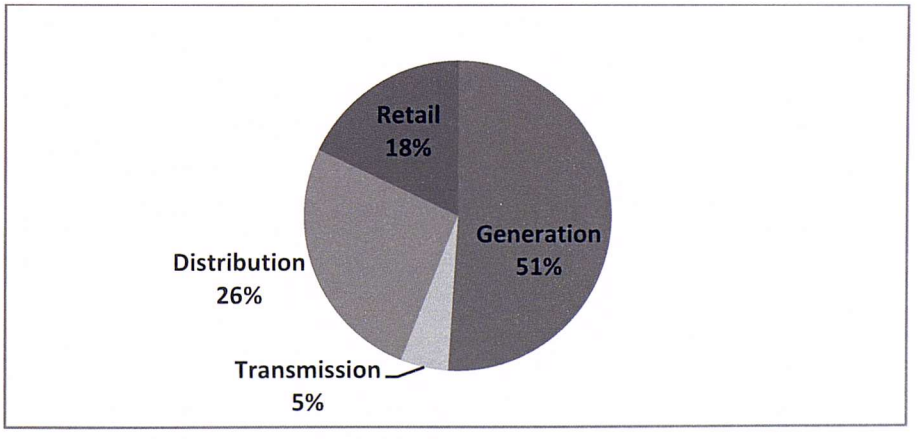



**Figure 10: Breakdown of Costs in a Typical Residential Electricity Bill from Williams and Strbac (2001)**

When considering the economics for a private investor in micro-CHP, the marginal price paid for a kWh of electricity or gas is observable. Residential tariffs in the UK are typically split into a certain price for the first *X* kWh consumed in a quarter, followed by a lower price for the next *Y* kWh consumed in that quarter. Some tariffs are structured with a standing charge, whilst others depend solely on the tiered aggregate kWh consumed. The marginal price for the vast majority of residential consumers is the lower price paid for the *Y* kWh consumed. This price is observable for each Supplier, but there is significant spread in values observed between Suppliers and over time. This is because in a liberalised market a Supplier can set any tariff structure desired and that price can be volatile over time, resulting in a wide range of possible marginal prices over the lifetime of the micro-CHP unit. There is also a wide range of possible export "buyback" prices (applicable when the micro-CHP owner-operator sells electricity back to the grid), ranging from net metering[10] arrangements through to zero reward for export. Based on inspection of Figure 10 it appears that net metering is difficult to justify, because it implies a supplier would involve paying the micro-CHP owner-operator for distribution, transmission and retail elements, which they do not actually incur. The wholesale price of electricity (i.e. the "generation" element in Figure 10) adjusted for embedded benefits as discussed in Elexon (2005), and metering, balancing, and settlement costs as outlined in Ilex Energy Consulting (2005) is probably the most justifiable export value, but little precedent exists for observing it. Indeed treatment of microgeneration in the Balancing and Settlement Code has not yet been finalised; an issue that must be resolved before support for substantial introduction of microgeneration can be expected. These issues are discussed further in Chapter 9, and the assumed central estimate of buyback price is 4 pence/kWh in the analyses presented in this thesis.

[10] Net metering is defined as the case where a supplier offers electricity buyback rate identical to the marginal cost of electricity consumption. This may be achieved by use of only one meter that has the ability to run backwards, but in reality would probably involve two meters (one for import, one for export) with equal value per kWh attached to each.

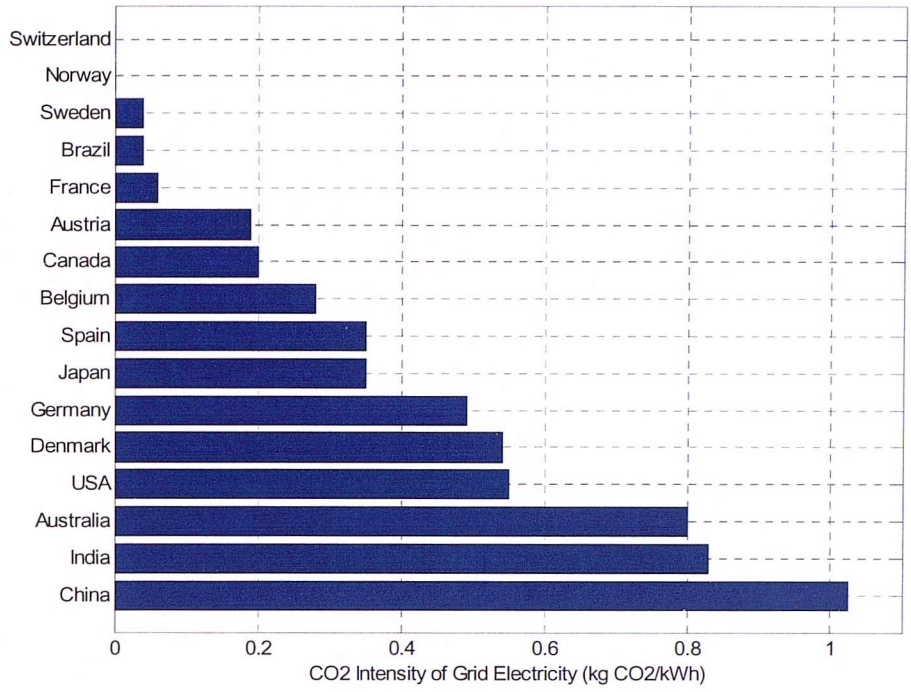



**Figure 11: Grid Electricity $CO_2$ Intensity for a range of countries according to OECD/IEA (2006) World Energy Outlook (note that the UK 5-year rolling average in 2006 was approx 0.53kg$CO_2$/kWh according to DEFRA (2007b))**

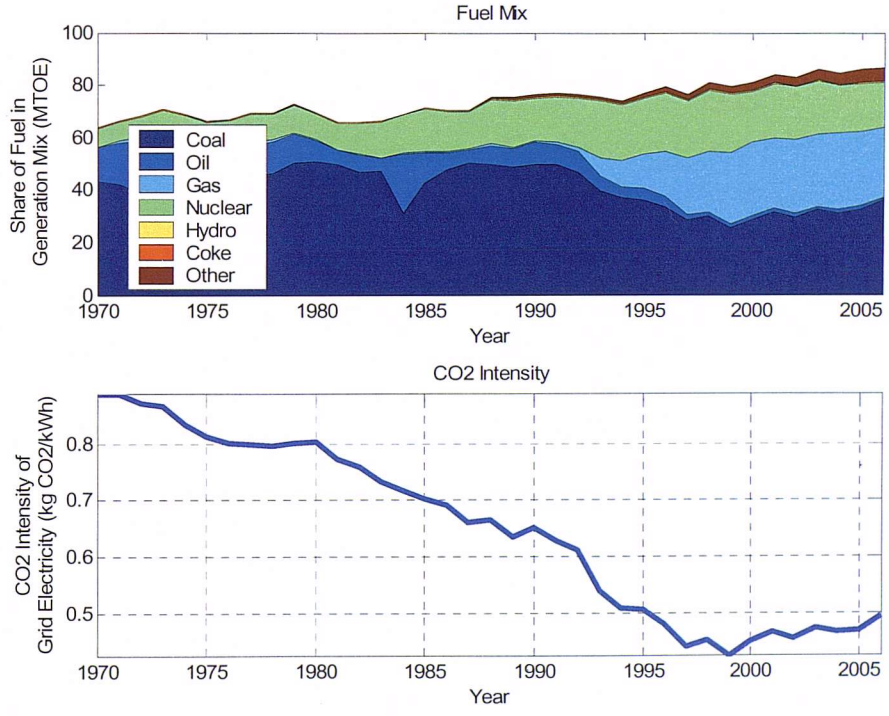



**Figure 12: Time Series for Fuel Mix and $CO_2$ Intensity of Grid Electricity in the UK as per BERR (2007)**

Choice of an appropriate carbon dioxide emissions rate is a more complex matter. Figure 11 presents the wide range of grid-average $CO_2$ intensities apparent in selected countries according to OECD/IEA (2006), demonstrating the marked impact a country's generating plant fuel mix can have on power sector $CO_2$ intensity. Indeed the $CO_2$ intensity of grid electricity can change rapidly within a country, as confirmed by the case of the UK in Figure 12, where the "dash for gas" in the 1990s caused $CO_2$ rates to plummet. When a micro-CHP system generates electricity, that electricity displaces generation that would have otherwise been produced by an incumbent generator. The $CO_2$ emissions avoided as a result of the micro-CHP generation are therefore dependent on which incumbent generator's output was displaced; the "marginal" generator. This issue is further complicated in that the particular generator displaced may change over the course of a time period (e.g. hour, day, week, month, season, etc), and a large penetration of micro-CHP generators may defer the build of the next centralised generation plant, implying that this "planned future plant" should be taken into account when determining the marginal $CO_2$ emissions impact of micro-CHP. A small number of investigations have considered the marginal emissions problem, but have come to opposite conclusions: Bettle et al. (2006) studied the influence of electricity saving measures on residential electric load profiles and the grid system in England and Wales and concluded that use of a grid-average emissions rate significantly underestimates $CO_2$ emissions avoided because dispatchable fossil-fuelled generators are the ones most likely to respond to the demand changes caused by the energy efficiency measures. Conversely, Voorspools et al. (2001) concluded that grid-average based studies overestimate achievable emissions reduction because micro-CHP forces more incumbent generators to run inefficiently at part-load, and due to a slowdown in the construction rate for new centralised generation plant. Based on the results of these two conflicting but largely defensible studies it is concluded that no proven methodology for predicting an appropriate displaced emissions rate exists, making this field a good candidate for future research (but is not covered specifically in this thesis).

The reference electricity system chosen as a central estimate for this thesis is based on the average marginal residential tariff for electricity for the London area, and $CO_2$ emissions rates reflecting current UK legislation, notably the Standard Assessment Procedure 2005 dwelling emission rate calculation methodology as described in BRE (2005). Values for these central estimates are displayed in Table 7. Given the uncertainties, sensitivities to variation in these parameters are investigated in later Chapters.

| Parameter | Value |
|---|---|
| **Marginal Residential Electricity Tariff** | 10.25 pence/kWh |
| **Electricity Buyback Price** | 4.0 pence/kWh |
| **Grid Electricity $CO_2$ Emissions Rate** | 0.422 kg $CO_2$/kWh |
| **Micro-CHP Electricity Generation $CO_2$ Emissions Credit Rate** | 0.568 kg $CO_2$/kWh |

**Table 7: Central Estimates of Parameters for the Reference Electricity System**

The $CO_2$ emissions rates presented in Table 7 correspond to the long-term grid-average rate for grid electricity and a notional current average or marginal rate for onsite generation. Use of these emissions rates makes the modelling results presented in this thesis more relevant for discussion related to policy support, and sensitivity analysis is presented in Section 7.1 as it is recognised that this central estimate is the subject of controversy.

### 3.2.2 The Reference Heating System

The reference heating system used in micro-CHP performance assessment studies varies according to two primary factors; the country of application, and an assumption regarding whether or not the micro-CHP purchase will replace an old incumbent system or displace purchase of a new conventional system. For the UK, some studies have assumed that the micro-CHP unit would displace an old non-condensing natural gas boiler with lower heating value (LHV) efficiency of roughly 65-75% (for example, Harrison and Redford (2001), Oxera (2003)). The majority of studies assume that the micro-CHP unit would displace a new condensing boiler with seasonal LHV efficiency from 86% to more than 100%. For the case of the UK the assumption that micro-CHP competes with a new condensing boiler purchase is more defensible because building regulations require that all new boiler installations are condensing models (ODPM (2006b)), and also because home heating system purchase is usually made under distress (i.e. the heating system is replaced due to breakdown of the old system during a cold weather period). Distress purchase implies that the decision the dwelling owner is faced with is between micro-CHP and the new condensing boiler. Keeping the incumbent boiler is not an option. Central estimates of reference heating system parameters are presented in Table 8.

| Parameter | Value |
|---|---|
| **Marginal Residential Gas Tariff** | 2.48 pence/kWh |
| **Gas Consumption $CO_2$ Emissions Rate** | 0.19 kg $CO_2$/kWh |
| **Reference Boiler LHV Efficiency** | 86% |

**Table 8: Central Estimates of Parameters for the Reference Electricity System**

The choice of boiler efficiency (i.e. 86% LHV) is based on the results of a recent boiler field trial conducted alongside a micro-CHP field trial. The report for this trial, available in Carbon Trust (2007), showed that the actual efficiency of highly-rated condensing boilers was around 86% in practice.

## 3.3 Review of Performance Studies for Micro-CHP Systems

This section builds on the review of modelling approaches presented in section 3.1. It presents a critique of results from selected modelling studies that considered a single micro-CHP system in terms of the case for private investment, $CO_2$ emissions reduction, energy consumption and other environmental impacts.

By far the majority of reviewed literature examining the performance of residential micro-CHP focus on one or more of the three pillars of energy policy; economics, environmental impact, and energy security. Economic studies generally concentrate on the case for investment in micro-CHP systems by private or commercial investors, by comparing the cost of meeting typical residential energy demands using a reference system with the cost of meeting the equivalent energy demand with a modelled micro-CHP system (for example, Aki et al. (2006), Alanne et al. (2006), Harrison and Redford (2001)). Environmental impact studies usually focus on climate change related $CO_2$ emissions, although some include other environmental parameters such as air pollutants and extend the boundaries of analysis out to consider the technologies' full life cycle (Pehnt, (2001)). Many studies also consider energy consumption of the micro-CHP system relative to the reference system, which can be interpreted in terms of national energy security where large penetrations are assumed.

The following paragraphs describe the approaches and results of two particular *simulation-based* studies (Cockroft and Kelly (2006), Peacock and Newborough) based on the UK situation that have the relevance to the present thesis. Results of other selected simulation studies are then presented, followed by the results of a specifically relevant *optimisation-based* study.

Cockroft and Kelly (2006) applied the ESP-r building simulation tool to predict the $CO_2$ emissions reduction provided by micro-CHP and heat pump systems relative to a reference

system consisting of grid-average electricity and a 91% LHV efficiency gas boiler. They considered the cases of existing and improved energy efficiency (representing an estimate of the 2020 situation) dwellings. The reference electricity system was also assumed to change between the 2005 and 2020 scenarios, with the grid electricity emissions rate reducing from 0.42 to 0.30 kg $CO_2$ per kWh. They concluded that air source heat pumps can provide the greatest $CO_2$ savings in the 2020 scenario; better than any micro-CHP technology. This analysis assumed that no $CO_2$ credit was given for electricity exported from the dwelling, an assumption that favours the air source heat pump technology. It also assumed that micro-CHP devices were sized to meet the maximum thermal demand of the building analysed, and that control of each unit was on/off (i.e. no modulation was possible). The study used hourly time-steps for the simulation. The combination of these assumptions has an influence on the results of the study, and it is arguable that $CO_2$ savings attributable to micro-CHP in the current and future scenarios have not been fairly estimated. The study specifically avoided economic analysis, citing variable energy prices and uncertain capital costs as the reason for this.

Peacock and Newborough performed a similar study examining the effect of heat-saving measures on the $CO_2$ savings attributable to micro-CHP systems in UK dwellings. This study simulated engine-based micro-CHP technologies operating in a heat-led manner (with basic dynamic approximations such as start times, etc) compared with a grid-average electricity and gas condensing boiler UK reference case. The study gave $CO_2$ credit for all electricity generated by the micro-CHP system, and used fine 1-minute time-steps to represent the dwelling's demand and micro-CHP response. The primary conclusions were that high electrical efficiency micro-CHP systems can provide modest $CO_2$ savings with respect to the reference case regardless of installation of heat saving measures. Low electrical efficiency systems were more challenged in this regard, and could actually result in an emissions increase where heat-saving measures had been installed.

In addition to those described above, there are many further simulation-based studies present in the literature. The results of a selection of these are presented here. Alanne et al. (2006) investigated the financial viability of a $1kW_e$ to $5kW_e$ SOFC-based micro-CHP in Canada. This study assumed constant full-power output of the micro-CHP unit, and used hourly time-steps in its analysis. It concluded that the maximum price a rational investor would pay for the unit depends greatly on the system being replaced (i.e. the reference system). The value of the system varied between close to C$0/kWe when the reference

system is a gas furnace, through to more than C$8,000/kWe when the reference system is an "electrical furnace". It concluded that the only viable system size for the SOFC unit was $1kW_e$ to $2kW_e$ for the Canadian situation, and that in general the technology would have trouble competing with gas furnaces. Staffell et al. also investigated the value (i.e. maximum price a rational investor would pay for the system) using a Monte Carlo approach and a relatively large demand data set comprising of 102-dwelling-years of demand at hourly temporal precision. It concluded that the value to an investor for fuel cell micro-CHP was €350-€625/$kW_e$ for a product with a 2.5-year lifetime, increasing to up to €1,000/$kW_e$ where system life could be extended to five years. Both of these simulation efforts (i.e. Alanne et al. (2006), Staffell et al.) used hourly precision for analysis, which is shown later in this thesis to produce misleading results. They investigated system capital cost targets and basic technical parameters, paying less attention to specific technology challenges in terms of their economics and environmental impacts.

Whilst the predominant use of optimisation methods relates system design considerations such as pinch technology or other objectives, there are some unit commitment based optimisation performance studies in the literature. These studies typically consider systems larger than appropriate for residential micro-CHP, but many aspects of the optimisation model formulation have strong parallels with the mathematical method presented in this thesis, and they are therefore included in this review. As was discussed regarding modelling approaches in section 0, probably the most relevant model development is that of El-Sharkh et al. (2005) who designed an evolutionary programming methodology with a hill-climbing technique to ensure feasibility of selected solutions. This methodology was applied in El-Sharkh et al. (2006a) to study the sensitivity of operating strategy of a $250kW_e$ PEMFC cogeneration unit supplying a residential neighbourhood to changes in price parameters (and including the option for the system to sell hydrogen). It was concluded that changes in price parameters could have significant influence on the optimal unit commitment. The model has also been applied in El-Sharkh et al. (2006b) and El-Sharkh et al. (2007) to consider the impact of hydrogen production and thermal energy management on operational economics and strategy. These studies did not explicitly seek to inform PEMFC system developers in terms of key technical characteristics, and the use of a $250kW_e$ system in the United States situation makes the results less relevant for the present thesis.

Several further examples of performance studies exist in the literature, with broadly similar approaches to those described above. These are referenced where relevant throughout this thesis. In general studies that consider system economics conclude that micro-CHP could be a competitor to the relevant reference systems, but challenging capital cost targets must be met. Where environmental credentials are considered the result is generally positive, but dependent on the carbon intensity of grid electricity as demonstrated in Cockroft and Kelly (2006) and the nature of the reference system assessed. No systematic studies exist that consider a range of market drivers and key technical characteristics, within an optimisation framework, with respect to economic and environmental credentials, as is presented in this thesis.

## 3.4 Studies of Mass Market Introduction of Micro-CHP

This section reviews local network impact and market studies relevant to micro-CHP, providing context for policy and market-driver related studies presented later in Chapters 6, 7, and 9.

### 3.4.1 Technical Local Network Impact Studies

A number of studies have considered the interaction between a large penetration of micro-CHP (or microgeneration in general) and the local electricity distribution network. These are primarily technical studies aimed at determining maximum penetration in the local network before network operating parameters exceed regulated requirements. These studies are important background for the present thesis because they address issues surrounding a potential cap on the market size for micro-CHP. Other than the obvious importance of such a cap to system developers and commercial investors, policy analysis also requires this information to understand the potential of micro-CHP to meet policy aims. A brief review of literature relevant to distribution network impacts is presented in the following paragraphs.

Mott MacDonald (2004) investigated the impact of system integration of additional microgeneration in the UK context. This report found that penetration of microgeneration in 100% of residential properties should be feasible in most circumstances with some low voltage network reconfiguration. The required network reconfiguration would only be required above 50% penetration in urban networks or 20% penetration in rural networks. The report also concluded that integration of up to 17GW of microgeneration could be achieved at relatively low cost, certainly lower than the broader economic benefit. The Mott Macdonald report was a follow-on analysis from a PBPower report (Ingram et al.

(2003)) which predicted penetration of 48% was possible before statutory voltage levels would be violated. The maximum penetration of 50% before voltage rise exceeds statutory levels in urban networks was also produced by at DTI commissioned report into the market potential for microgeneration (Energy Saving Trust et al. (2005)). This report also noted that maximum acceptable penetration is dependent on the electrical generating capacity of systems installed, with higher capacity individual units resulting in lower maximum penetration. Peacock and Newborough (2006) have investigated the impact of micro-CHP on local network energy flows. They found that deployment of $1kW_e$ Stirling engine and fuel cell based micro-CHP units would not result in reverse energy flow through typical distribution transformers until penetration level exceeds about 50%. For $3kW_e$ fuel cell units, reverse flow could occur at penetration levels of around 15%, reflecting the Energy Saving Trust's result regarding impact of system size on maximum penetration. Peacock and Newborough (2006) used a relatively small set of 13 dwellings for their study, and diversity effects could alter the outcome for larger penetrations.

Overall this body of research suggests that around 50% penetration of $1kW_e$ micro-CHP is possible without significant local network impact or necessity for network upgrade. In the context of this study, and if one takes the assumption that dwellings that are suitable for gas-fuelled micro-CHP installation (i.e. about 80% of dwellings with gas-fuelled heating) are clustered together, this result means that national micro-CHP penetration is limited to approximately 40% of the housing stock (about 10,000,000 dwellings at present). However, the reader should note that local network reconfiguration could result in allowable penetrations near 100% as per the results of the Mott Macdonald study. An alternative to network reconfiguration is virtual power plant (VPP) style control of micro-CHP as suggested in Peacock and Newborough (2007), where output of micro-CHP systems can be co-ordinated to ensure they are operating as "good citizens" on the local network. The VPP approach would also enable larger penetrations in local electricity distribution networks.

### 3.4.2 Market Studies

In addition to technical network limitations regarding the potential for penetration of micro-CHP, market factors will also influence its commercial uptake. Therefore a review of existing market studies is presented here to provide an indicative estimate of economic market size and as a context for results presented later in this thesis.

In general, micro-CHP is seen as a boiler replacement technology, and according to Micro-Map (2002) approximately 1.3 million boilers are replaced each year in the UK. It is assumed micro-CHP could capture a certain percentage of this market. Therefore potential penetration in the next 20 years is substantial, perhaps explaining the significant commercial interest in this technology.

Table 9 shows the housing stock disaggregation for Great Britain in 2004 according to Utley and Shorrock (2006). This provides important information about the nature of the market for residential micro-CHP, given the typical "split-incentives" barrier to energy-related investment in the residential sector. "Split-incentives" refers to the situation where the investor in an energy efficiency measure (i.e. the landlord) does not have access to the cost savings provided by that measure, which would normally accrue to the tenant. Therefore, without resolution to this barrier, the primary market for micro-CHP systems will be the owner-occupied dwellings. Those with private landlord would be unlikely to adopt micro-CHP, whilst social landlord and local authority situations may adopt through the influence of various national and local government incentives. Inspection of Table 9 reveals that the split incentives barrier is a relatively minor issue in terms of market size, with by far the majority of residences being owner-occupied. If it is assumed that all dwellings are appropriate for micro-CHP (i.e. economical, environmentally positive, space-permitting, access to fuel, etc), the potential final market size in 2004 is between 17 million and 20 million units. However, in practice there are many restrictions on the installation of micro-CHP, which have been investigated in detail in several studies. These studies are discussed below.

| | Owner-Occupied | Private Landlord | Social Landlord | Local Authority | Total |
|---|---|---|---|---|---|
| **Terraced** | 4,602 | 196 | 781 | 892 | 6,471 |
| **Semi Detached** | 5,573 | 601 | 523 | 761 | 7,458 |
| **Detached** | 3,864 | 75 | 74 | 8 | 4,021 |
| **Bungalow** | 1.626 | 45 | 141 | 273 | 2,085 |
| **Flat** | 1,384 | 664 | 1,035 | 1,635 | 4,718 |
| **Total** | 17,049 | 1,581 | 2,554 | 3,569 | |

**Table 9: Housing Stock in Great Britain in 2004 Disaggregated by Tenure Type and Construction (thousands)**

The Micro-Map project reported that approximately 80% of UK dwellings have central heating systems and the majority of these were deemed to be suitable for micro-CHP. It concluded that by 2020 between 5 million and 12 million installations could be completed in European Union countries (Crozier-Cole and Jones (2002), Micro-Map (2002)). In 2005 the UK Department of Trade and Industry (DTI) commissioned a report considering the UK potential for microgeneration (Energy Saving Trust et al. (2005)). This report indicated a

much lower penetration by 2020 of only a few tens-of-thousands of each micro-CHP technology for the case where there are no government incentives. However, it also suggested approximately 8 million Stirling engine installations, and a similar number of fuel cell based micro-CHP installations are possible by 2050. It was noted that Stirling engine and fuel cell micro-CHP would therefore contribute roughly 6% and 9% of the United Kingdom's electricity supply respectively, and a significant portion of its residential heat supply. In 2006, the Society of British Gas Industries (SBGI) updated its analysis of market potential of a variety of micro-CHP technologies in the UK until 2020 in SBGI (2006). The result of primary interest in this study is that by 2020, 5.6 million dwellings may have micro-CHP installed in the UK. If a high level of government support were given to the technology, up to 12.5 million dwellings could have the technology, whilst with a low level of support as little as 715,000 dwellings might adopt. More recently, in Element Energy (2008) considered policy incentives to support microgeneration and their influence on uptake in light of consumer surveys. It concluded that under a baseline "existing policies" scenario approximately 400,000 fuel cell micro-CHP systems and 350,000 Stirling engine micro-CHP systems would be installed by 2020. These figures rise to up to 6.7 million (fuel cell) and 3.6 million (Stirling engine) units under various policy support scenarios by 2020.

All of these studies indicate a large final market exists. Some claim a sizeable penetration can be achieved by 2020, whilst others suggest that it may take longer (without government support). Nonetheless the market potential context for this thesis has been established. Therefore analyses of the economics drivers of that market and its implications in term of achieving policy goals is warranted, as is analysis of policy instruments that can incentivise micro-CHP uptake where appropriate.

# Chapter 4: Development of a Techno-Economic Modelling Framework

This chapter develops the choice of primary and further metrics for assessment of micro-CHP system performance, and presents the full mathematical formulation of the unit commitment optimisation approach developed. It then briefly discusses hardware and software implementation and tractability issues.

## 4.1 Justification for Choice of the Primary Performance Metric

The reasons for applying an optimisation-based approach have been discussed in section 0. This section explores choice of the objective (i.e. the primary performance metric to minimise or maximise) of the optimisation through consideration of the modelling aims. The modelling framework must of course be tuned to these aims, which as discussed in previous chapters are:

1. To understand the potential of mature micro-CHP technology, and use it to assess the key market drivers, and assess the ability to meet policy aims.
2. To investigate key technical parameters to understand their influence on economic and environmental credentials, with the aim of improving the knowledge of system developers.
3. To use the modelling results to critique current, proposed and potential new policy and regulation surrounding the introduction of micro-CHP.

In one sense the aims all speak to the primary considerations of energy policy; economics, environment, and energy security and the ability of micro-CHP to contribute to beneficial outcomes in these three areas. However, in order for the technologies to be commercially successful, consumers must adopt it in large numbers, so deployment pathways and the theory of diffusion of innovations becomes relevant, along with the aims of energy policy. Deployment models for microgeneration are considered, leading to discussion of theory of diffusion of innovations to gain an understanding of what metrics may drive adoption/diffusion and demarcate successful micro-CHP products. This leads to choice of a primary performance metric for the optimisation modelling (i.e. an objective function), and further assessment metrics.

### 4.1.1 Micro-CHP Commercial Deployment Pathways

The nature of the driving force in a micro-CHP investment decision depends largely on which stakeholder is making that decision. It order to gain understanding of appropriate metrics for modelling of the systems, it is useful to consider which actors are associated with each potential route to market. To investigate this issue a set of deployment models were developed in Watson (2004) and applied to investigate social acceptance of microgeneration in Sauter and Watson (2007). These three deployment pathways are considered here to inform choice of performance metrics. They are:

1. **Plug-and-play.** This pathway assumes the decision to invest in microgeneration is taken independently by the dwelling owner or occupier who finances the purchase.
2. **Company control.** This pathway involves more passive consumers that provide a site for the system which is owned and/or operated by an Energy Service Company (ESCO) or energy supplier.
3. **Community Microgrid.** Where a group of individuals/businesses group together to provide some of their collective energy needs, and own and operate the units. *The community microgrid option is beyond the scope of this thesis as it relates more to larger scale systems.*

The plug-and-play and company control pathways are discussed in the following two sub-sections, with reference to the theory of diffusion of innovations. This theory is instructive here because it attempts to define how information about a new product spreads through a social system and the processes individual adopters go through regarding an uptake decision. The theory can therefore elucidate what factors may be important in individuals' investment decisions, aiding choice of primary performance metrics for this thesis.

#### *4.1.1.1 Plug-and-Play Deployment Pathway and Diffusion of Innovations*

When considering the individual private investor (i.e. owner or occupier of a dwelling for the case of micro-CHP in the plug-and-play pathway), the market is typically split into a number of "types" of investor based on their propensity for innovation. Rogers (2003) classified these as innovators, early adopters, early majority, late majority, and laggards. This disaggregation, known as the Rogers Adoption Curve, is displayed in Figure 13, and leads to typical "S" penetration curves. According to Rogers the primary variables determining the rate of adoption of an innovation are its;

- perceived attributes,

- the type of innovation decision,
- the type of communication channels,
- the nature of the broader social system, and
- the extent of change agents' promotion efforts.

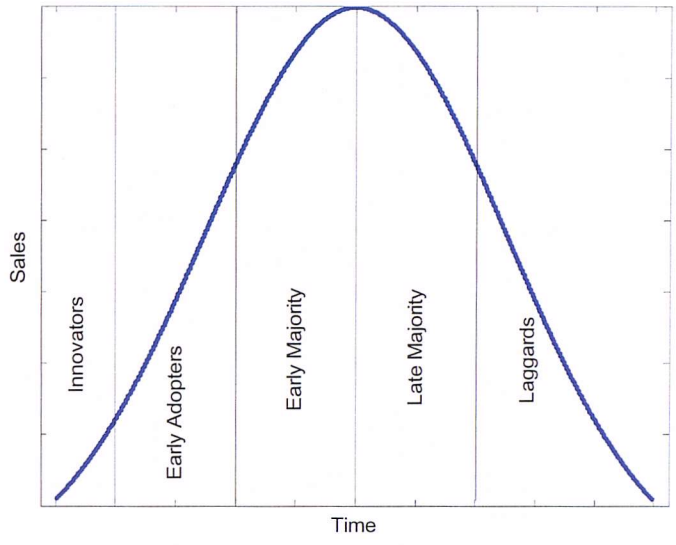



**Figure 13: Typical Rogers Adoption Curve**

The discussion presented here focuses on the "perceived attributes" variable as it is the most relevant to techno-economic analysis of micro-CHP. Within the perceived attributes category the first sub-dimension is the *relative advantage* of the innovation, followed by *compatibility*, *complexity*, *trialability* and *observability*. Micro-CHP can be considered in terms of these attributes given the fact that it is a technology designed to replace existing home heating systems such as boilers. Therefore it is reasonable to assume that it is "compatible" with lifestyle and values in the UK, as it many respects it resembles boiler systems and performs an almost identical function. Likewise it is reasonable to assume that micro-CHP, when well designed, can be simple to use, circumventing any "complexity" barriers. Trialability and observability could be more challenging issues, but the nature of the technology suggests they are just as trialable and observable as any competing home heating systems, with the exception of the incumbent technology. However, at this stage of micro-CHP's development, the most important perceived attribute for micro-CHP is related to its relative advantage.

Relative advantage is the degree to which an innovation is perceived as being better than the idea it supersedes. Typically the first listed relative advantage of a product is related to

initial cost or economic profitability. Therefore, as one would presume, economic elements play an important part in relative advantage, although they are certainly not the only important factor. For example, it would be expected that innovative adopters in Rogers' bell-shaped curve are less influenced by economics, and laggards may resist (or be unaware of) change despite economic advantages. Other relative advantages typically cited in the theory of diffusion of innovations are decrease in discomfort, social prestige, saving time/effort, and immediacy of reward. This list of further relative advantages does not bode well for micro-CHP which could have modest impact on comfort, little social visibility, few obvious service advantages, and little inherent immediate reward. Therefore, economic profitability, possibly combined with social prestige if "green" credentials can be marketed effectively or become visible via other channels, appear to the main relative advantages that could apply to micro-CHP.

Specific studies considering diffusion theory and micro-CHP relevant to the plug-and-play deployment model are available in the literature, further indicating that economics will play a vital role in achieving a mass market: El Mehdi and Kunsch developed a Bass[11] diffusion model for micro-CHP and used it to investigate the effectiveness of incentives such as grants or other policy instruments in influencing its adoption. They found that incentives based on the price of energy or the electricity buyback price should be most effective because they engage the consumer more with their energy use than upfront grant support. Meijer et al. (2007) considered the importance of various uncertainties in "take-off" of micro-CHP diffusion in the Netherlands, and concluded that resolving uncertainty regarding buyback prices and taxation arrangements was an important element of a future market.

Overall, the theory of diffusion of innovations and all the reviewed applications of diffusion models to micro-CHP indicate that economic metrics are important in the plug-and-play deployment model. It may be concluded that if performance can be demonstrated, and

[11] Similarly to Rogers, Bass, F. M. (1969), 'A New Product Growth Model for Consumer Durables', *Management Science,* **13** 203-223. posited that the probability an individual will adopt an innovative product is influenced by the number of previous adopters in a social system and a constant relating to the number of innovators. The number of previous adopters becomes the primary driving force in diffusion when it reaches a significant quantity, whilst innovators are more important in the early stages where uncertainty of performance is an issue. Norton, J. A. and Bass, F. M. (1987), 'A Diffusion Theory Model of Adoption and Substitution for Successive Generations of High-Technology Products', *Management Science,* **33** (9), 1069-1086. extended this model to account for technology substitution, which deals with successive generations of competing products, as is arguably the case for home heating systems such as micro-CHP. Bass' work is frequently used to characterise technology diffusion and substitution, and is therefore probably the most important adoption/diffusion model for the case of micro-CHP.

this information is spread effectively via typical "Bass" communication channels, the economic credentials of the system will become key elements of a penetration threshold being broken, and the technology becoming mass-market. This is partly because other drivers of adoption are not so relevant for micro-CHP, which is effectively a product that will substitute existing boiler systems and offer little visibility and few service advantages. Therefore, although economic performance of micro-CHP is certainly not the only important factor dictating an investment decision, it is surely a critical element.

#### *4.1.1.2 Company Control Deployment Pathway*

The company control or Energy Service Company (ESCO) deployment pathway assumes a service-led approach, where a company offers to supply heat and other energy services to a dwelling, and applies micro-CHP technology to achieve this. The dwelling occupier pays for this service, and implicitly pays for the micro-CHP system as well, although direct payment of system capital costs may be avoided. Avoidance of direct payment of capital costs plays well to Rogers' "low initial cost" and "immediacy of reward" relative advantages, which are identified barriers for the plug-and-play pathway discussed above. The ESCO model also complements current added-value arrangements between customers and energy suppliers, where the customer could engage the supplier to provide energy services in an ESCO-like arrangement.

The company control pathway is also arguably more effective at introducing efficiency and generally improved performance in the residential sector because it largely takes the investment decision out of the hands of the dwelling occupier, and therefore allows that decision to be more explicitly economically-driven than in the plug-and-play pathway. ESCO (or energy suppliers acting as ESCOs) actors can almost always be assumed to be economically rational, making investment decisions based on classic parameters such as net present value. Therefore the success of the company control deployment pathway in allowing micro-CHP to reach a mass market can be closely linked to the economic advantage the systems offer. Likewise with the plug-and-play pathway, other factors relating to diffusion of innovations will also play a role, but economics is likely to be crucial.

### 4.1.2 The Primary Performance Metric

Based on the above discussion it is clear that economic considerations form a primary concern in terms of achieving a mass market for micro-CHP for both plug-and-play and company control deployment pathways. They are not the sole issue, but where other factors are addressed, economic profitability will be critical to achieving a large market

share. Therefore system economics is chosen as the pivotal performance metric in this thesis. The primary issues relating to formulating a valid economic metric for analysis are ensuring relevance to both deployment pathways and circumventing the lack of established capital costs for micro-CHP systems[12], without which calculation of typical investment metrics (such as net present value) are not possible. As discussed above regarding the relative advantages of micro-CHP, attitudes and expectations regarding performance are inextricably linked to those of current residential heating systems. Where economic profitability is the most important relative advantage, the investment decision for micro-CHP can be compared to that of the competing reference boiler systems, and it is the capital cost difference between the two options (that provide an essentially comparable service) that the potential adopter faces. Therefore, the primary metric chosen in this thesis to address these issues is the **marginal net present value of the micro-CHP system with respect to the competing reference system**. The deployment pathway this relates to is that where an ESCO or energy supplier (i.e. the company control model) provides a micro-CHP system under leasing arrangement with a specific interest rate. [13] Therefore the metric broadly corresponds to the discounted revenue the ECSO could obtain from installing micro-CHP in the customer's dwelling[14], and can hence act as a guide for maximum system capital costs for developers. This metric is cost-neutral for the dwelling occupier in that it assumes gains afforded through reduced operational costs (where the cost of meeting the energy demand using micro-CHP are lower than the cost using the reference system) are offset by the leasing cost (i.e. the annualised capital cost) of the micro-CHP equipment. Therefore it could also be interpreted as the maximum capital cost a dwelling occupier would pay for outright purchase of the micro-CHP system in the plug-and-play model, if they would accept the chosen cost of capital. Nevertheless, as observed empirical costs of capital for private residential energy-related purchases vary widely, the ESCO revenue interpretation is preferred.

The chosen primary metric therefore caters directly to the company control (ESCO or energy supplier led deployment pathway), and also has relevance to the plug-and-play

[12] Whilst capital cost indicators do exist in the early developing market (see section 2.2), there is little basis to assume these will reflect the prices of mature mass market products.

[13] 12% is chosen as it is a defensible commercial rate. The energy supplier continues to offer electricity and gas to the customer, and offers terms for buyback of any electricity exported to the grid. The micro-CHP system is maintained by the ESCO, at a cost of £20/year more than the maintenance cost of the competing reference system.

[14] It is assumed that residential tariffs adequately reflect energy costs and expected revenue to the ESCO/supplier.

deployment pathway. It also avoids the issue of incorporating uncertain capital costs into economic calculations, representing the maximum allowable capital cost rather than guessing at a specific capital cost. Furthermore it has strong synergies with the economic element of energy policy aims. Finally, it maintains relevance of results for micro-CHP system developers, who require targets costs for manufacturing of systems.

### 4.1.3 Further Performance Metrics

In addition to the primary economic metric discussed above, further metrics are required to assess the ability of micro-CHP to aid in achieving the aims of energy policy. Foremost among these are reduction of greenhouse gas emissions, followed by achieving a measure of energy security, and ensuring economically-efficient investment in generating capacity.

For greenhouse gas emissions reduction the adopted metric is the **annual $CO_2$ savings provided by the micro-CHP system when compared to that of the competing reference system**. This measure considers only the operational greenhouse gas emissions. Lifecycle emissions due to manufacturing, fuel chain, disposal/recycling are not included. For a discussion of life cycle assessment of micro-CHP systems (which does not consider system operation in detail) readers are referred to Pehnt (2008). Greenhouse gas emissions are not only a policy-related metric; they may also be important for adoption and diffusion if micro-CHP is marketed as a "green" product, generating relative advantages like social prestige as discussed in above in section 4.1.1.

The energy security metrics chosen for consideration is the **change in mix of primary fuel consumption for an average dwelling for the micro-CHP case compared to the reference system case**. The primary concern regarding energy security and micro-CHP is likely to be a perceived reliance on natural gas, and this metric will enable examination of this issue.

The final policy-related metric, which does not arise directly from the optimisation model presented, is **capacity credit**. Capacity credit is a measure of the relative contribution a new alternative generator type makes to meeting system peak load (with corresponding influence on required system capacity of conventional generators). It is a technical metric that bears upon the economic efficacy of investment in electricity system generating capacity. Capacity credit is discussed in detail in section 7.3.

The $CO_2$ and energy security metrics are calculated based on the results of the optimisation. Therefore they relate to a situation where the economic performance of the system has been optimised, leading to $CO_2$ and energy security results; carbon dioxide and

energy security concerns are not the objective of the optimisation. Similarly, the capacity credit calculations are informed by optimisation results. In summary this implies that the primary driver for micro-CHP adoption is assumed to be economic, and the influence of micro-CHP on $CO_2$, energy security and capacity credit are consequential.

## 4.2 Overview of the Optimisation Modelling Approach

In order to investigate influences on the primary economic metric, optimisation is applied. Specifically, the cost of meeting the annual electricity and heat demand of the dwelling using a grid-parallel micro-CHP system is minimised. This is then compared to the cost of meeting an identical demand with the reference system (a condensing boiler and grid electricity, as described in section 3.2). This results in the annual marginal value of the micro-CHP system relative to the reference system. The marginal net present value of the micro-CHP system can then be calculated based on the lifetime of the micro-CHP system and a given cost of capital (i.e. the primary economic metric, as discussed in section 4.1). The inputs and outputs of this process are described in Figure 14.

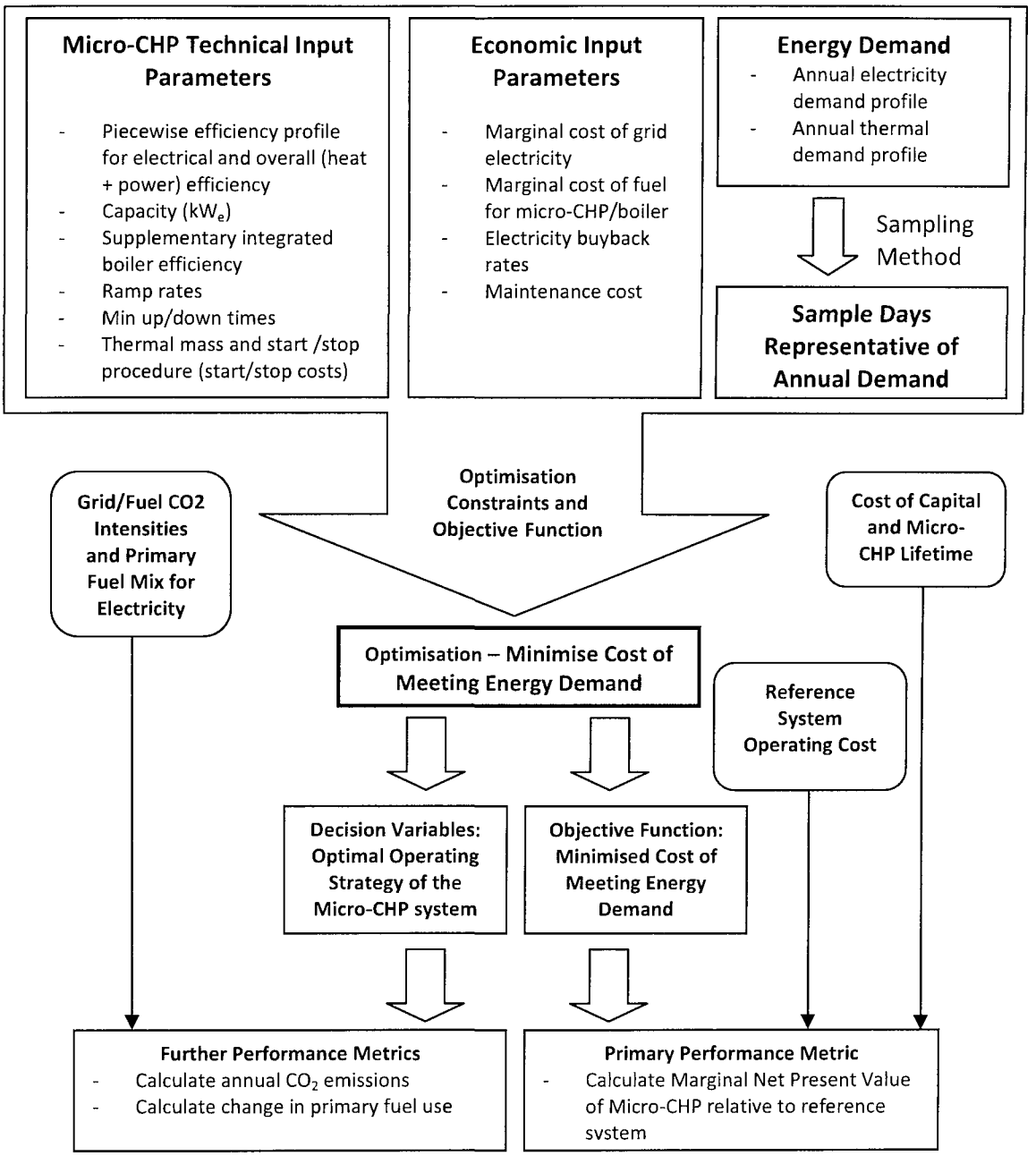



**Figure 14: Inputs, Outputs and Flow Diagram for Optimisation Modelling Framework**

The central "optimisation" box in Figure 14 forms the core computational effort of the modelling. The micro-CHP system technical inputs and energy demand profiles form the optimisation constraints, and the economic inputs and some technical micro-CHP characteristics combine to form the objective function. The complete mathematical formulation of the optimisation problem is presented in section 4.3.

## 4.3 Optimisation Formulation - Mixed Integer Linear Programming

This section develops the mathematical formulation for minimising the cost of meeting a specific electricity and heat demand profile using a micro-CHP system. As discussed in

section 2.2, this system consists of a prime mover and balance of plant, and a supplementary heat-only unit (e.g. a condensing boiler) to help meet heat demands. The system is grid connected, and may import electricity from the grid or export electricity to the grid. Furthermore, simple linear characterisation of electricity storage and thermal energy storage are included in the formulation to demonstrate how this can be achieved.

The unit commitment problem is a frequently visited area of research, with several texts such as Wood and Wollenberg (1996) covering structures of problems and solution methods. Previous studies have formulated optimisation mathematics for the case of one or several generators operating in various market systems, often subject to technical constraints. A survey of recent work regarding unit commitment can be found in Padhy (2004). However these cases are generally for electricity generators as opposed combined heat and power. The author has formulated non-linear programming (NLP) mathematics for the case of micro-CHP (Hawkes et al. (2007), Hawkes et al. (2006)), but due to some important limitations in that approach has developed this alternative method: Mixed integer linear programming (MILP) improves on non-linear programming in that decision variables can be defined as yes/no or specified integer decisions. Therefore MILP can consider generator on-off decisions, minimum set-points and minimum up and down times. Conversely, in NLP, all decision variables in the objective function must be "smooth" (i.e. twice continuously differentiable) and therefore on/off dynamics etc cannot be characterised. The relative advantage of NLP is that it enables definition of non-linear efficiency profiles, but this benefit is offset by the ability to define efficiency curves in MILP piecewise (discussed further in section 4.3.1.2.2 below).

Overall the primary aspects that this chapter adds to the field of literature are:

- Mixed integer linear programming (MILP) unit commitment for the case of micro-CHP, with a supplementary thermal system, and thermal and electrical storage.
- Explicit characterisation of dynamic aspects of the systems, namely; start up cost and energy use, shutdown cost and energy use, minimum up time, minimum down time, and turndown ratio for the case of micro-CHP.
- Degradation characterisation for the case of fuel cell based micro-CHP.

As micro-CHP units may incur relatively large start up cost and may take some time to begin operating, modelling of this aspect of operation will lead to improved prediction of system performance. Explicit characterisation of fuel cell stack degradation will provide

system developers with better information regarding maximum installed capital cost in the target market, given this unique technical characteristic.

### 4.3.1 Mathematical Formulation

This sub-section presents the objective function and constraints of the optimisation of micro-CHP system unit commitment. Variables (including demarcation of those that are decision variables) are defined in the Nomenclature.

#### *4.3.1.1 Objective Function*

The objective of this optimisation is to minimise the annual cost for meeting a given electricity and heat demand, represented by the following equation:

$$Annual\ Cost = AM + OP$$

**Equation 1**

Annual cost consists of annual maintenance costs for each piece of equipment (AM), and operating energy costs (OP) made up of fuel cost per year for the fuel cell and supplementary heat-only unit, costs for any electricity bought from the grid, minus revenue from any electricity sales to the grid. These two quantities are formulated as per Equation 2 and Equation 3 respectively.

$$AM = \zeta(m_{CHP}) + m_{SHU} + \theta(m_{ES}) + \mu(m_{TES})$$

**Equation 2**

$$OP = \sum_{y=1}^{\lambda_{FC}} \left\{ \sum_{z=1}^{Z} \omega_z \left( \sum_{t=1}^{T} \left[ \left( \sum_{k=1}^{L} \frac{a_{k,t}\gamma_t}{\eta_{t,CHP,k}} \right) + \frac{b_t\gamma_t}{\sigma_{SHU}} + \varepsilon_t c_t - \beta_t d_t + S_{st,t} + S_{sd,t} \right] \right) \right\}$$

**Equation 3**

Equation 3 sums the fuel and electricity cost (minus revenue from electricity sold) and start up and shutdown costs over a sample day, and then weights the result according to how many days there are of that type in a year. This process is repeated for each sample day[15] in the problem. The result to this point represents the annual energy cost for meeting the electricity demand. For the case of micro-CHP without degradation this annual energy cost can be used (compared with the cost of operating the reference system) to calculate the primary economic metric. For cases where degradation is present, the entire lifetime of the system must be considered simultaneously (as opposed to only considering one year of operation) such that operating strategy decisions at the beginning of life can reflect on

[15] A sample day is defined as energy demand profiles for a day that is chosen to represent overall characteristics of annual energy demand for the target dwelling. Typically a set of sample days would be used in an analysis to characterise all aspects of demand. The relevance of choice of sample days is investigated in Chapter 5.

performance later in life. See section 4.3.2 for presentation of how degradation influences $\eta_{t,CHP,k}$.

### *4.3.1.2 Constraints*

#### 4.3.1.2.1 Minimum Up Down and Minimum Down Time

Generators are typically constrained to be "on" or "off" for certain minimum time periods. This is to prevent rapid cycling of a unit, which may cause damage. Micro-CHP can be subject to this type of constraint because thermal cycling can lead to rapid wear and tear on prime mover and balance of plant.

The minimum up time and minimum down time constraints are formulated as per Nowak and Romisch (2000) such that they rely only on the first integer variable (i.e. on/off state) for the micro-CHP prime mover for each time period. Equation 4 and Equation 5 present minimum up time and minimum down time constraints respectively.

$$\alpha_{1,t-1} - \alpha_{1,t} + \alpha_{1,\tau} \geq 0 \qquad \tau = t+1, \ldots, \min(t+\tau_u - 1, T) \quad t = 2, \ldots, T.$$

**Equation 4**

$$\alpha_{1,t-1} - \alpha_{1,t} + \alpha_{1,\tau} \leq 1 \qquad \tau = t+1, \ldots, \min(t+\tau_d - 1, T) \quad t = 2, \ldots, T.$$

**Equation 5**

Consequently both minimum up time and minimum down time can be represented with one constraint per time period except in cases where the minimum up time is greater than the minimum down time or vice versa (which requires more constraints).

#### 4.3.1.2.2 Micro-CHP Piecewise Electrical Dispatch Order

In conventional mixed integer linear programming unit commitment problems, dispatch order of each segment of the piecewise generating cost function is often not constrained. This is because where the cost function is strictly monotonically increasing the first segment will always be used first, followed by the second segment, etc, which correctly represents the physical system. An example of this approach can be found in Carrión and Arroyo (2006). However, when the cost function is not strictly monotonically increasing (i.e. non-convex), or constraints interact with the objective function in other ways, it becomes necessary to constrain the order in which segments are used. For example, if the generator cost curve was as per Figure 15 and the dispatch order was left unconstrained, segment $a_3$ would be dispatched before segment $a_2$ because its gradient is smaller. In reality the physical system requires that $a_2$ is completely dispatched before $a_3$, so it is necessary to provide constraints to ensure that this happens.

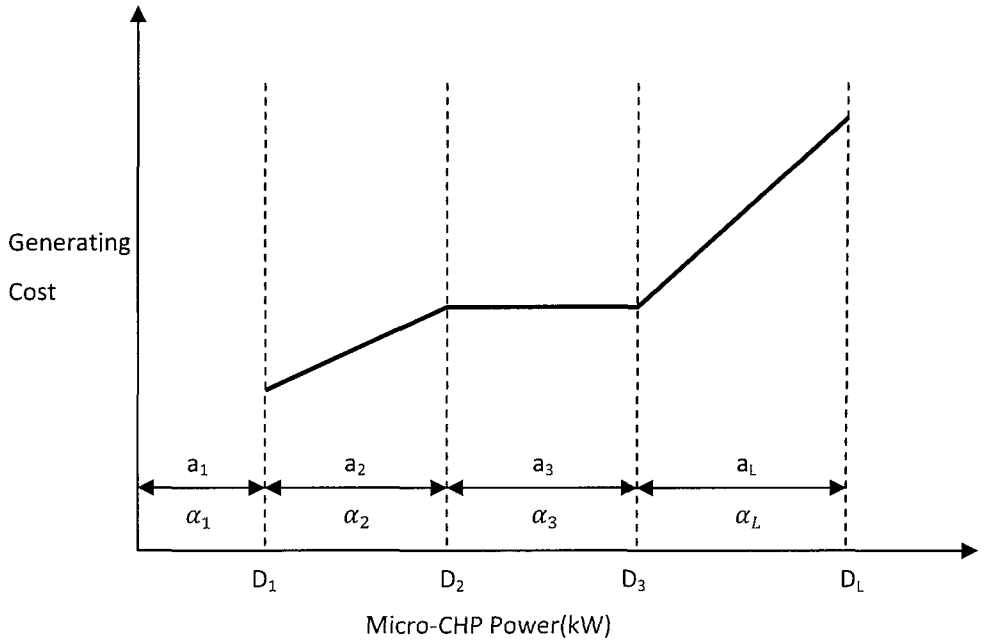



**Figure 15: A Hypothetical Piecewise Linear Construction of Generating Cost Curve**

In the present case of micro-CHP, the necessity of the thermal supply/demand constraints (i.e. the generator produces heat as well as power) requires these dispatch order constraints, regardless of convexity or non-convexity of the generator's cost function. The dispatch order constraints are formulated as per Arroyo and Conejo (2000) in equations Equation 6, Equation 7 and Equation 8:

$$(D_k - D_{k-1})\alpha_{k,t} \leq a_{k,t} \qquad k = 2, \dots, L-1 \quad t = 1, \dots, T$$

**Equation 6**

$$a_{k,t} \leq (D_k - D_{k-1})\alpha_{k-1,t} \qquad k = 2, \dots, L \quad t = 1, \dots, T$$

**Equation 7**

$$\alpha_{k,t} \in \{0, 1\}$$

**Equation 8**

#### 4.3.1.2.3 Minimum Set Point Constraint

Generators typically have a minimum set-point for operation, below which technical constraints such as relatively large balance of plant loads make operation excessively expensive or physically damaging to the system. In this formulation segment $a_1$ (see Figure 15) of the generator's output is multiplied by integer $\alpha_1$, which when combined with the piecewise electrical dispatch order constraint forces the generator to operate no lower

than the minimum set-point $D_1$, but allows it to switch off entirely. This constraint is achieved implicitly through Equation 7.

#### 4.3.1.2.4 Start Up and Shutdown Costs

Start up and shutdown costs are incurred by generators due to use of fuel and electricity during the start/stop process. For example, compressors or other balance of plant may operate as the prime mover starts, requiring a draw of electricity from storage or the electricity grid. As per conventional generators, it is expected that the start up cost will be exponential with respect to the amount of time the generator has been off (corresponding to large start-up costs if the generator is completely cold, reducing to small values when the generator is still warm). Following Nowak and Romisch (2000), start up cost is expressed as per Equation 9. Shutdown cost is modelled as a single fixed cost incurred for a system shutdown as per Equation 10. These two equations are also subject to $S_{st,t} \geq 0$ and $S_{sd,t} \geq 0$.

$$\mathbf{S_{st,t}} \geq s_{start,\tau}\left(\alpha_{1,t} - \sum_{m=1}^{\tau} \alpha_{1,t-m}\right) \qquad \tau = 1, \dots, min(\tau_s, t-1) \quad t = 2, \dots, T.$$

**Equation 9**

$$\mathbf{S_{sd,t}} \geq s_{shutdown}(\alpha_{1,t-1} - \alpha_{1,t}) \qquad t = 2, \dots, T.$$

**Equation 10**

#### 4.3.1.2.5 Equipment Capacity Constraints

Each piece of equipment must not exceed its nameplate output capacity. Equation 11 constrains the micro-CHP unit, Equation 12 constrains the boiler, Equation 13 limits the amount of energy charge in the electricity storage unit, and Equation 14 limits the amount of charge in the thermal energy storage unit.

$$\left(\sum_{k=2}^{L} \mathbf{a_{k,t}}\right) + D_1\alpha_{1,t} \leq CHP_{cap} \quad t = 1, \dots, T.$$

**Equation 11**

$$\mathbf{b_t} \leq B_{cap} \quad t = 1, \dots, T.$$

**Equation 12**

$$\sum_{i=1}^{t} (\mathbf{e_i}\eta_{ch-es} - {}^{\mathbf{f_i}}/_{\eta_{dis-es}}) \leq ES_{cap} \quad t = 1, \dots, T.$$

**Equation 13**

$$\sum_{i=1}^{t} (\mathbf{g_i}\eta_{ch-tes} - {}^{\mathbf{h_i}}/_{\eta_{dis-tes}}) \leq TES_{cap} \quad t = 1, \dots, T.$$

**Equation 14**

#### 4.3.1.2.6 Electricity Balance Constraint

The onsite electricity demand must be met by a combination of power from the micro-CHP, electricity from the grid and electricity discharged from the electricity storage unit. Any electricity exported or used to charge to the electricity storage unit must be subtracted from that available to meet the onsite load. This constraint relationship is presented in Equation 15.

$$\mathbf{c_t} + \mathbf{f_t} - \mathbf{e_t} - \mathbf{d_t} + \left(\sum_{k=2}^{L} \mathbf{a_{k,t}}\right) + \boldsymbol{D_1}\boldsymbol{\alpha_{1,t}} = \boldsymbol{EDem_t} \quad \boldsymbol{t = 1, \dots, T.}$$

**Equation 15**

#### 4.3.1.2.7 Heat Balance Constraint

The onsite heat demand must be met by a combination of useful heat from the micro-CHP unit, the boiler, and discharge from the thermal energy storage (TES) unit (minus any charge to the TES). This constraint is displayed in Equation 16.

$$\mathbf{b_t} + \mathbf{h_t} - \mathbf{g_t} + \left(\sum_{k=2}^{L} \mathbf{a_{k,t}}\left(\frac{\sigma_{t,CHP,k}}{\eta_{t,CHP,k}} - \mathbf{1}\right)\right) + \mathbf{D_1}\boldsymbol{\alpha_{1,t}}\left(\frac{\sigma_{t,CHP,1}}{\eta_{t,CHP,1}} - \mathbf{1}\right) = \boldsymbol{HDem_t} \quad \boldsymbol{t = 1, \dots, T}$$

**Equation 16**

#### 4.3.1.2.8 Micro-CHP Ramp Constraints

The rate at which the micro-CHP can change its electrical output level may be constrained in order to reduce mechanical stress or other problems caused by thermal gradients in the prime mover, and to reduce wear and tear caused by thermal cycling. The formulation of this constraint is presented in Equation 17.

$$\boldsymbol{r_{down}} \leq \sum_{k=2}^{L} \mathbf{a_{k,t}} - \sum_{k=2}^{L} \mathbf{a_{k,t-1}} \leq \boldsymbol{r_{up}} \quad \boldsymbol{t = 2, \dots, T.}$$

**Equation 17**

#### 4.3.1.2.9 Electrical and Thermal Energy Charge and Discharge Rate Constraints

Similarly to capacity constraints, the rate at which energy can be stored or discharged is technically limited. These constraints, on the electricity storage unit and thermal energy storage unit charge and discharge variables, are presented in Equation 18, Equation 19, Equation 20 and Equation 21.

$$\boldsymbol{e_t} \leq \boldsymbol{u_{ch}} \quad \boldsymbol{t = 1, \dots, T.}$$

**Equation 18**

$$\boldsymbol{f_t} \leq \boldsymbol{u_{dis}} \quad \boldsymbol{t = 1, \dots, T.}$$

**Equation 19**

$$\boldsymbol{g_t} \leq \boldsymbol{v_{ch}} \quad \boldsymbol{t = 1, \dots, T.}$$

**Equation 20**

$$h_t \leq v_{dis} \quad t = 1, \ldots, T.$$

**Equation 21**

### 4.3.2 Degradation Efficiency Characterisation for Fuel Cell Systems

Fuel cell stacks experience degradation over their lifetime. This results in operating efficiencies being lower than original values as the unit progresses through its life. The following mathematical characterisation is applied to represent output-based and thermal cycling-based efficiency degradation. In this model degradation is characterised for a fuel cell system for electrical efficiency only. The amount of fuel used by the micro-CHP unit is influenced by degradation coefficients κ and ϕ. These two coefficients are defined as follows:

- κ is the efficiency degradation per kWh of electrical output from the fuel cell stack.
- ϕ is the efficiency degradation per thermal cycle of the fuel cell stack.

Both degradation coefficients are applied to give total degradation up to the specified point in time, which is then subtracted from the original efficiency of the unit. Therefore this formulation represents linear degradation of the fuel cell stack which gradually reduces its electrical efficiency proportionally to the two coefficients. For these two parameters, efficiency in time period $t$ is related to the original efficiency via the following equations:

$$\eta_{t,CHP,k} = \eta_{0,CHP,k} - \kappa_\eta \sum_{i=1}^{t} \left( D_1 \alpha_{1,i} + \sum_{k=2}^{L} a_{k,i} \right) - \varphi_\eta \frac{\sum_{i=1}^{t} S_{sd,i}}{S_{sd,t}}$$

**Equation 22**

This creates a linear relationship between electrical efficiency degradation and cumulative use, but a subsequent non-linear relationship between fuel cost and cumulative use (the present optimisation approach (MILP) requires this relationship to be linear). An example linearisation of an element of the objective function, using a truncated Taylor series expansion, is presented below.

The fuel consumption for each segment of the piecewise linear production curve, in time period $t$ is given by:

$$y_{k,t} = \frac{a_{k,t}}{\eta_{FC,k} - \kappa_\eta \sum_{i=1}^{t-1} (\sum_{j=1}^{L} a_{j,i})}$$

**Equation 23**

It is possible to make a first order linear approximation of Equation 23, which is valid for a small region around the vector $a = a^*$, where $a^*$ is the best guess at the final optimised

value of decision variables $a$. This approximation takes the form of a truncated Taylor series;

$$y(a) \approx y(a^*) + J \cdot (a - a^*)$$

**Equation 24**

where $J$ is the Jacobian. The terms of the Jacobian can be calculated using the chain rule:

$$\frac{\partial y}{\partial a_{k,i}} = \frac{\kappa_\eta a_{k,t}}{\left(\eta_{FC,k} - \kappa_\eta \sum_{i=1}^{t-1}(\sum_{j=1}^{L} a_{j,i})\right)^2} \; for\ all\ i \neq t$$

**Equation 25**

$$\frac{\partial y}{\partial a_{k,i}} = \frac{1}{\eta_{FC,k} - \kappa_\eta \sum_{i=1}^{t-1}(\sum_{j=1}^{L} a_{j,i})} for\ i = t$$

**Equation 26**

Substituting Equation 25 and Equation 26 into Equation 24 results in Equation 27.

$$y_{k,t} \approx \frac{a^*_{k,t}}{\eta_{FC,k} - \kappa_\eta \sum_{i=1}^{t-1}(\sum_{j=1}^{L} a^*_{j,i})} + \frac{\kappa_\eta a^*_{k,t}(\sum_{i=1}^{t-1}\sum_{j=1}^{L}(a_{j,i} - a^*_{j,i}))}{\left(\eta_{FC,k} - \kappa_\eta \sum_{i=1}^{t-1}(\sum_{j=1}^{L} a^*_{j,i})\right)^2} + \frac{(a_{k,t} - a^*_{k,t})}{\eta_{FC,k} - \kappa_\eta \sum_{i=1}^{t-1}(\sum_{j=1}^{L} a^*_{j,i})}$$

**Equation 27**

Equation 27 can be simplified to arrive at Equation 28.

$$y_{k,t} \approx \frac{\kappa_\eta a^*_{k,t}(\sum_{i=1}^{t-1}\sum_{j=1}^{L}(a_{j,i} - a^*_{j,i}))}{\left(\eta_{FC,k} - \kappa_\eta \sum_{i=1}^{t-1}(\sum_{j=1}^{L} a^*_{j,i})\right)^2} + \frac{a_{k,t}}{\eta_{FC,k} - \kappa_\eta \sum_{i=1}^{t-1}(\sum_{j=1}^{L} a^*_{j,i})}$$

**Equation 28**

This linearisation of degradation represents a good approximation subject to the condition $\eta_{FC,k}/\kappa_\eta - \sum_{i=1}^{t-1}(\sum_{j=1}^{L} a_{j,i}) \gg 0$. Essentially this means that for small values of degradation as would be expected, and for micro-CHP operating lifetimes up to a target of 40,000 hours, this linearisation represents a reasonably accurate approximation. The primary drawback of using this method is the requirement for iterative optimisation solution, increasing the amount of time required to complete the computation.

Note that the method applied in this linearisation is used for all variables influenced by degradation in the present optimisation problem. Derivation of the linearisation does not vary significantly from that presented here for any of these cases.

## 4.4 Model Implementation and Tractability

The optimisation problem described in section 4.3 above must be implemented using a Mixed Integer Linear Programming (MILP) solver due to the presence of both integer and linear decision variables and constraints. The solver chosen for this research is ILOG CPLEX 10.2, which is a recognised commercial package with MILP capabilities, and suitable for analysis of problems with sparse constraint matrices (as is the case in the formulation developed). Visual C++.NET is the programming language used to call the C++ application programming interface (API) of CPLEX.

Tractability is an issue for this optimisation problem. For relatively simple problems involving 6 sample days of demand data with 5-minute time-steps, basic technical, demand, and capacity-related constraints, and no energy storage, the resultant constraint matrix contains approximately 30,000 non-zeros elements. Solutions time for such a problem using C++ and CPLEX is of the order of a few seconds. Larger problems with more sample days or finer temporal precision of demand data, and all of the possible constraints presented in section 4.3, can have up to 1 million non-zeros, creating a very tough optimisation problem, with solution times of over an hour on a dual 2.6GHz Intel Xeon processor workstation with 3GB RAM, etc (i.e. a high specification workstation). Such solution times are not acceptable for sensitivity analysis where solutions must be obtained for many sets of input data. Furthermore, only slightly larger optimisation problems exceed 32-bit computing memory allocation limits (i.e. roughly 2GB per application), which would prevent any solution being obtained. The only solution to that issue is upgrade to 64-bit computing.

Despite these limitations, the implementation constructed allows solution times that are manageable for the purposes required, with most problems solvable in under 30 seconds. More complex problems involving more decision variables or constraints would require a) parallel computing to speed solution times or undertake several optimisations simultaneously, and/or b) 64-bit computing to avoid memory allocation constraints.

# Chapter 5: The Influence of Modelling Approaches and Assumptions

This chapter serves to establish that the model formulation and implementation produces a reliable and repeatable result, and establishes an appropriate level of detail for implementation of the modelling formulation presented in Chapter 4. In general techno-economic modelling is used to illustrate the likely economic and environmental benefit of the technology with particular characteristics, which contributes to directing research and development for micro-CHP, and to the case for policy support. Therefore modelling that produces accurate results is critical to its development.

Firstly a common fault with residential generation systems modelling is addressed; studies often use course time-series data for model inputs and outputs, possibly leading to misleading results. Secondly, "sample days" which should represent an annual demand profiles are often chosen in an ad-hoc manner, leading to poor repeatability of results. Finally the results of this modelling approach are briefly compared with the performance of existing installed systems.

Besides contributing to the development and validation of the methods, the results of these studies also form distinct contributions to the wider modelling literature, helping guide other modellers.

## 5.1 Temporal Precision of Modelling

This section considers the impact of temporal precision in modelling for micro-CHP technologies. The impact on economic and environmental analysis of residential micro-CHP systems through analysis results is explored through $1kW_e$ examples of the micro-CHP systems described in section 2.2. Results presented in this section have been published by the author in Hawkes and Leach (2005b).

Most economic and environmental analyses of microgeneration systems use electrical and heat demand data for each hour or half-hour of the day, often for a number of typical days that are used to represent a typical year (for example, Cockroft and Kelly (2006), Wallmark and Alvfors (2003)). Splitting demand data into such coarse precision results in substantial averaging of load, which in the case of residential properties that often exhibit particularly peaky heat and power demand characteristics, could lead to erroneous modelling results.

The peaky nature of residential load was shown previously in Figure 5 (section 2.1.4), and the electricity and heat demand data at a temporal precision of 5-minutes as described in section 2.1.4 is applied here. Demand profiles are input to the optimisation model, along with other relevant input data relating to technical and economic characterisation, to determine the primary performance metric and a variation on a further assessment metric:

- Maximum capital cost difference between the micro-CHP system and the reference boiler-only system.
- Lifetime $CO_2$ emissions reduction with respect to the reference system.

For this analysis, the four different micro-CHP technologies have been modelled against one set of demand profiles; those corresponding to a mean UK demand (i.e. the "existing Terrace" dwelling from Table 1). The temporal precisions used are 1-hour, 30-minute, 10-minute, and 5-minute demand blocks, and the reader should note that the primary economic metric is calculated with a discount rate of 0% in this case. Coarser temporal precisions are obtained through aggregating the 5-minute precision demand data. Cost-optimal results for the different temporal precisions are compared against one another, with respect to the cost and $CO_2$ footprint of operating the reference system.

### 5.1.1 Results: Impact of Temporal Precision

The temporal precision of input and output data is found to have a substantial impact on the economic, energy consumption, and environmental results. Figure 16 shows the sensitivity of the primary economic metric; the maximum cost difference between the micro-CHP system and the reference system. In the most extreme example the maximum cost differential for the SOFC-based micro-CHP system in this demand case is over £2,100 for hourly precision, but reduces to £1,300 for the more accurate 5-minute precision. Therefore, if hourly precision were used, micro-CHP system value could be overestimated by 70%. This result is consistent across the micro-CHP technologies, although less pronounced for the engine-based systems which exhibit overestimate of allowable capital cost of around 30% between hourly and 5-minute precisions.

Likewise, the $CO_2$ emissions result is altered according to chosen temporal precision. As apparent from Figure 17, use of a course precision tends to result in lifetime $CO_2$ savings being overestimated. The range of influence is from 30% in the case of the ICE engine, roughly 20% in the case of the SOFC-based system, 15% for the PEMFC-based system,

down to no discernable influence for the case of the Stirling engine which offered meagre $CO_2$ savings in all cases.

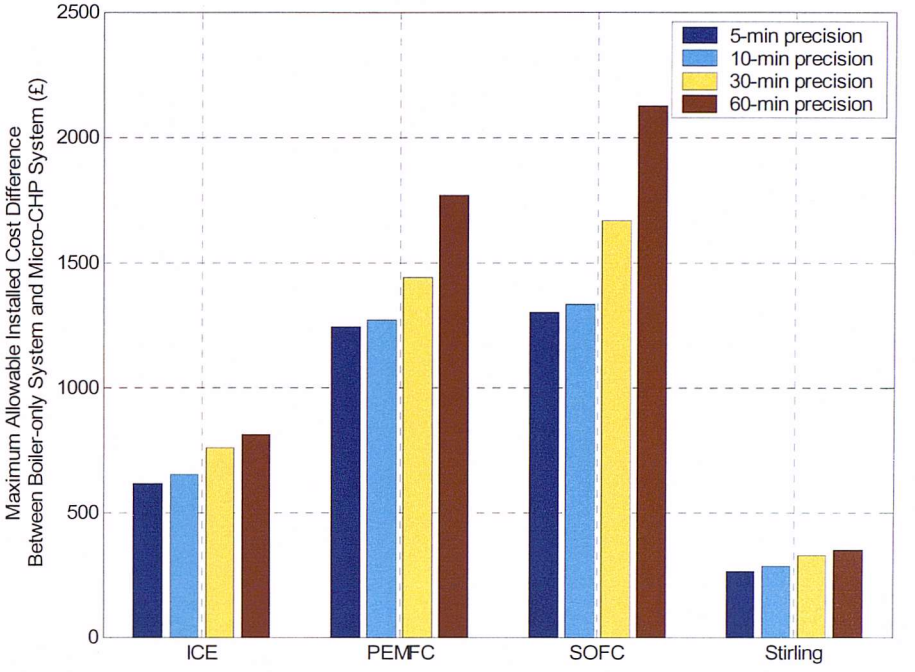



**Figure 16: The Impact of Temporal Precision on Maximum Cost Differential Between Micro-CHP System and Reference Boiler-Only System (£)**

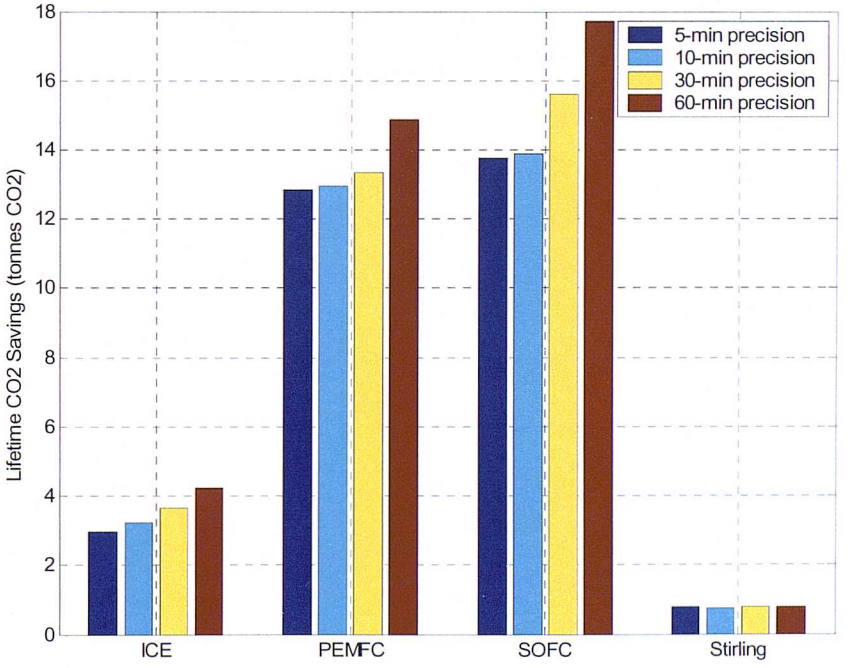



**Figure 17: The Impact of Temporal Precision on Lifetime $CO_2$ Emissions with respect to Reference Boiler-Only System (tonnes $CO_2$)**

Clearly the choice of temporal precision is critical in arriving at accurate results. Depending on the accuracy required, either 5-minute or 10-minute resolution of input and decision variables appears to be necessary to produce a defensible result. The relatively comparable outcomes between 5 and 10-minute precision suggest that further disaggregation of demand and decision variables to (for example) 1-minute precision should probably not significantly improve accuracy of results, and will certainly significantly deteriorate tractability. Testing of the supposition that finer resolution does not improve accuracy is not possible with the available data set which was measured at 5-minute intervals.

This conclusion regarding the impact of temporal precision on outcomes of modelled performance assessments of residential microgeneration casts doubt on the findings of a large number of published studies. Depending on the nature of demand in each case, models with coarse precision can greatly overestimate the potential of technologies and lead to (for example) ill-advised policy support decisions. The remainder of this thesis employs demand and decision variables at 5-minute precision, except where explicitly stated.

The following section discusses the source of variation between precisions observed.

### 5.1.2 Source of the Temporal Precision Result

The observed differences in optimisation results between various temporal precisions can be investigated through analysis of a single hour of demand. Figure 18 shows the 12 five-minute average power demands over a sample 1 hour period and average power demand over the hour (the solid line at 661W) – i.e. the values for demand that would be used in an analyses using 5-minute and hourly precision respectively.

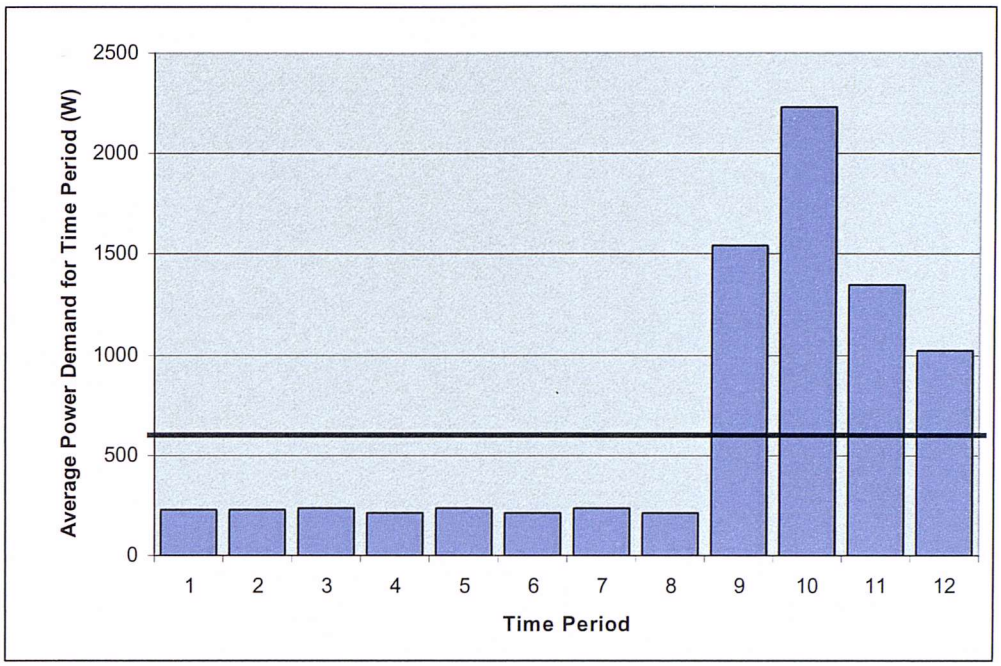



**Figure 18: Power Demand for a Single House for 1 Hour (i.e. each bar represents a 5-minute period)**

If hourly precision were used in the optimisation analysis and the capacity of the micro-CHP generator was chosen to be 0.9kW$_e$ (i.e. just above the average demand over the hour), the result may have been that the generator meets all the power demand over the hour. However, when the average power demand on a 5-minute time-step basis is observed, it is apparent that there are 4 time periods (periods 9, 10, 11, and 12) where a 0.9kW$_e$ generator could not have met the full demand, and additional power would have been needed from the grid. The hourly precision would also have enabled the apparent export of small amounts of power in the first eight time periods, which is also not possible in reality. Clearly the hourly precision does not represent the physical reality very well.

A similar argument applies to other optimisation constraints in the developed model. For example, the 5-minute precision data in Figure 18 displays a significant ramp in power demand between time periods 8 and 9. The micro-CHP generator could be constrained in its response to this ramp, implying that additional power needs to be imported from the grid to meet the full demand. Of course the hourly precision does not exhibit this ramp, indicating that the generator can meet all of the demand without resorting to grid electricity. Another example is apparent when the micro-CHP minimum set-point (i.e. maximum turndown) constraint is considered. If, for example, a generator has a minimum set-point of 0.5kW$_e$, the hourly temporal precision can result is the system remaining running (i.e. in a electricity load following operating strategy), whilst the physical reality would have required it to switch off. Furthermore, temporal resolution issues do not relate

solely to electrical demand; the averaging effect of using a coarse time step also applies to domestic hot water demand, which is also by nature peaky and interacts with micro-CHP system technical constraints.

Whilst the above discussion explains why coarse precision demand data and associated decision variables do not represent the physical situation well, further explanation is required to demonstrate how this reflects onto the cost of meeting demand and the potential for $CO_2$ emissions savings. The observed difference between costs (expressed via the primary economic metric) and $CO_2$ savings across the temporal precisions investigated relates to the underlying fuel types used by the micro-CHP system, reference system, and centralised power generation. For example, if analysis at coarse temporal resolution results in the apparent consumption of one fuel type (e.g. gas for the micro-CHP system at approx 6.9 pence per electrical $kW_eh$ produced) when the true physical situation required consumption of an alternative fuel (e.g. coal-fired centralised generation at a cost of 10.2 pence per $kW_eh$ consumed) then clearly both the overall cost and $CO_2$ savings will be influenced by the choice of that coarse precision. For the fuel type considered in this thesis the issue is particularly important for electricity demand, and less so for thermal demand, because it is always met via natural gas as the primary fuel, so temporal resolution issues resulting in the swap of one heating source for another has relatively little economic or $CO_2$ impact. Temporal resolution in thermal characterisation is more important when it comes to thermal constraints, which can cause the system to cycle as discussed above.

Based on this reasoning, it is expected that if the fuelling options of the components used to meet demands were more dissimilar in terms of cost or embodied $CO_2$, a more pronounced difference in economic or $CO_2$ outcomes would be observed across different temporal precisions. Given that in the UK residential micro-CHP is likely to be fuelled by piped natural gas and assuming current grid emissions rates, the observed impact of temporal precision is to overestimate the value and environmental benefit of micro-CHP, but it is noted that this result depends on fuel types, costs, and grid $CO_2$ intensities assumed.

## 5.2 Choice of "Sample Days"

This section considers another common assumption in energy modelling; that a set of sample days is representative of an annual demand profile and can be used to assess a

technology in that demand situation. Residential electricity and heat load profiles exhibit a wide variety of shapes and sizes. As discussed in section 2.1, differences in observed demand are influenced by a vast array of factors including number of occupants and size of dwellings to name a few. More broadly, behavioural patterns of dwelling occupants, which also drive energy demand, are shaped by cultural, social, economic and technical factors. Therefore, although attempts to characterise residential demand do exist, it remains a difficult task to adequately represent the depth and breadth of possibilities in a meaningful way.

It is common in industry and academia to use a set of typical "sample days" that are perceived to represent an annual energy demand profile. The use of sample days achieves two aims; firstly, the problem becomes more computationally tractable when the data set size is reduced, and secondly, the expensive and time-consuming requirement to meter energy demands for a large number of properties over a long time-span might be avoided.

The aim of this section is to show that it is necessary to carefully choose these sample days in order to furnish the accurate estimation of energy consumption and associated cost of energy provision using a micro-CHP system. To achieve this aim, the model developed in section 4.3 is applied to minimise the cost of meeting energy demand for a set of given load profiles and a set of price input parameters, across two distinct sampling methodologies. Solid Oxide Fuel Cell (SOFC) based micro-CHP as described in section 2.2.3.1 is used as an example to illustrate the issue.

Although it may be possible to use modern statistical methods to characterise a load profile (for example, using statistical tests to determine how representative a particular day is of the season it is in), it is endeavoured to avoid complex statistical tests because they may not appeal to a wide range of energy modellers. Indeed, even if a systematic statistical test is conceivable, its designer must have knowledge of what drives performance outcomes for micro-CHP in relation to the nature of demand. The approach adopted herein first asks this question "What basic demand characteristics have the primary influence on micro-CHP economic credentials?"

The following section examines the value drivers for micro-CHP and variation in residential demand in a single dwelling in more detail. This leads to choice of important parameters to enable selection of sample days from a demand profile. The ability of the sampling

technique to select days that produce results commensurate with those of the entire annual demand profile is then assessed via application of the developed model.

### 5.2.1 Choice of Parameters that Define Representative Sample Days

When considering the important characteristics of sample days for economic performance assessment of micro-CHP it is necessary to consider drivers of its value relative to the reference system. Where combined heat and power uses an identical fuel to the reference system, and overall efficiency is identical (i.e. the sum of thermal and electrical efficiency of the micro-CHP system equals the thermal efficiency of the reference heat-only system), the primary value driver is the price differential between the fuel and electricity. A complication for the case of residential micro-CHP is that the value of electricity is dependent on whether it is consumed onsite, or sold to a supplier (i.e. exported to the grid).

As shown in Table 10 the best economic result for micro-CHP occurs when meeting onsite electricity demand and heat demand simultaneously. It can be competitive when meeting electricity demand and dumping heat, and high-efficiency systems such as the SOFC investigated are marginally competitive when exporting electricity and meeting heat demand (for the energy price combination investigated here). Therefore a primary driver of value for micro-CHP is the extent to which the demand it serves exhibits simultaneous demand for electricity and heat, followed by the presence of electricity demand without thermal demand (and the extent to which the system can dump heat).[16]

[16] It should be noted that further factors influence the value of micro-CHP, for example the maximum ramp rate, the maximum turndown (i.e. minimum operating point), start/stop cost, etc. These factors are highly non-linear (indeed some relate to step functions) and challenging to quantify in terms of sample day choice. It is assumed here that co-incidence of electricity and thermal demand is more important factors in terms of sample day choice.

| Energy Demand Situation | System Applied | SOFC Micro-CHP Fuel (pence) | Boiler Fuel (pence) | Imported Electricity (pence) | Value of Exported Electricity (pence) | TOTAL (pence) |
|---|---|---|---|---|---|---|
| **Meeting 1kWh onsite electricity demand and 1kWh heat demand** | SOFC Micro-CHP | *6.2* | *0* | *0* | *0* | **6.2** |
| | Grid/Boiler | *0* | *2.9* | *10.2* | *0* | **13.1** |
| | | | | | ***Difference=*** | **6.9** |
| **Meeting 1kWh thermal demand with no electricity demand** | SOFC Micro-CHP | *6.2* | *0* | *0* | *4.0* | **2.2** |
| | Grid/Boiler | *0* | *2.9* | *0* | *0* | **2.9** |
| | | | | | ***Difference=*** | **0.7** |
| **Meeting 1kWh electricity demand with no thermal demand** | SOFC Micro-CHP | *6.2* | *0* | *0* | *0* | **6.2** |
| | Grid/Boiler | *0* | *0* | *10.2* | *0* | **10.9** |
| **NB/ Final situation involves the system micro-CHP system dumping heat** | | | | | ***Difference=*** | **4.0** |

**Table 10: Analysis of Value Drivers for SOFC-based Micro-CHP Using Central Estimates of Energy Prices**

Although this co-incidence of electrical and thermal demand can clearly have a large impact on the cost for a grid-parallel micro-CHP system to meet demand, it still will not be necessary to consider this parameter in sample day choice if it does not exhibit significant variability though a year (i.e. if all days generally exhibit comparable co-incidence of electrical and thermal demand, it is not necessary to consider this factor when differentiating between them). Figure 19 displays a histogram of co-incident demand (in the ratio of 1:1; consistent with the heat-to-power ratio of the SOFC prime mover) over a year, showing that the variability of this parameter is indeed significant. This indicates that choice of sample days with representative co-incidence of electrical and thermal demand is important, and studies that do not take this into account may produce misleading results.

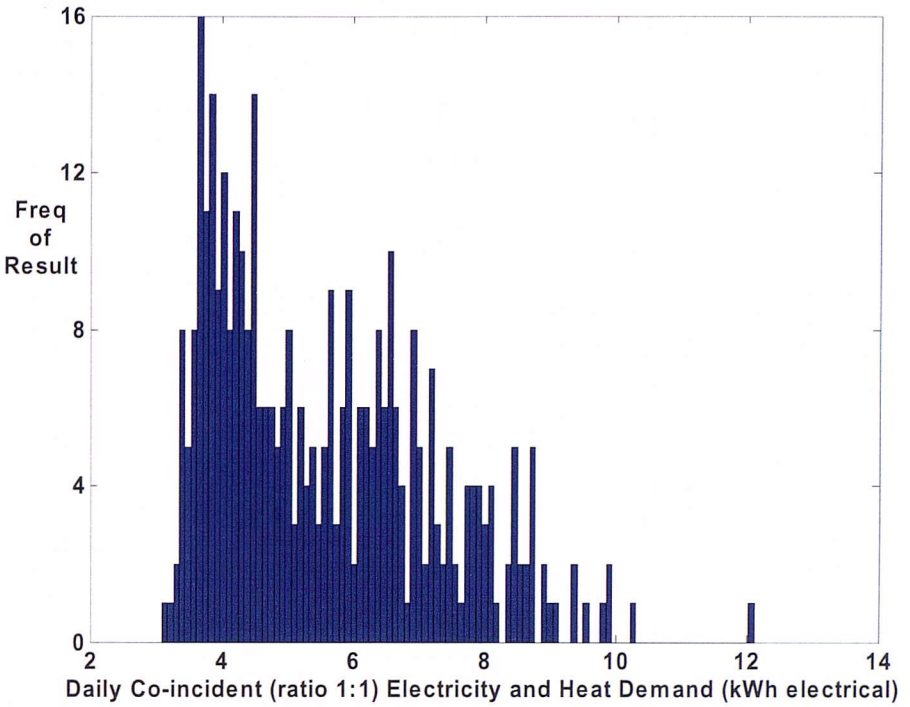



**Figure 19: Daily Co-incident Demand (kWh) Histogram Over One Year for the Existing Detached Dwelling**

In addition to micro-CHP co-incidence of demand, there are some further important cost/value related considerations in choosing sample days. As the primary objective function of the optimisation approach developed in section 4.3 relates to the annual cost of meeting a specified electricity and thermal demand profile, a choice of sample days that adequately reflect that annual demand must be an important cost driver. For example, if the chosen sample days, when weighted to reflect the number of days of each "type", present an electricity demand of 3,000kW$_e$h, but the actual demand from summing the annual profile was 5,000kW$_e$h, one would expect the sample days to produce a poor representation of the cost of meeting that demand. To shed light on this issue and consider the importance of the value drivers in context, the variation in daily residential demand is considered below.

As discussed in section 2.1, energy demand in a single residential dwelling is notoriously unpredictable. Figure 20 and Figure 21 display histograms of daily electricity and thermal consumption in kWh respectively for a UK average dwelling over an entire year. The three seasons depicted are winter (December to April), shoulder (October, November, April, May), and summer (June to September). Clearly the daily electricity demand exhibits a wide range of possibilities, with winter demand higher than other seasons. Thermal demand is more consistent, and presents the expected clear differentiation between

seasons. As the dwelling from which these demand profiles where obtained had a boiler heating system, the clear grouping of the daily thermal demand result for the shoulder season is certainly related to this system being switched on/off according to the occupier's preference.

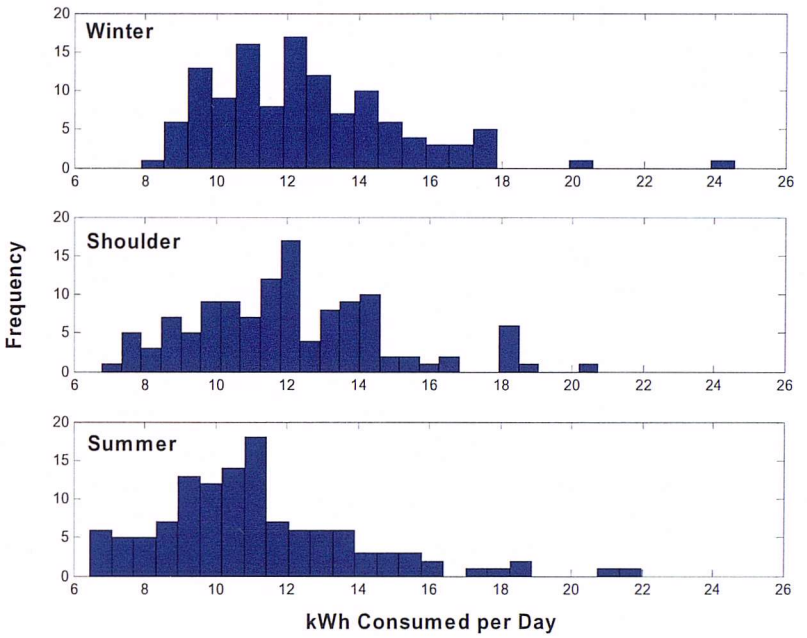



**Figure 20: Daily Electricity Consumption (kWh/day) Histograms for Winter, Shoulder and Summer Seasons**

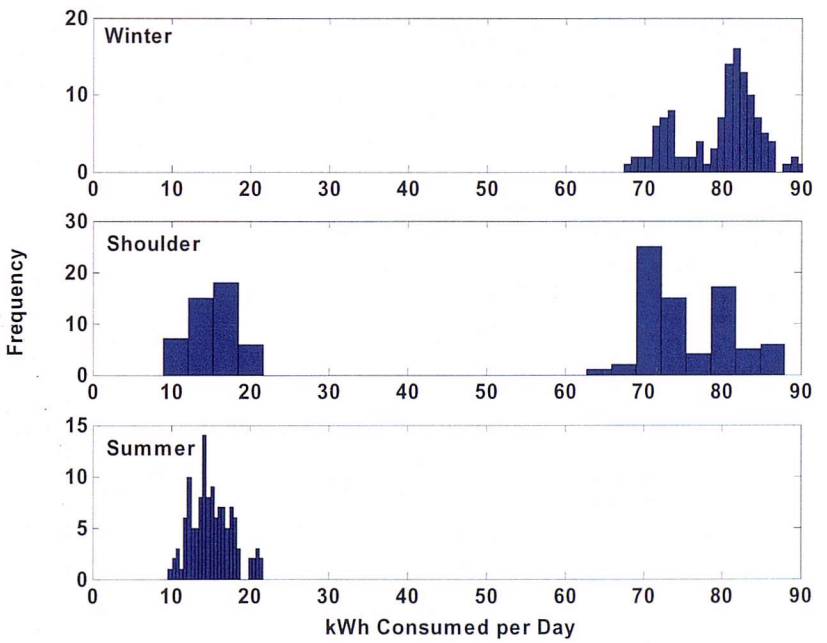



**Figure 21: Daily Thermal Consumption (kWh/day) Histograms**

From inspection of Figure 20 and Figure 21 it is again apparent that random choice of sample days could lead to large departures from representation of average demand. For

electricity demand this applies in all seasons, whilst for thermal demand it is particularly relevant in the shoulder season. Therefore another requirement of the sampling method developed is that the sample days must be representative of the annual average energy consumption.

Based on the above analysis, four considerations are chosen to enable choice of the "best" sample days:

1. Sample days must be present to represent at least three seasons (winter, shoulder summer).
2. Sets of sample days within a season, when weighted, must reflect the aggregate electricity demand of the season to which they belong.
3. Sets of sample days within a season, when weighted, must reflect the aggregate thermal demand of the season to which they belong.
4. Sets of sample days must reflect the average seasonal co-incident electrical and thermal demand (kWh) at the heat-to-power ratio of the micro-CHP system under consideration.

These four considerations were implemented in MATLAB to parse an annual demand profile and select appropriate days from it. As discussed further below, days that perfectly reflect the characteristics of the annual demand rarely exist, and tolerances must be relaxed to identify the "best" days. The following sections consider the impact of the four considerations on the economic result for SOFC-based micro-CHP using the optimisation approach developed.

### 5.2.2 Method of "Sample Days" Analysis

One UK residential energy demand profile based on the "existing" Terraced dwelling variant presented in Table 1 is analysed – consisting of metered demand for each 5-minute period of an entire year. The following analysis method is then adopted:

1. In order to show the impact of a sampling in a semi-random fashion, such as the case where an analyst meters demand for a few days in each seasonal period, the annual profile is divided into seasons and a random sample of days is taken from each season. The developed model, with characterisation of SOFC-based micro-CHP as per section 2.2.3.1, is then applied to find the minimum cost of meeting the demand for the set of sampled days (and thus allows calculation of the primary economic metric, with a discount rate of 0%). This process is repeated 30 times

(with a different sample of days each time), and the distribution of results is considered.

2. 'Candidate' sample days are chosen based on the four factors deemed significant in section 5.2.1. As there may be many possible candidate days, a random sample is then taken from them, and the optimisation analysis is performed on the sample. This process is repeated 30 times (i.e. with a different set of candidates making up the selected sample each time), and the distribution of results is considered.

In order to assess the relative merits of the sample day choice technique an estimate of the true cost of meeting the entire annual demand profile is required. This estimate is achieved through application of the developed optimisation approach sequentially to each week in that profile and summation of the results. This method is computationally intensive and therefore not appropriate for routinely determining optimum operating costs (thus the necessity of choosing sample days). This estimate of the true cost can be used to compare the relative accuracy and repeatability of the random sampling versus controlled sampling methods.

### 5.2.3 Results of the "Sample Days" Analysis

Figure 22 and Figure 23 show histograms of the primary economic metric for the random and structured sampling methods respectively (i.e. the maximum installed cost difference between the micro-CHP system and the reference boiler system). Clearly the spread of results for random sampling in Figure 22 is substantially more significant than that of the structured sampling approach in Figure 23.

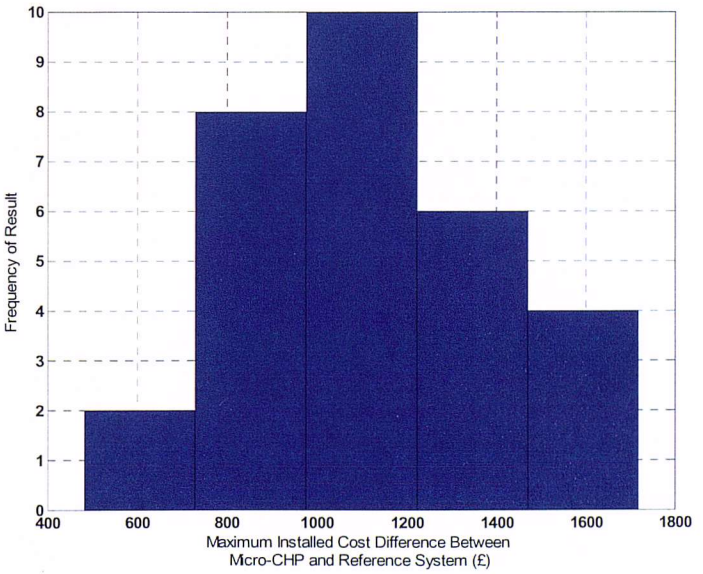



**Figure 22: Spread of Economic Results when Sample Days Are Chosen Randomly**

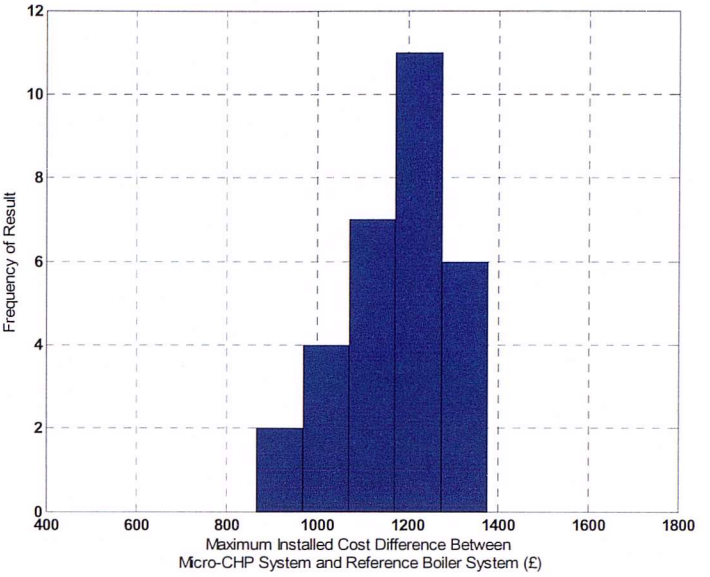



**Figure 23: Spread of Economic Results when Structured Sampling Approach is Applied**

In order to deduce that the structured sampling is indeed better than random sampling, it is also necessary to evaluate whether or not the contraction in spread of results is centred on the true cost. As described above, this is achieved by applying the developed modelling approach to each week in the annual demand profile sequentially. The operating cost saving for each week (with respect to the reference system) is then summed, and discounted over the lifetime of the unit to arrive at the primary economic metric. For the case of the demand profile investigated this value was approximately £1,200. Therefore the contraction in spread of results between Figure 22 and Figure 23 is a convergence toward the true result, and it may be concluded that the structured sampling method offers an improvement on random sampling.

It should be noted that the spread of results in Figure 23 is still significant; the maximum price the investor would pay for the micro-CHP system in addition to the reference system price is between £900 and £1,400, a possible deviation of -25% to +16% of the true value. However, the best set of sample days identified (i.e. those that adhere to the requirements of the structured sampling approach most closely) produce a result of roughly £1,200, indicating that the sampling approach can produce accurate results. The spread of results under the structured sampling approach is caused by the fact that the annual demand profile simply does not contain sub-sets of days that closely mirror the important characteristics of that annual demand (tolerances on selecting these days need relaxation in order to identify 30 sets of days for the above analysis, resulting in the spread of results).

Therefore the conclusion can be restated; the sampling method does represent a robust approach that is certainly an improvement over a random sampling approach.

The spread of results produced by the sampling method is not of great significance to the accuracy of results presented in this thesis. This is because it can be assumed that the samples used hereafter are perfectly accurate representations of annual demand profiles very similar but not identical to the observed demands. For example, if the sample days examined indicates annual demand of 3,300kW$_e$h and 15,000kW$_{th}$h, then it can be assumed that the annual demand also exhibits these demands even if the actual annual demand profiles they were drawn from are slightly different. In this case, as shown above, the modelling framework developed produces accurate results. The sampling method simply provides an improved method to capture important characteristics from real demand profiles, and ensures that broad features of observed residential energy demand are adequately represented in chosen sets of sample days.

## 5.3 Comparison of Modelled and Actual Performance

A final assessment of the model formation and implementation carried out is consideration of its ability to accurately reflect the performance of actual systems installed in "live" situations. Unfortunately relatively few published field trial results exist, with the notable exception of Carbon Trust (2007); the Micro-CHP Accelerator Interim Report. Therefore only limited comparison of modelled and actual performance is possible at present.

Figure 52 in Carbon Trust (2007) displays the range of expected carbon savings for domestic and commercial micro-CHP. For domestic micro-CHP, the stated range of carbon savings is between -5% and 15% for Stirling engine systems, with a "likely range" between 0% and 10%. The characteristics of the Stirling engine system described in Carbon Trust (2007) are input to the modelling framework developed in this thesis, for the range of "existing" dwellings described in Table 1, and results compared to this range. Modelling results yielded a range of 2% to 7% $CO_2$ savings across dwelling types, which is approximately consistent with the range reported in Carbon Trust (2007), although more tightly clustered around the mean $CO_2$ reduction value experienced in actual systems (i.e. 5%). The difference between modelled and actual performance can be attributed to differences in energy demand profiles and micro-CHP prime mover dispatch strategy; the modelling approach optimises dispatch to minimise cost, whilst the systems in the field trial were designed to dispatch when thermal demand is present (i.e. not a cost-optimal

operating strategy). However, it is apparent that modelled results are an acceptable approximation of actual performance, and it is unlikely that there are systematic or significant errors in either the approach or input data.

## 5.4 Conclusions Regarding Modelling Approaches and Assumptions

This chapter has investigated the robustness of the developed modelling approach and contributed to its design by examining selected aspects of energy demand characterisation and then comparing modelled performance with that of actual systems.

It has been shown that the way energy demand is characterised has significant bearing on the results of economic and environmental analyses of microgeneration for residential energy provision. The leading concern is the temporal precision of the demand data used in the analysis. Where coarse demand data is used, as is the case in the majority of pre-2005 studies, the value of micro-CHP can be overestimated by up to 70% (see Figure 16), and the lifetime $CO_2$ savings can be overestimated by up to 30% (see Figure 17). The discrepancy between different temporal resolutions is caused by averaging effects, where peaks in demand are smoothed out, making it seem possible for an onsite generator to meet those demands when in fact they are beyond the capacity of the device. Whilst this issue is relevant for any energy modelling situation, it is particularly significant for the residential sector, where individual households often exhibit particularly volatile electrical and thermal demands. Clearly credible economic/energy/environmental modelling of onsite generation for residential energy provision must use data at least 10-minute precision, preferably 5-minute or 1-minute. For the remainder of this thesis, 5-minute precision demand data has been used in the analyses, except where explicitly stated.

The second issue investigated relates to a method for selecting "sample days" from annual demand profiles. Such a method is necessary because consideration of the entire demand profile is not tractable given the limitations of modern computing. It was shown that the characteristics of demand, such as co-incidence of thermal and electrical demand, can have a strong bearing on economic results. It was also shown that there is substantial variation in three key demand parameters (daily electricity demand, daily thermal demand, and co-incidence between electrical and thermal demand) between days. Based on these observations, a method to choose sample days was developed, based on a) ensuring representation across seasonal patterns, b) ensuring sample days are representative of the thermal and electrical demand of the season to which they belong, and c) respecting co-

incidence between thermal and electrical demand evident in the annual demand profile. Modelling results when using sample days selected using this structured approach were compared to using randomly selected sample days. It was found that the structured sampling method produced a more repeatable result, closer the predicted actual economic/environmental outcome when the whole annual demand profile is considered. However, results still exhibited some spread, reflecting the fact that sets of sample days which very closely reflect characteristics of annual demand may not exist within the annual demand profile. Nonetheless, the structured sampling method improves demand characterisation, and in the case where the annual demand profile does exhibit similar "key" characteristics to the sample day set, results are likely to be very accurate.

Finally, modelled results were compared with actual results from field trials of pre-commercial micro-CHP technologies reported in Carbon Trust (2007). It was shown that the model produces outcomes reflective of those experienced in field trials. Discrepancies are due to differences in micro-CHP operating strategy and the demand to which they are applied.

# Chapter 6: **Key Economic Drivers for Micro-CHP**

This chapter applies the model discussed and developed in Chapters 3 and 4, along with technology characterisations described in section 2.2, and the reference system described in section 3.2, to explore the key economic drivers for the micro-CHP technologies in the dwellings with a set of the energy demands described in section 2.1.5.

## 6.1 Sensitivities Regarding the Case for Investment in Micro-CHP

Sensitivities chosen for analysis include the prime mover capacity, annual energy demand, spark spread of residential energy provision, buyback rate for electricity generated onsite and "exported" to the electricity grid, and the cost of capital of the investor. These correspond to the primary sources of cost/value variation for the residential energy situation, and also coincide with metrics that can be the subject of policy intervention (e.g. grant support, feed-in tariffs, low or zero interest loans, guaranteed spark-spread, etc).

### 6.1.1 Prime Mover Generating Capacity

Choice of prime mover nameplate capacity is an important concern for micro-CHP systems developers in terms of where their product fits into the market, and those concerned with assessing the economic credentials of micro-CHP (as is the case here). This sub-section considers sensitivity of the primary economic metric to capacity choice. This is important because examination of a single capacity system may miss valuable opportunities for micro-CHP developers to scale-up or scale-down their products.

Figure 24 displays the primary economic metric (i.e. the difference in value between the micro-CHP system and the reference grid-boiler system) for ICE, PEMFC, SOFC, and Stirling-based micro-CHP. Each subplot in Figure 24 shows the sensitivity of results to annual energy demands of each "existing" dwelling variant as presented in Table 1, across a range of electricity generation capacities for each micro-CHP technology. This figure is designed to inform consideration of appropriate generating capacity for micro-CHP products.

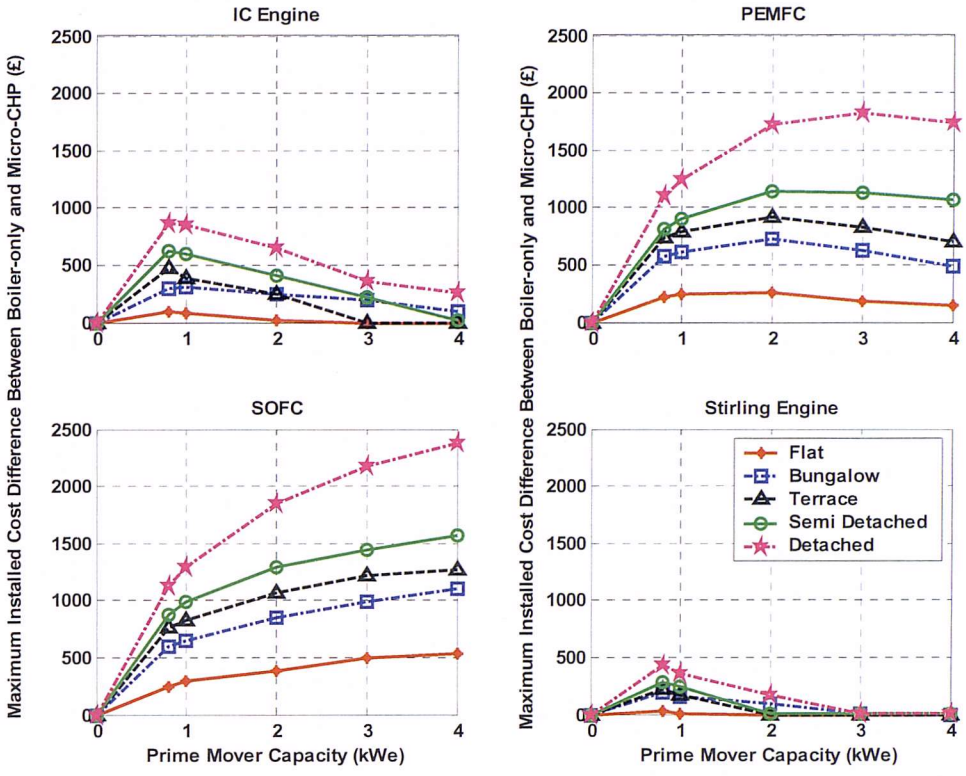



**Figure 24: Sensitivity of Maximum Installed Capital Cost Difference Between Boiler-only System and Micro-CHP System (£) to ICE Prime Mover Capacity (kWe)**

The first point to note with regard to Figure 24 is the considerable variation in value between micro-CHP technologies with respect to competing conventional boiler systems (i.e. the primary economic metric, plotted on the vertical axes). For 1kW$_e$ fuel cell based systems operating in a mean demand situation (i.e. the Terrace house) a rational investor with 12% cost of capital would pay between £700 and £800 more than the cost of the competing boiler. Conversely, a rational investor would only pay approximately an extra £200 for the modelled Stirling engine system. One cannot draw conclusions regarding comparison between the economic attractiveness of the technologies based on this result because manufacturing and installation costs for systems incorporating each prime mover type are not yet readily observable, but it is clear that fuel cell system developers have more room to move. Moreover, it is obvious a challenging economic situation exists for any micro-CHP developer seeking a mass market. The marginal production cost of including the micro-CHP prime mover and balance of plant (in addition to the boiler) in the system is likely to be significant, and a challenge for system developers to achieve with a margin of less than £1,000 pounds including any potential profit. Early markets are likely to focus on dwellings with larger demands which have access to higher value, up to £1,300 per installation.

The second point to note with regard to Figure 24 is the value per $kW_e$ installed for each technology. This relates to the slope of the lines in each subplot (i.e. the first derivative of the curves). All lines have the largest positive gradient between $0kW_e$ and $1kW_e$ prime mover capacity. As prime mover capacity increases thereafter, value per $kW_e$ installed decreases. This suggests that there may be little justification in providing a product to the UK single residence dwelling market with prime mover capacity greater than $1kW_e$. This result does vary between technologies; the value per $kW_e$ installed for fuel cell-based systems is not as sensitive to increasing capacity as the engine-based systems. Indeed a very large $4kW_e$ SOFC-based system is has a marginal value of almost £2500, which is possibly an economic manufacturing proposition if economies of scale entail cheaper production (per $kW_e$) of larger systems. Regardless of such possibilities, micro-CHP systems with $1kW_e$ electricity generating capacity present the highest value per $kW_e$ installed, and are arguably the best proposition for the UK market which is dominated by single-residence dwellings and does not have widely available heat distribution networks. The remainder of this thesis considers only $1kW_e$ micro-CHP systems, except where explicitly stated.

The final point regarding Figure 24 is the variation of economic result between the building variants. Clearly, the larger the energy demands in the building, the better the case for investment in micro-CHP. This result is apparent across technologies. The following section investigates the influence of demand in more detail.

### 6.1.2 Annual Energy Demand

It has been widely reported that there is a relationship between the thermal demand met by CHP units and their economic viability, with consistent thermal demand often associated with positive results. Whilst it is not expected that micro-CHP is an exception to this rule, it is informative to investigate the extent to which annual demand influences the value of micro-CHP, given the special nature of residential tariffs and demand. It is also informative to investigate the influence of annual electricity demand, because as shown in section 5.2.1, there is high value using micro-CHP to displace onsite electricity demand.

Figure 25 displays the variation in economic result for the four micro-CHP technologies with respect to annual thermal demand (for this figure annual electricity demand has been held constant at the mean value of 4300kWh/year, which is a departure from the electricity demands presented in Table 1). Therefore the only source of variation in each plot is the annual thermal demand profile applied. Thermal demand scenarios correspond to each of the five dwelling construction types presented in Table 1, with each construction type

connected by a line joining "existing", "refurbished" and "new" insulation standards. Inspection of the figure reveals that the dependence of the economic result on annual thermal demand is evident in all cases, but is more obvious in the cases of micro-CHP prime movers with higher heat-to-power ratios (i.e. the IC engine and the Stirling engine). The IC engine and Stirling engine benefit most from increasing thermal demand, and both fuel cell-based systems show a weak improvement of economic result as annual thermal demand increases. SOFC-based systems are the most economically-resilient to changes in annual thermal demand.

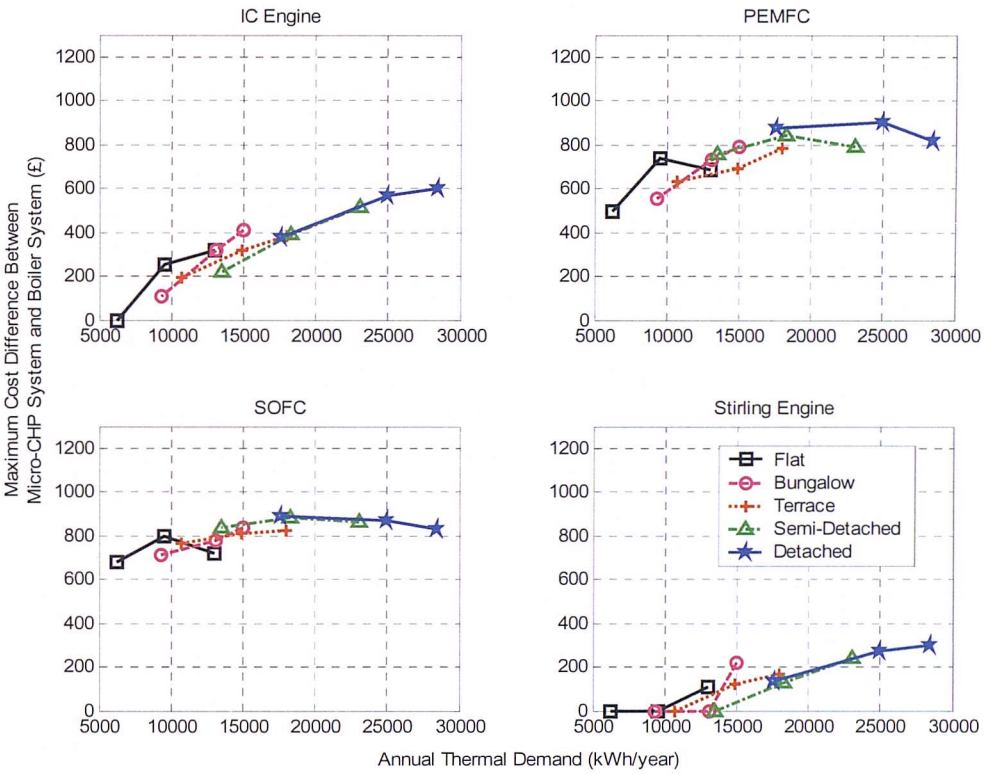



**Figure 25: Sensitivity of Maximum Installed Capital Cost Difference Between Boiler-only System and Micro-CHP System (£) to Annual Thermal Demand**

Figure 26 displays the sensitivity of the economic result to annual electricity demand (plotted across three cases of annual thermal demand corresponding to Table 1; low (existing flat - ≈13,000kWh), average (existing terrace - ≈18,000kWh), and high (existing detached house - ≈28,500kWh)). It is apparent from Figure 26 that both fuel cell-based systems show strong dependence of economic result on annual electricity demand; much stronger than their sensitivity with respect to annual thermal demand observed in Figure 25. Conversely, the two engine-based systems show approximately the same sensitivity to annual thermal demand as they do to annual electricity demand. It can be deduced that electricity demand and thermal demand are both important for a positive economic result

for the engine-based systems, but electricity demand is the primary driving factor for the fuel cell-based systems.




**Figure 26: Sensitivity of Maximum Installed Capital Cost Difference Between Boiler-only System and Micro-CHP System (£) to Annual Electricity Demand for Three Annual Thermal Demand Scenarios**

Overall the results in Figure 25 and Figure 26 can be synthesised to arrive at a key conclusion of this research: Those systems that produce more heat are more likely to be more influenced by the level of annual thermal demand. Lack of thermal demand, or significant heat production for a given electricity output (i.e. a high heat-to-power ratio of the micro-CHP prime mover), corresponds to a constraint on system operation. Essentially these thermal issues limit the ability of a system to benefit from displacing onsite electricity demand. Conversely, the economics of systems that produce less heat (i.e. low heat-to-power ratio) is strongly driven by annual electricity demand. This relates to the fact that thermal constraints do not interfere so much with their operation, and they can therefore access the value associated with generating electricity to displace onsite demand (which would otherwise have been met by more expensive grid electricity). Lack of onsite electricity demand obviously limits the ability of the system to displace it and gain access to this value. In summary, low thermal demand or excessive heat production are constraints for micro-CHP that prevent systems generating electricity and achieving corresponding value creation. Primary value for micro-CHP lies in generating electricity to displace onsite

demand; access to this value is enabled by the presence of thermal demand (and onsite electrical demand) and/or application of a prime mover with a low heat-to-power ratio.

The importance of thermal constraints with regard to micro-CHP value suggests a further metric will be of interest in determining value; the thermal output capacity of the prime mover. This deduction follows from results regarding prime mover capacity presented in section 6.1.1 above, taking into account the differing heat-to-power ratios of technologies. Taking the example of $1kW_e$ systems, high heat-to-power ratio cases high maximum thermal output whilst low heat-to-power ratio cases have low maximum thermal output. As thermal capacity increases (i.e. systems larger than $1kW_e$) value per $kW_e$ installed decreases due to escalating interaction between demand constraints and thermal output. Therefore thermal capacity of a system must also be taken into account (along with heat-to-power ratio and the annual energy demands of the target dwelling) in order to predict economic performance of micro-CHP under central estimates of energy tariffs.

### 6.1.3 Residential "Spark Spread" Between Electricity and Gas Tariffs

The "spark spread" is a metric typically associated with the attractiveness of investment in electricity generation or combined heat and power. It is defined as the price difference between the fuel consumed in the CHP generation process, and the value of electricity produced. For electricity-only generation (i.e. no capture of waste heat streams as in combined heat and power) the larger the relative difference between fuel and electricity price, the more attractive investment becomes. However, this interpretation of the applicability of spark spread becomes less clear for the case of regular and micro combined heat and power. This is because;

a) CHP adds the complexity of heating economics within the electricity generation economics considerations, and
b) for micro-CHP the value of electricity is dependent on whether it is consumed onsite or "exported" to the grid (i.e. sold to an energy supplier), and
c) CHP is typically constrained to met thermal demands, which may prevent exploitation of profitable electricity price opportunities.

Given these issues, it is informative to investigate the sensitivity of the case for investment in micro-CHP to spark spread. Figure 27 commences this analysis by considering the difference between micro-CHP technologies with regard to electricity price changes (in an "existing terrace" dwelling and central estimates of all other variables). Changing

electricity price implies a change in spark spread for any electricity use onsite (i.e. electricity export and gas price is kept constant at its central estimate value for Figure 27).

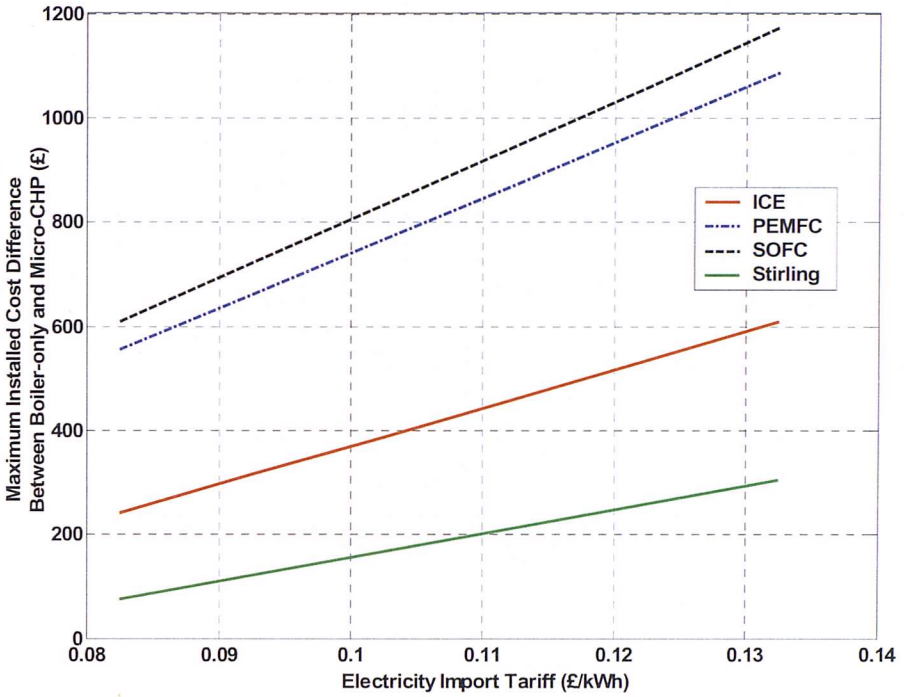



**Figure 27: Relative Impact of Changing Electricity Tariff on Micro-CHP Technologies (with central estimate of gas tariff and electricity export price) for an Average Dwelling (i.e. Existing Terrace House)**

Two inferences may be drawn from inspection of Figure 27. Firstly, it is clear that high electricity price (i.e. larger spark spread) is important for a defensible case for investment in micro-CHP is apparent. All of the systems have significant sensitivity to the electricity tariff, with the value relative to the reference case system of the engine-based systems reducing by more than 50%, and by almost 50% for the two fuel cell systems across a realistic range of marginal electricity tariff values. Based on Table 10 (section 5.2.1) this result is expected, because the most important fundamental value drivers for micro-CHP occur when the system is meeting onsite electricity demand. The second conclusion to be drawn from Figure 27 is regarding the relative impact of increasing spark spread with respect to technology type. In absolute terms, the fuel cell based technologies are more sensitive to changes in electricity tariff than their engine-based counterparts (i.e value gradients are steeper). This is because the fuel cell technologies can displace more onsite generation (i.e. overall, they generate more electricity), and therefore benefit more when the electricity tariff increases. The linear nature of the plots in Figure 27 indicates that the change in electricity tariff does not invoke a corresponding change in operating strategy for any of the systems (which would have been identified by the unit commitment

optimisation if it had resulted in lower cost). Therefore the observed changes in value for the systems are purely a result of increased "displaced" electricity import price.

However, electricity price, as a solitary parameter, does not capture the relative importance of electricity and gas prices individually. Therefore the remainder of this analysis is presented via 3-dimensional plots where electricity and gas prices are plotted on x and y axes, and the primary economic metric is plotted on the vertical z axis in Figure 28. Electricity export price is kept constant for this figure which considers each of the micro-CHP systems in the mean "existing terrace" dwelling as per Table 1. These figures show some non-linearity of the marginal value of the micro-CHP system with respect to the boiler-only case: All surface plots exhibit perceptible increasing value gradient with decreasing gas price, whilst value gradient with respect to increasing electricity tariff remains relatively constant (as shown more clearly in Figure 27). The slight non-linearity of these surfaces indicates a change in optimal operating strategy of the micro-CHP system, almost universally in response to a change in the gas tariff.

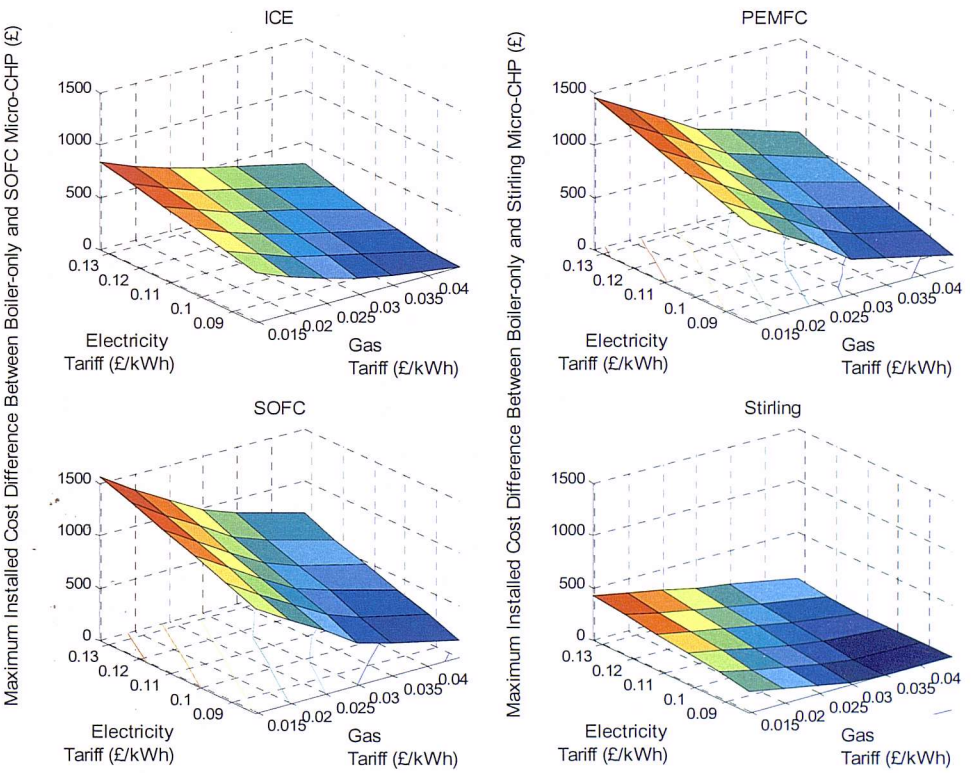



**Figure 28: Sensitivity of Maximum Installed Capital Cost Difference Between Boiler-only System and the Four Micro-CHP Systems (£) to Gas and Electricity Tariffs (£/kWh)**

Overall Figure 28 reinforces the result that spark spread is a very important parameter in micro-CHP economics: Virtually all systems have difficulty offering any significant value advantage over the reference case system when electricity price is low and gas price is high. However, the case for investment in the two fuel cell systems can be relatively strong with high spark spread, with any value above that of the central estimate tariffs offering an arguably attractive case for investment. The engine-based systems do not fair so well, particularly the Stirling-based system which can achieve a maximum value of only £400 (at 12% discount rate) over the reference boiler-only system, and has zero marginal value for the high gas and low electricity tariff scenario.

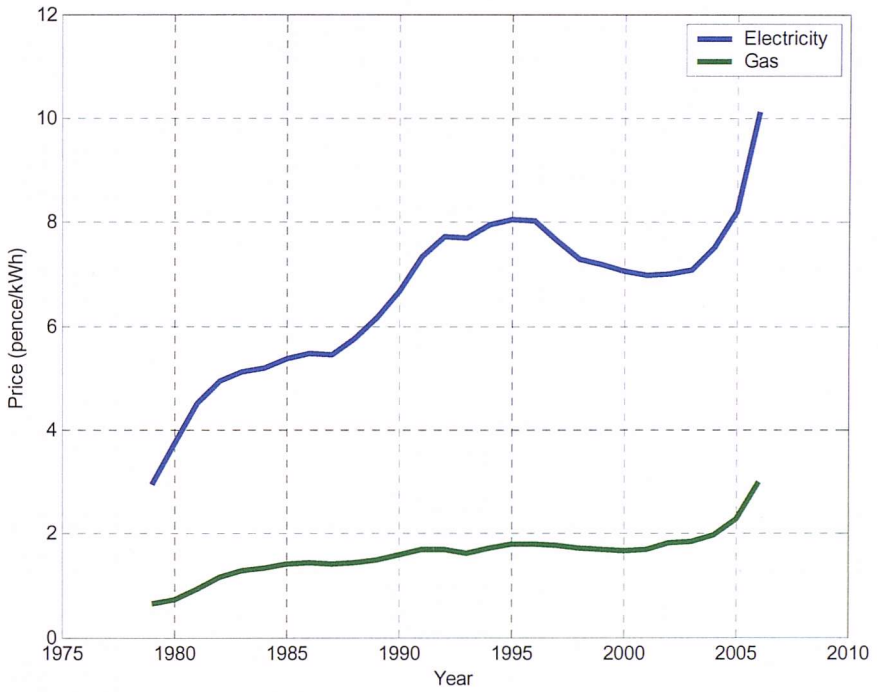



**Figure 29: Historical Average Annual Residential Electricity and Gas Prices in the UK as Reported in BERR (2008c)**

Finally, Figure 28, when considered alongside Figure 29 also offers a qualitative estimate of the risk inherent in micro-CHP investment under uncertain gas and electricity prices. Whilst a precise calculation of this risk is beyond the scope of this thesis, one can conclude that this risk is not insignificant because the range of prices observed in Figure 29 are comparable to the range of prices investigated in the spark spread sensitivity analysis. In regard to this issue it should also be noted that in the UK electricity prices and gas prices exhibit some correlation (approx 0.8 correlation co-efficient). This is logical given the substantial use of gas in UK centralised electricity generation. This correlation serves to reduce the risk of micro-CHP investment, because it indicates that any change in gas price

is likely to be reflected by a corresponding change in electricity price, resulting in more certainty in the economic case for micro-CHP operation.

The following section investigates another energy price related metric; electricity buyback price. This is related to the spark spread discussion above in that the value of electricity generated by the micro-CHP system is dependent on whether it is consumed onsite or exported to the grid.

### 6.1.4 Electricity Buyback Price

The electricity buyback price is the price offered by suppliers to purchase power from customers with micro-CHP when electricity is exported to the distribution network (i.e. the grid). It is an important market and policy metric for consideration with respect to the economic case for micro-CHP. For example, HM Government (2006) presents the recent statute that obliges the secretary of state to consider requiring suppliers to offer terms for buyback of electricity, and HM Government (2008c) proposes a "feed-in tariff" (where one possibility is that additional monies are paid to microgenerators in order to incentivise investment and utilisation of micro-CHP) for UK microgeneration. Figure 30 displays the sensitivity of the primary economic metric to buyback price for the case of the mean existing terrace dwelling.

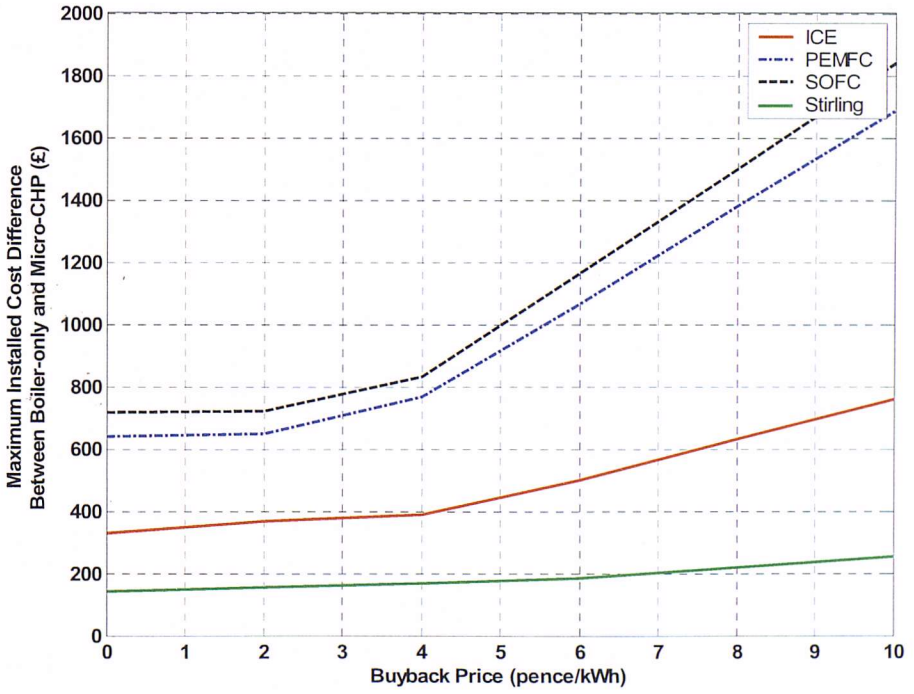



**Figure 30: Sensitivity of Maximum Installed Capital Cost Difference Between Boiler-only System and the Four Micro-CHP Systems (£) to Electricity Buyback Price (pence/kWh)**

Clearly buyback price can have a strong influence on the value of micro-CHP. For fuel cell and ICE-based technologies this relationship is non-linear between approximately 1 and 5 pence/kWh, implying that the optimum operating schedule has changed across buyback prices (i.e. the unit commitment optimisation responds to higher buyback prices by dispatching in a way to increase exposure to buyback prices). Above roughly 5 pence/kWh response is linear, suggesting the systems have maximised electricity output in order to benefit from higher export prices, and no further operating strategy changes are desirable. The fuel cell-based systems, which generate relatively more electricity per kilowatt thermal output, are able to gain additional benefit from higher buyback prices. This occurs for the same reasons discussed in section 6.1.1; a low heat-to-power ratio enables more electricity generation because thermal constraints are less likely to interfere. The economics and environmental impacts of buyback prices are discussed in more detail in section 7.1, detailing an important tension between buyback price and environmental outcomes.

### 6.1.5 Investor Cost of Capital

The final economic parameters investigated in this chapter relates to the cost of capital of the micro-CHP investor, which is expected to have a marked influence on the investment case. In the company control model discussed in section 4.1.1, it would be expected that a typical commercial discount rate would be applied to the purchase, leading to the choice of 12% cost of capital as the central estimate applied in this thesis. However, the actual discount rates applied in the investment decision may vary from this figure depending on the perceived risk in the project and the nature of financing arrangements (note that more detailed discussion of the justification for particular discount rates can be found in Brealey et al. (2008)). Furthermore, under the plug-and-play model, it would be the individual owner making the investment decision. Hausman (1979) and others have shown that home owners typically (and by indirect means) apply very high discount rates to energy efficiency investment, of the order of 20% to 30%. At the other end of the spectrum, policy makers, when considering the cost of public support for a class of technologies may apply discount rates closer to the rate of inflation. Therefore it is of interest to explore the sensitivity of the economic case to the discount rate assumption. Rates investigated are 2.5%, 5%, 10%, 15%, 20%, and 30%.[17]

[17] Note that this investigation of discount rates can also be interpreted as a sensitivity analysis to system lifetime (assumed to be 10 years throughout this thesis). Shorter or longer system lifetimes will broadly correspond to higher and lower discount rates, respectively.

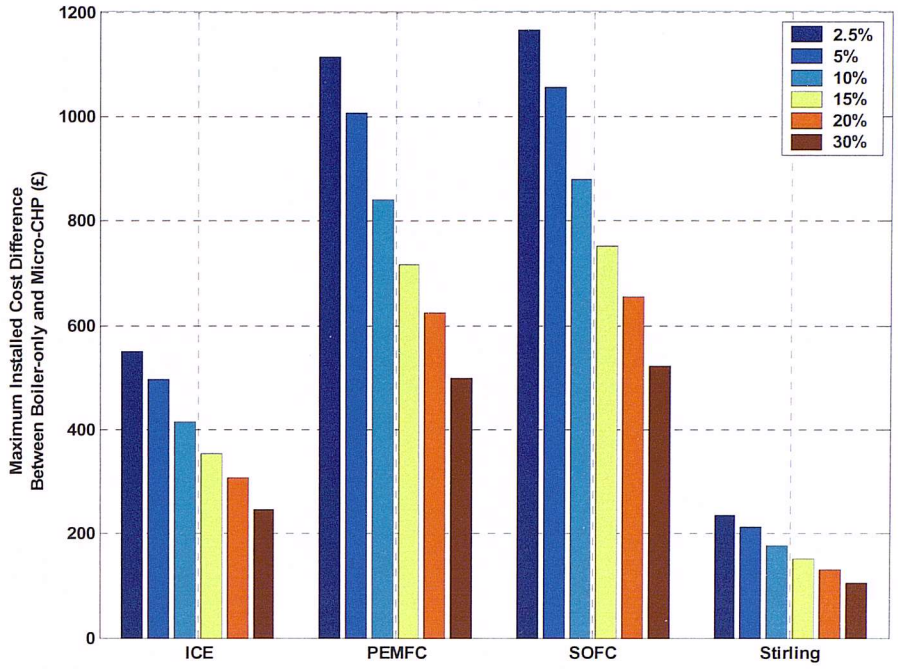



**Figure 31: Sensitivity of Maximum Installed Capital Cost Difference Between Boiler-only System and the Four Micro-CHP Systems (£) to Applied Discount Rate for 1kWe Systems in Existing Terrace Dwelling**

Figure 32 displays the results of this sensitivity analysis. As expected the cost of capital of the investor plays a significant role in value. For policy makers with low discount rates close to inflation, systems have much higher value, whilst typical plug-and play investors perceive very low value and are (for example) unlikely to make the investment in fuel cell based system unless the capital cost differential between the micro-CHP and the reference system is of the order of £500 to £600. For the company control deployment pathway, with likely costs of capital in the range of 10% to 20%, the maximum capital cost differential is between £600 and £800. This is a range of approximately -20% to +7% around the central estimate maximum capital cost.

## 6.2 Conclusions Regarding Market Drivers

The major conclusions stemming from this analysis of the key market drivers for micro-CHP relate to system capacity, energy demand, energy buy and sell prices, and investor cost of capital. Any of these factors can make or break the economic case for micro-CHP, reflecting the sensitivity of performance to plausible changes in market/demand metrics and suggesting it may be a relatively high-risk investment. The best case economic performance is arguably that of a $1kW_e$ low heat-to-power ratio micro-CHP system (e.g. a SOFC-based fuel cell system) serving demand in a dwelling with significant annual thermal

and electrical demand, with large (and fixed) spark spread and high electricity buyback rate. The worst performer is a micro-CHP system that produces a lot of heat for a given electricity output, serves a small thermal and electrical demand (e.g. a "new" flat), with low and variable spark spread and little or no reward for electricity buyback.

| Metric | Technology Type | Metric Range Investigated | Range of Economic Values Observed (i.e. values of primary economic metric) |
|---|---|---|---|
| **Annual Thermal Demand** | ICE<br>PEMFC<br>SOFC<br>Stirling | 6000kWh – 28000kWh (const electric demand at average dwelling level) | £0 - £600<br>£500 - £900<br>£700 - £900<br>£0 - £500 |
| **Annual Electricity Demand** | ICE<br>PEMFC<br>SOFC<br>Stirling | 1100kWh – 8300kWh (const thermal demand at average dwelling level) | £100 - £850<br>£200 - £1200<br>£300 - £1250<br>£0 - £400 |
| **Prime Mover Capacity for case of Average Dwelling** | ICE<br>PEMFC<br>SOFC<br>Stirling | 0.8$kW_e$ – 4$kW_e$ | £0 - £600 per $kW_e$<br>£175 - £900 per $kW_e$<br>£300 - £950 per $kW_e$<br>£0 - £550 per $kW_e$ |
| **Spark Spread for case of Average Dwelling** | ICE<br>PEMFC<br>SOFC<br>Stirling | 1.5 – 4.5 p/kWh Gas<br>8 – 13 p/kWh Electricity | £0 - £800<br>£100 - £1400<br>£200 - £1500<br>£0 - £400 |
| **Electricity Buyback Price for case of Average Dwelling** | ICE<br>PEMFC<br>SOFC<br>Stirling | 0 – 10 p/kWh | £350 - £750<br>£650 - £1700<br>£700 - £1850<br>£150 - £250 |
| **Investor Cost of Capital for case of Average Dwelling** | ICE<br>PEMFC<br>SOFC<br>Stirling | 2.5%-30% | £250-£550<br>£500 - £1,100<br>£500 - £1,150<br>£100 - £200 |

**Table 11: Summary of Results for Key Economic Drivers of Micro-CHP**

An abridgment of results from this chapter is displayed in Table 11, providing a means for estimating the relative importance of each metric investigated. Of these metrics, spark spread and prime mover capacity are important for all technologies. Annual thermal and electric demands are important for engine-based systems, and annual electric demand is most important for fuel cell systems. Electricity buyback price is a powerful driver for fuel cell-based systems and the IC engine system, but relatively unimportant for the Stirling engine which is the most thermally constrained (i.e. it has the highest heat-to-power ratio) of the systems investigated and therefore produces little electricity. As expected, cost of capital is also a strong value driver, confirming the relevance of the company control type deployment pathway where discount rates could be applied based on informed judgement regarding exposure to risk and financing model.

Regarding system sizing, the highest value per electrical $kW_e$ installed occurs when systems are sized at approximately 1$kW_e$, regardless of technology type, although fuel cell-based

systems could arguably be produced with higher capacities, but this depends on economies within the manufacturing process, which are beyond the scope of this thesis.

On the whole, the basic underlying driver of economic performance is the ability to meet onsite electricity demands and to export electricity when export prices are high. Thermal constraints can prevent this from happening because they may require the prime mover to modulate of switch off, thus producing less electricity. Thermal constraints can arise for three primary reasons;

1. high heat-to-power ratio of the micro-CHP prime mover, which implies more heat is generated for given electricity output, so output is more likely to be curtailed,
2. low thermal demand, which implies thermal constraints are likely to exist more frequently at lower $kW_{th}$ levels.
3. high thermal capacity of the micro-CHP prime mover. A developer's choice of prime mover electrical capacity influences economic performance via thermal capacity (i.e. thermal capacity equals electrical capacity multiplied by the heat-to-power ratio).

In addition to these factors that bear upon value in terms of constraints, it is also important for the target dwelling to have a moderate to large onsite electricity demand, which provides potential for value creation in that it can be displaced. Changes in energy prices, buyback rate, and cost of capital simply serve to amplify or moderate value created via the tension between thermal constraints and electricity production, which is the key basic driver of value.

# Chapter 7: The Ability of Micro-CHP to Meet Policy Objectives

This chapter first presents analyses of two important and frequently considered policy-related metrics – greenhouse gas emissions reduction and primary energy consumption changes – with respect to the defined boiler-only and "grid" electricity reference case defined in section 3.2. It then considers a further metric – capacity credit – which is important in terms of electricity system expansion and understanding the relative contribution micro-CHP could make. The reasons why capacity credit is important are discussed and a mathematical formulation for calculation of capacity credit is presented. It is then evaluated for a Stirling engine, ICE engine, and a generic fuel cell based micro-CHP technology, across a variety of associated possible operating strategies.

The examination of these environmental, energy security and electricity system impact factors leads to a better understanding of the ability of micro-CHP to meet an important set of policy objectives; clean, secure and economically-efficient investment in energy supply.

## 7.1 $CO_2$ Emissions Performance

A critical factor in the success of micro-CHP is likely to be its greenhouse gas (GHG) emissions reduction performance. Government policy and regulation are more inclined to support technologies that provide proven GHG reductions, and are likely to inhibit technologies that perform poorly in this regard. One example of a stakeholder capturing the value of $CO_2$ reduction is energy suppliers under the governments Carbon Emissions Reduction Target (discussed in detail in Chapter 10). Also, "green" credentials are likely to form in important relative advantage in marketing the technologies, suggesting that other commercial stakeholders will also have potential to capture value in $CO_2$ reduction.

This section first presents sensitivity of $CO_2$ emissions reduction for each of the four technologies and for each of the building variants ("existing" buildings from Table 1), across a range of generating capacities. The sensitivity of $CO_2$ reduction to annual energy demand is then considered, followed by sensitivity to electricity buyback price. This mirrors the analysis performed in Chapter 6 regarding sensitivity of the primary economic metric to the same set of market-related drivers, with the exclusion of spark spread and cost of capital. This is because changes in spark spread has only minor influence, and cost of capital has no influence on operating strategy (and subsequently on $CO_2$ emissions). Finally some further

factors regarding emissions reduction are assessed; the $CO_2$ intensity of grid electricity and other "external" issues that may impact on overall $CO_2$ outcomes.

### 7.1.1 Prime Mover Generating Capacity

Figure 32 shows the sensitivity of annual $CO_2$ emissions reductions to system nameplate capacity for the four micro-CHP systems. There is clear differentiation between micro-CHP technologies, with the two fuel cell-based systems offering an unmistakable performance advantage.

Similarly to the results relating to the relative economics of micro-CHP systems presented in Chapter 6, these $CO_2$-related results can be attributed to the different heat-to-power ratios between the technologies. Those technologies with a low heat-to-power ratio prime mover are less constrained by lack of thermal demand and are subsequently able to generate more electricity and thereby gain $CO_2$ credit for offsetting more grid electricity.

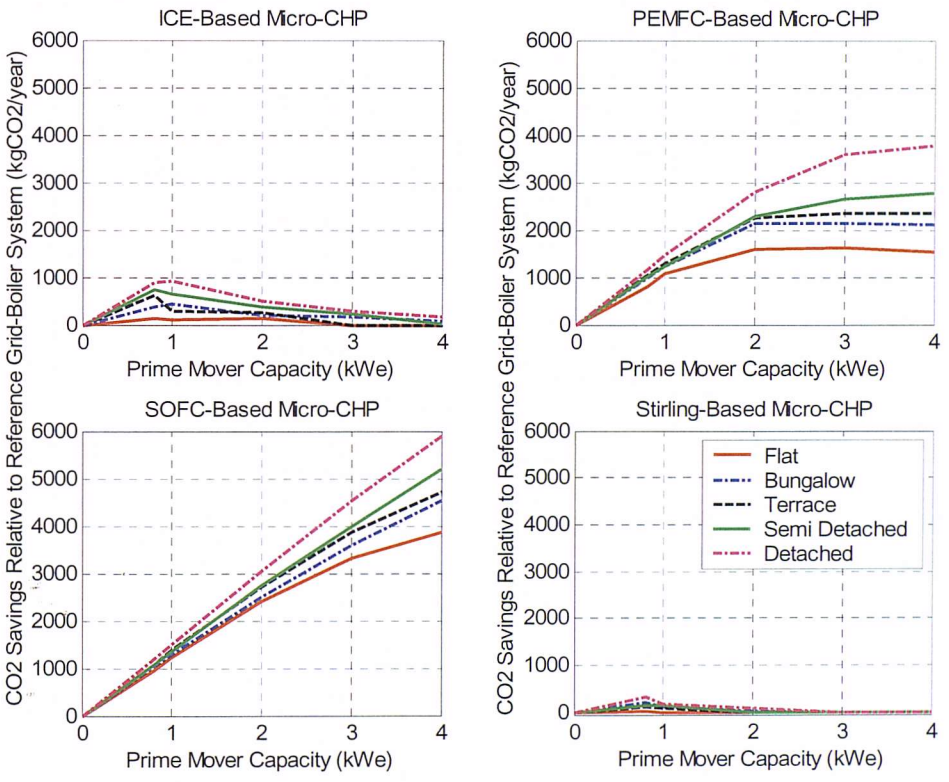



**Figure 32: Sensitivity of Annual $CO_2$ Emissions Reduction for Four Micro-CHP Technologies with Respect to System Nameplate Capacity**

A further point of interest from Figure 32 is that the SOFC-based micro-CHP is able to virtually eliminate the entire operational $CO_2$ footprint of the dwelling when a $4kW_e$ system is installed. Whilst such large nameplate capacity systems may be prohibitively expensive

in the near term, the result still presents an interesting possibility for delivering housing in the line with the UK's current low carbon policy. For example, the $4kW_e$ system could single-handedly achieve the government's 2050 60% or 80% emissions reduction target for that dwelling (although extension of this concept to a large number of dwellings is problematic due to interactions between installations and network impacts of larger systems).

In order to gain a deeper understanding of the drivers of $CO_2$ performance, a disaggregation of sources and credits for $CO_2$ for selected $1kW_e$ and $4kW_e$ systems operating in an existing terraced dwelling is presented in Table 12. The thermal constraints on the high heat-to-power ratio Stirling engine system are apparent in that it does not produce much electricity. Subsequently, achievable emissions reduction are low, because electricity production is the only possible source of $CO_2$ credit for gas fuelled micro-CHP (when it is compared to gas-fuelled boilers). Conversely, the result for the low heat-to-power ratio SOFC-based systems is vastly different, with the significant electricity production gaining $CO_2$ credit and resulting in a substantially improved overall emissions result when compared to the reference case. The primary driver for this result is $CO_2$ credit for exported electricity, which provides gross 22% and 101% of the observed emissions reduction for the $1kW_e$ and $4kW_e$ systems, respectively.

| | | Electricity Import | Electricity Export | Gas for Boiler + Micro-CHP | Onsite Generation Credit[18] | Total $CO_2$ |
|---|---|---|---|---|---|---|
| **Reference Case** | kWh | 4,348 | 0 | 20,886 | 0 | |
| | $CO_2$ (kg) | 1,835 | 0 | 3,968 | 0 | **5,803** |
| **1kW$_e$ Stirling** | kWh | 3,624 | 123 | 23,015 | 850 | |
| | $CO_2$ (kg) | 1,529 | -52 | 4,373 | -124 | **5,726** |
| | Relative $CO_2$ Savings Contribution | -5% | -1% | +7% | -2% | **-1%** |
| **1kW$_e$ SOFC** | kWh | 2,454 | 3,039 | 28,391 | 4,937 | |
| | $CO_2$ (kg) | 1,036 | -1,282 | 5,394 | -721 | **4,427** |
| | Relative $CO_2$ Savings Contribution | -14% | -22% | +25% | -12% | **-23%** |
| **4kW$_e$ SOFC** | kWh | 2,282 | 13,828 | 43,636 | 15,897 | |
| | $CO_2$ (kg) | 963 | -5,835 | 8,291 | -2,321 | **1,098** |
| | Relative $CO_2$ Savings Contribution | -15% | -101% | +75% | -40% | **-81%** |

**Table 12: Comparison of 1kW$_e$ Stirling Engine and 1kW$_e$/4kW$_e$ SOFC Micro-CHP $CO_2$ Performance Relative to Reference Scenario**

The primary point to note when differentiating the 1kW$_e$ and 4kW$_e$ SOFC-based systems is that the relative $CO_2$ reduction contribution of displaced onsite electricity demand has not increased substantially (i.e. the 4kW$_e$ system in only displaces approximately 200kWh/year more onsite electricity demand than the 1kW$_e$ system). Credit for electricity export is the primary driving force behind the exceptional $CO_2$ reduction result for the 4kW$_e$ system, with differentiated $CO_2$ credit for onsite generation also playing a role.

Overall the information presented in Table 12 indicates that where $CO_2$ reductions are more plausible (i.e. lower heat-to-power ratio technologies), $CO_2$ credit for exported electricity is critical. For smaller systems, proper $CO_2$ credit for avoided import of electricity is also important. Credit for both export and displaced import is relatively simple to achieve in practice through generation, import and export metering, although the cost of

[18] "Onsite Generation Credit" refers to the difference in $CO_2$ rate applied to onsite consumption versus production in the UK building regulations. Consumption is penalised at a rate of 0.422kg $CO_2$/kWh, whilst production is assumed to displace centralised generation at a rate of 0.568kg $CO_2$/kWh. See section 3.2.1 for a complete description.

such metering may outweigh the potential gains to the owner/operator. Metering and related issues are discussed further in Chapter 9.

### 7.1.2 Annual Energy Demand

The above analysis considers the drivers for a low carbon result across micro-CHP prime mover capacities ($kW_e$), and across the "existing" building variants described in Table 1. It is also instructive to consider the sensitivity of the $CO_2$ result to annual thermal demand (holding electricity demand constant), and annual electricity demand (holding thermal demand constant, once again mirroring the economic analysis). Figure 33 and Figure 34 present these sensitivities for $1kW_e$ systems, operating in each of the five dwelling construction types and across "existing", "refurbished", and "new" building thermal performance standards.

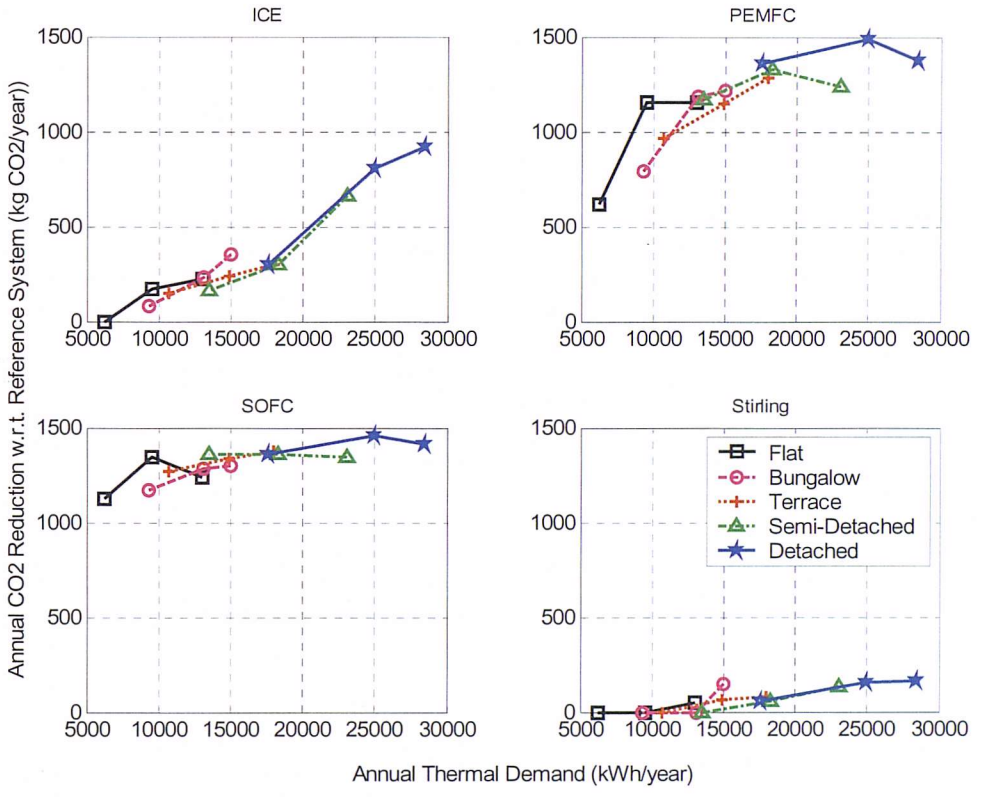



**Figure 33: Sensitivity of Annual $CO_2$ Reduction w.r.t. Reference System (kg $CO_2$/year) to Annual Thermal Demand for Five Annual Electricity Demand Scenarios with $1kW_e$ Micro-CHP Systems**

Figure 33 shows that annual thermal demand can be important in micro-CHP achieving $CO_2$ reductions. This is particularly apparent for the mid-range heat-to-power ratio (HPR) ICE and PEMFC-based systems. The Stirling engine has difficulty producing noteworthy emissions reduction for any annual thermal demand scenario, and the SOFC-based system provides reductions largely independent of annual thermal demand. These two extreme

cases (i.e. the Stirling and SOFC systems) relate once again to HPR; the Stirling engine (high HPR) is unable to provide reductions because its operation is frequently curtailed by thermal constraints, whilst the SOFC-based prime mover (low HPR) can operate almost all the time because it rarely encounters these constraints regardless of demand scenario. Mid-range HPR systems are more sensitive because as thermal demand increases, thermal constraints bear less upon systems ability to operate and thus reap associated $CO_2$ reductions.

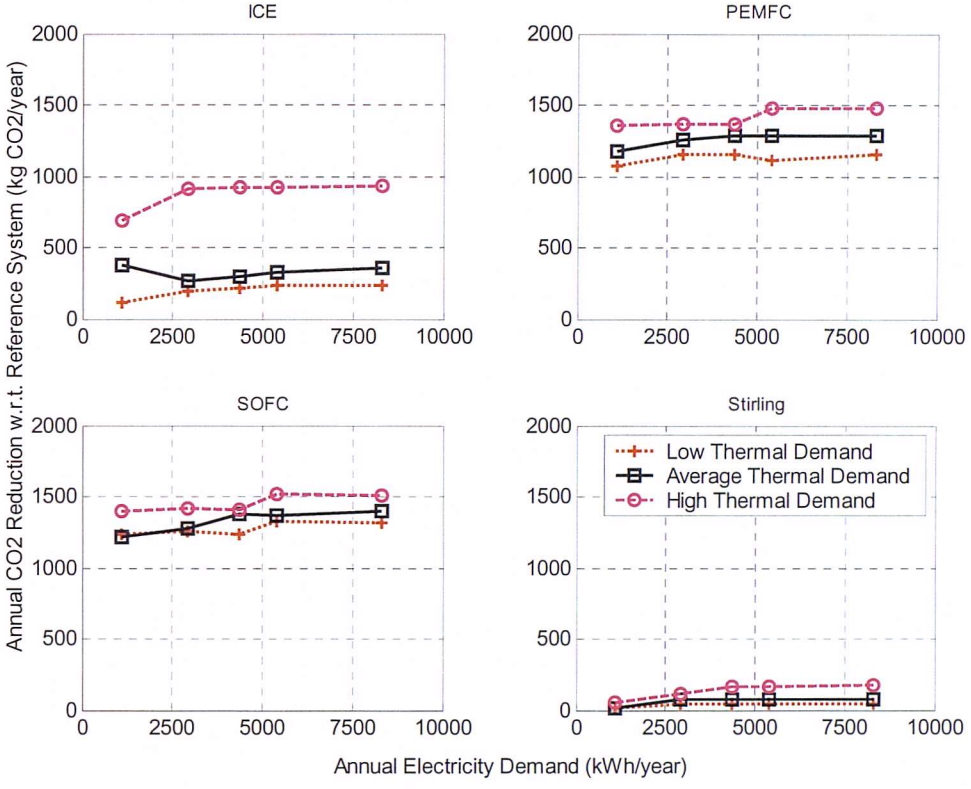



**Figure 34: Sensitivity of Annual $CO_2$ Reduction w.r.t. Reference System (kg $CO_2$/year) to Annual Electricity Demand for Three Annual Thermal Demand Scenarios with 1kW$_e$ Micro-CHP Systems**

Figure 34 shows the $CO_2$ reduction achievable by 1kW$_e$ micro-CHP systems across a range of annual electricity demand scenarios (each line represents constant annual thermal demand corresponding to existing flat, existing terrace and existing detached dwellings from Table 1). This figure demonstrates that there is little reliance of $CO_2$ reduction on annual electricity demand. This can be contrasted with the equivalent economic result presented in section 6.1.2 (Figure 26), which showed great dependence of economic result on annual electricity demand particularly for low HPR prime movers. The reason for this contrasting $CO_2$ result is that displaced grid electricity $CO_2$ rates are the same regardless of whether generation is consumed onsite or exported to the grid (conversely, in the

economic case, export attracts a lower value than onsite generation under central estimate values).

### 7.1.3 Electricity Buyback Price

A further aspect of $CO_2$ emissions reduction relates to interaction between electricity buyback price and the ability of a system to dump heat, or ability of an owner/occupier to bring about increased demand for heat through demand side actions. Whilst technical controlled heat dump to a significant extent is unlikely (because it would generally be limited to a fan-assisted flue as per current boiler systems), an owner/occupier has an option to achieve effective heat dump by (for example) opening windows. Alternatively, unnecessary demand for heat may be achieved by avoided or deferred retrofit of insulation or air-tightness measures, or demand for higher internal temperatures. Given these possibilities it is constructive to examine the tension between electricity buyback price, heat dump and the performance of micro-CHP systems.

In terms of changes to the modelling framework to enable this analysis, Equation 16 in section 4.3.1.2.7 can be altered to allow dump of heat from the system. This is achieved by constraining thermal output from all sources to be at least equal to (but possibly greater than) the thermal demand.

Figure 35 demonstrates the dependence of the economic and environmental result for the four micro-CHP systems with respect to the electricity buyback price offered by the supplier. In the case where discharge of heat is restricted (i.e. "Heat Dump Constrained") the economic case improves with increasing buyback price as would be expected, and annual $CO_2$ emissions reduction reaches a peak at buyback price of between 4 and 6 pence per kWh. Conversely, where heat dump is not constrained, the interaction between buyback price and annual $CO_2$ reduction becomes more complex. At relatively low buyback prices in the range of 4 to 6 pence/kWh, the $CO_2$ reduction is slightly improved upon the "heat dump constrained case". This is particularly apparent for the low heat-to-power ratio SOFC-based system, which can achieve improved reductions for the reasons discussed in relation to thermal constraints (i.e. the relaxed thermal constraint means it can generate more electricity). However, an important effect is observable in that the $CO_2$ emissions reduction achieved by the PEMFC-based system decrease as buyback prices increase between 8 and 10 pence/kWh. This is accompanied by an increase in the value of the primary economic metric for the PEMFC system. Therefore the unwelcome situation where an owner-occupier could profit from creating unnecessary $CO_2$ emissions has arisen.

This could be a perverse incentive and has important ramifications for policy support of micro-CHP systems, where a fine balance between maximising emissions reduction and simultaneously maximising the value of systems could be required. Indeed the point where buyback price provides the best incentives varies between technologies, implying further complication if policy makers attempt to set feed-in tariff rates.

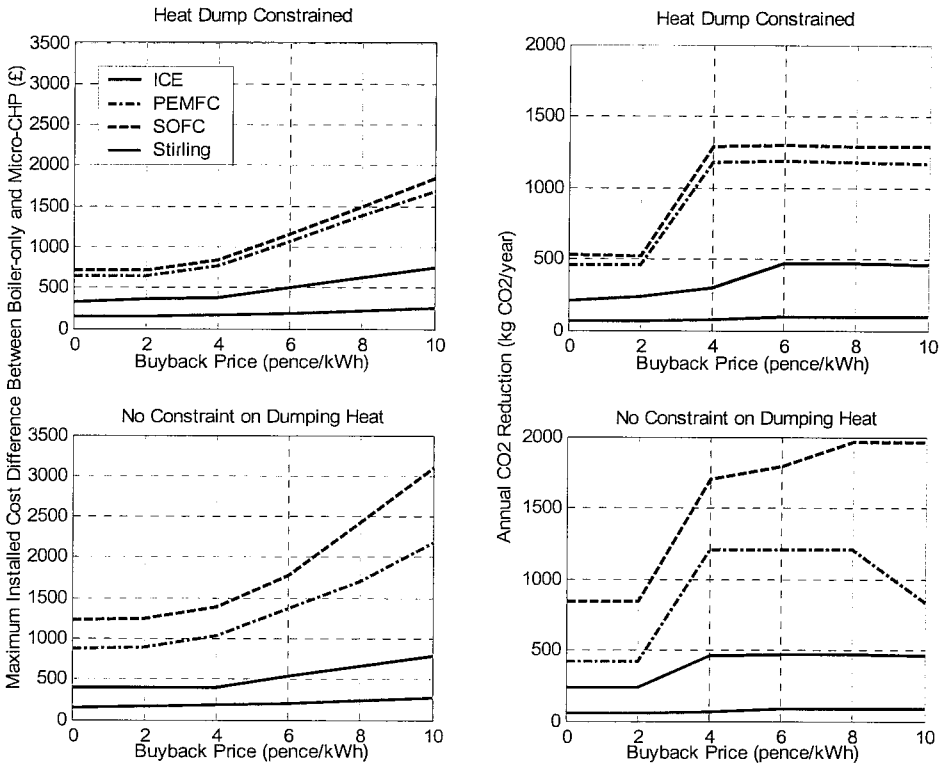



**Figure 35: The Influence of the Ability to Dump Heat on Micro-CHP Economics and Annual $CO_2$ Emissions Reduction for a Range of Electricity Buyback Prices**

To further consider this interaction, a surface plot of buyback price, electrical efficiency[19], and the primary economic metric is shown in Figure 36, for the case where heat dump is possible. The corresponding annual $CO_2$ reduction surface is presented in Figure 37. This generally confirms the information in Figure 35, but gives more detail as to the efficiency range and buyback prices under which a sub-optimal emissions result can arise, and therefore can be used to comment more broadly on the situation. Firstly, Figure 36 shows that both buyback price and electrical efficiency are powerful drivers of system value. With regard to the $CO_2$ result in Figure 37, for any electrical efficiency value there is little $CO_2$-related justification for a buyback price above 6 pence/kWh as there is no substantial

[19] Note that the technical characteristics of the micro-CHP systems investigated have been altered to perform this analysis. The system modelled is essentially an "average" system in terms of ramp limits, minimum up-time and down-time, and start/stop costs. This approach is necessary to present sensitivity to electrical efficiency and thereby approximate a range of micro-CHP systems.

additional $CO_2$ savings above this value. The second point in relation to Figure 36 is that for the electrical efficiency range of 25% to 40%, there is a possibility that a high buyback price would result more $CO_2$ being produced than at a lower buyback price (as with the PEMFC system in Figure 35). This effect is predominant for the very high buyback prices, and electrical efficiency close to 25%. The explanation for this result relates to the situation where the system can profit from dumping heat, but cannot compete with grid electricity in terms embodied $CO_2$ per kWh of electricity. Higher electrical efficiency systems can also profit from dumping heat, but when electrical efficiency reaches above roughly 40%, the embodied emissions for micro-CHP electricity is lower than that of grid electricity and thus better $CO_2$ performance is assured (although it should be noted that this result is sensitive to assumed grid embodied emissions rates, as discussed further in section 7.1.4).

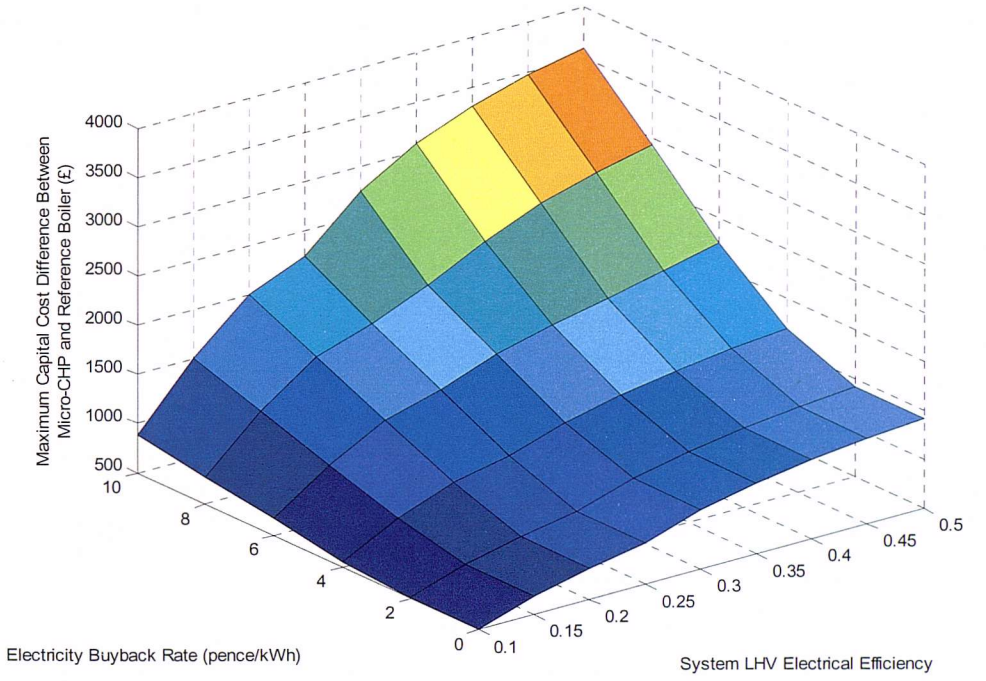



**Figure 36: Maximum Capital Cost Differential between Micro-CHP and Boiler-Only System (£) versus Electricity Buyback Price (pence/kWh) and Net System Electrical Efficiency**

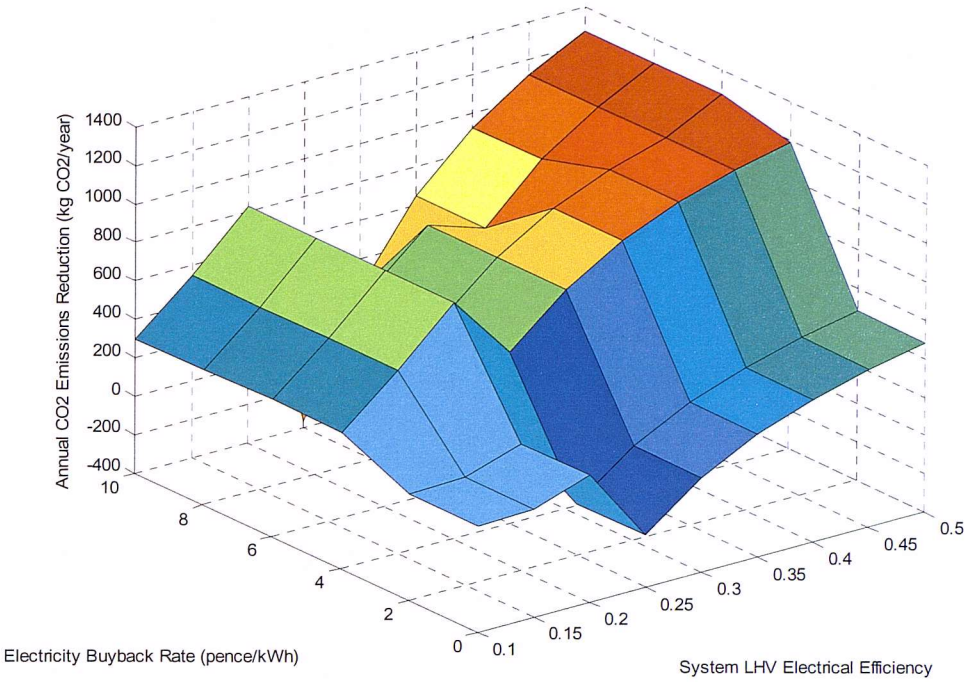



**Figure 37: Estimated Annual $CO_2$ Emissions Reduction (kg $CO_2$/year) versus Buyback Price (pence/kWh) and System Net Electrical Efficiency**

From a public policy point of view, the situation where additional public (or otherwise distributed across society) money is spent in order to achieve the unchanged or worse $CO_2$ reduction could be seen as inefficient. Likewise, it is also important to note that little or no export reward (i.e. in this case, a buyback price of zero to 2 pence) also leads to a sub-optimal result in that substantially more $CO_2$ reductions could have been achieved if the buyback price were slightly higher. It seems that the most effective buyback price is between 4 and 6 pence/kWh, but any deviation from this can lead to a poor outcome in comparison to what could be achieved. This creates a challenge to policy makers, and suggests that perhaps regulation of buyback price could be a reasonable strategy, although possibly at odds with free market principles and almost certainly a bureaucratic burden. Indeed the "best" buyback price is likely to vary amongst micro-CHP technologies, and is a function of energy prices and embodied grid $CO_2$ rates, creating a complex relationship that would be onerous to monitor and maintain. It is interesting to note that the current wholesale electricity price (which is arguably close to the fair electricity buyback price for micro-CHP) is of the order of 4 pence/kWh, indicating that the free market may choose the best $CO_2$-related solution at the moment. However, this outcome is dependent on the fuel mix, cost of grid electricity, and value of the microgeneration proposition to the supplier, with no guarantees that the current situation will not change.

Overall, the results of this analysis indicate challenges regarding effective performance-based incentives for micro-CHP. Any production-based incentive (whether it be for electricity generated, electricity exported, or heat generated) can lead to the described situation because it can incentivise gratuitous operation of the device. Nevertheless, some form of performance-based incentive is also clearly a strong driver for value of micro-CHP, and a certain level of such an incentive is arguably required to achieve the best greenhouse gas reduction the systems can offer.

It should also be noted that low cost $CO_2$ reductions are not the only driving factor for residential sector energy policy. For example, energy security and fuel poverty are key concerns, as is support for domestic business, providing for innovation, engaging actors regarding their energy provision, and supporting local development. Certain adverse (or identical) $CO_2$ results may be warranted if another policy aim is achieved, or alternatively the aggregate effect of an incentive could be positive in terms of $CO_2$ even though some cases are negative. These issues are discussed further in Chapter 9, which seeks to formulate appropriate policy instruments in support micro-CHP.

### 7.1.4 $CO_2$ Intensity of Grid Electricity

As discussed in section 3.2, an appropriate $CO_2$ intensity of grid electricity displaced by onsite generation is a subject of controversy. To address this issue a sensitivity analysis is presented here to investigate the influence of changing the grid $CO_2$ intensity. Figure 38 displays this sensitivity for the case of an "existing" terraced house. For this analysis the regulatory credit afforded to residential onsite generation is ignored (i.e. demand/production of electricity attract $CO_2$ debit/credit at the rate indicated on the horizontal axis), and grid $CO_2$ intensities from zero (i.e. a carbon free electricity system) through to 0.9kg $CO_2$/kWh (i.e. a low efficiency coal-fired power station) are analysed.

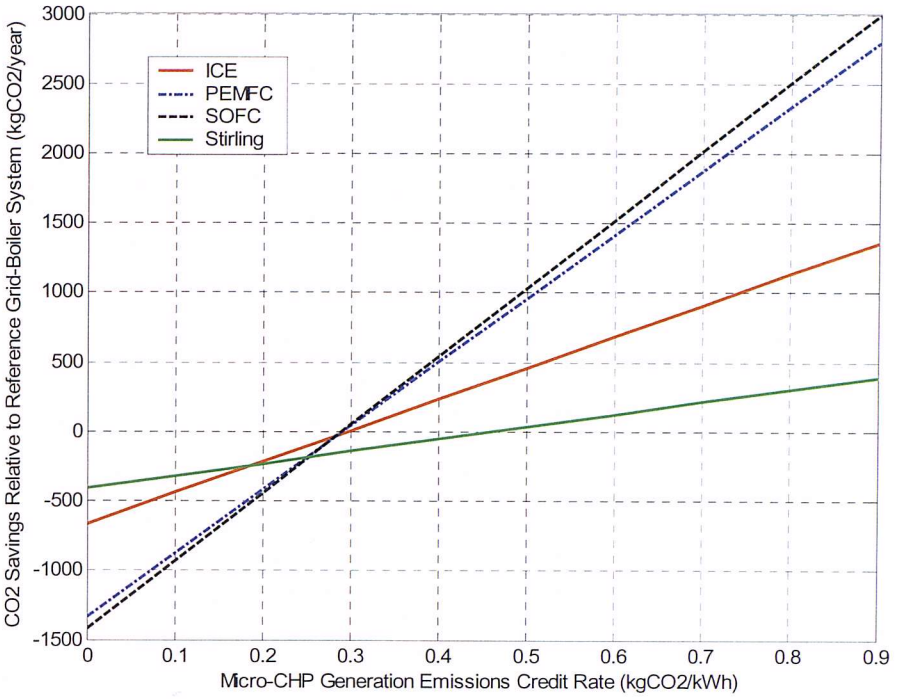



**Figure 38: Sensitivity of Annual $CO_2$ Emissions Reduction (kg $CO_2$/year) to Emissions Credit Rate Granted for Onsite Generation (kg $CO_2$/kWh) for 1kW$_e$ Micro-CHP Systems and Existing Terraced House Demand Scenario**

Clearly as grid $CO_2$ intensity increases the performance of all micro-CHP systems improve. The relationship is linear because the developed optimisation model minimises costs and therefore optimal operating strategy is not influenced by changes in grid $CO_2$ rates. The most interesting aspect of Figure 38 is the point at which the $CO_2$ savings afforded by micro-CHP become negative. This corresponds with the uptake of a micro-CHP unit resulting in more $CO_2$ being produced than the reference boiler-only and grid electricity case. For the Stirling engine system this occurs close to the current assumed long-term grid $CO_2$ intensity near 0.43kg $CO_2$/kWh. For the other technologies it occurs just below 0.3 kg $CO_2$/kWh. This is a point with important implications for commercialisation and policy support: Figure 38 shows that if current policies supporting introduction of large scale renewable electricity such as the Renewables Obligation Certificates (ROCs) and broad support for new nuclear generation capacity are effective to a degree such that $CO_2$ embodied in grid electricity falls below 0.3kg $CO_2$/kWh, micro-CHP systems will be unable to compete in environmental terms with modern boiler technology. This is an important point regarding potential policy support and suggests that micro-CHP is near to medium term technology, applicable while grid electricity $CO_2$ rates are relatively high.

### 7.1.5 Further Potential Sources and Sinks of $CO_2$

In addition to the above factors that influence $CO_2$ related outcomes for micro-CHP systems, it is worth noting that there are other possible sources of differentiation between micro-CHP and the reference system in this regard. Although these are beyond the scope of this thesis, they are discussed briefly below to provide context.

Firstly, total $CO_2$ emissions reduction achieved is not solely related to the operation performance of the system. Life cycle analysis (LCA) is required to fully understand the impact of fuel chain and manufacturing and disposal related emissions associated with each micro-CHP product. Pehnt (2008) has investigated this issue and found that micro-CHP is still competitive in terms of $CO_2$ and other environmental factors, although this study did not consider operation of the device in any detail. As the micro-CHP systems considered here are a boiler replacement technology fuelled by natural gas, fuel chain emissions are likely to be comparable, and manufacturing (etc) emissions somewhat similar. Further evidence is required to make conclusions regarding LCA analysis of mature micro-CHP systems.

Related to the above consideration regarding LCA, leakage from low pressure natural gas networks could negatively influence $CO_2$ performance of micro-CHP. Hawkes (2004) investigated this issue, and found that reported leakage rates from low pressure mains supply in the UK could lead to $CO_2$-equivalent emissions that counterweigh improvements from reduced electricity transmission and distribution (T&D) losses (a benefit commonly associated with distributed generation, where onsite generation reduces the need for T&D, and thus reduces T&D losses). This result is due to the high global warming potential (GWP) of natural gas compared to $CO_2$, and higher leakage rates from low pressure residential gas distribution when compared to high pressure systems associated with centralised power stations.

Finally, behavioural changes associated with a dwelling owner/occupier becoming more attuned to their energy consumption after microgeneration installation can produce "knock-on" benefits that reduce $CO_2$ production. Keirstead (2007) investigated this issue for PV systems, and found that energy consumption can decrease, and owner/occupiers were more likely to perform further energy efficiency (or other) actions to improve the performance of the energy provision.

## 7.2 Energy Consumption Performance

In order to examine the impact of large scale introduction of micro-CHP on energy security (in terms of reliance on any one primary fuel type based on geo-political instability raising questions regarding its supply in the future) it is necessary to consider the average primary fuel content of grid electricity. Table 13 shows the percentage makeup of electricity supplied and embodied primary energy by fuel according to BERR (2007) for the 2006 scenario and national Updated Energy Projections "central carbon savings" projection in BERR (2006) for the 2020 scenario.

| | Coal/Other (kWh) | Gas (kWh) | Oil (kWh) | Nuclear (kWh) | Renewables /Other (kWh) |
|---|---|---|---|---|---|
| **% of Gross Electricity Supplied in 2006** | 39% | 36% | 1% | 18% | 6% |
| **Content in 1kWh Grid Electricity 2006 (kWh)** | 1.14 | 0.81 | 0.04 | 0.52 | 0.24 |
| **% of Gross Electricity Supplied in 2020** | 19% | 53% | <1% | 7% | 16% |
| **Content in 1kWh Grid Electricity in 2020 (kWh)** | 0.56 | 1.19 | 0.01 | 0.2 | 0.62 |

**Table 13: The Primary Energy Content by Fuel of 1kWh of Electricity in 2006 and Projections for 2020**

Table 13 presents a perceived shift away from coal and nuclear fuelled generation towards gas-fired systems, an eventuality that is now somewhat debatable due to renewed interest in nuclear power as a low carbon and geo-politically secure energy source. The possible fuel mix information from Table 13, along with energy balance from micro-CHP modelling results[20] can be used to formulate a depiction of the percentage (based on energy-equivalence) share of each fuel under reference cases and micro-CHP cases for 2006 and 2020 grid electricity generation mix scenarios. Figure 39 shows these shares.

[20] The specific modelling results presented here relate to a mixture of $1kW_e$ micro-CHP systems operating in a variety of "existing" dwellings (see Table 1), with results generated through application of the modelling framework described in section 4.3.

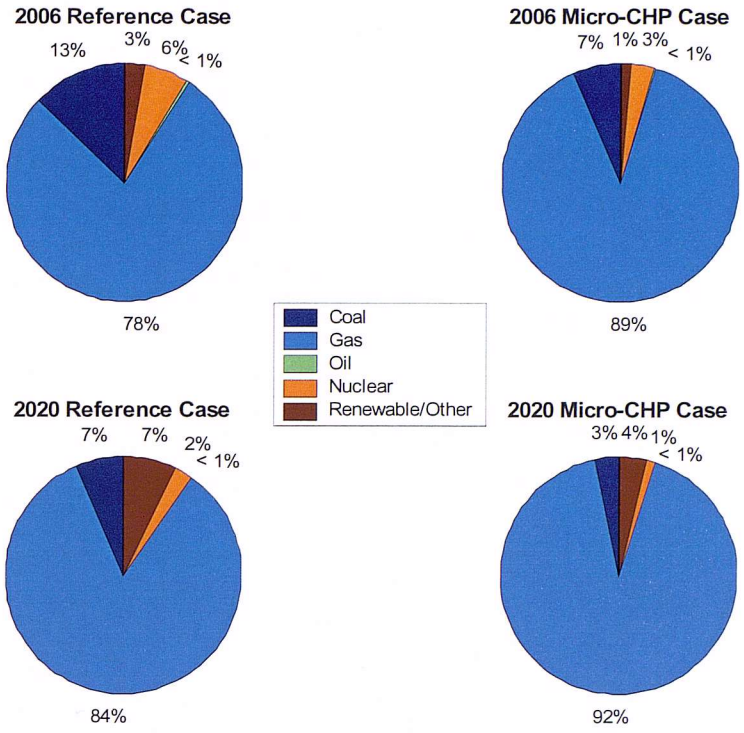



**Figure 39: Share of Primary Fuels in Average UK Residential Supply Including 2006 Reference and Micro-CHP Scenarios, and 2020 Reference and Micro-CHP Scenarios**

Figure 39 demonstrates the fact that the UK residential sector is reliant on natural gas, predominantly for space/water heating and some electricity production. The increase from 78% natural gas in the 2006 reference case to 89% in the 2006 micro-CHP case is caused by decreased use of grid electricity and its replacement with the solely gas-fuelled micro-CHP system. This movement is exacerbated in the 2020 scenario, where the shift towards gas-fired grid electricity in the BERR (2006) scenario is compounded with the uptake of micro-CHP.

Overall there is a clear trend towards increasing reliance on natural gas for the residential sector, which could be interpreted as a national security risk as UK-managed gas reserves become depleted and the country relies more heavily on foreign sources. However, the increase in dependence in the residential sector could be offset by changes in other sectors (for example, if nuclear rather than gas centralised generation is favoured in the future), and indeed a change from 78% reliance to 92% reliance may be seen as irrelevant for practical purposes because either scenario entails heavy dependence of the UK residential sector on natural gas. Furthermore, a number of observers including Watson and Scott (2008) have commented that perceived reliance on natural gas is not in fact a severe risk and diversity of sources and supply routes should actually increase over coming years.

Detailed discussion of these topical energy security issues is beyond the scope of this thesis on the basis that the residential sector is heavily reliant on natural gas for heating, and the changes caused by micro-CHP do not materially alter this situation.

## 7.3 The Capacity Credit of Micro-CHP

This sub-section presents background, mathematics, analysis method, results and discussion related to the capacity credit of micro-CHP. As this policy-related metric is less mainstream than those discussed above, detailed descriptions of its relevance are provided along with a comprehensive discussion of factors bearing on outcomes. This results in quantitative estimates of capacity credit for micro-CHP, and sheds light on possible future directions for related research. Information presented here has been published by the author in Hawkes and Leach (2008a).

Overall economic efficiency in electricity systems is desirable because it is linked with general societal benefits through reduced total cost of electricity supply. When properly understood and applied, one important measure of this economic efficiency is capacity credit, where the contribution of a certain amount of installed capacity of a particular type of electricity generator toward meeting the national system electricity demand is determined. For example, if investment is made in a particular alternative generator type, but that capacity is rarely operating or is unpredictable, additional generating capacity may need to be made available to meet increasing peak national demand or to balance a less predictable electricity system. It might be concluded that the cost of the alternative generator, from a system-wide point of view, should include the cost of these other assets or actions required to support it. Capacity credit measures the extent to which the new generator type contributes to meeting demand compared to the average generator in the existing system, thereby reflecting the technical aspects of this economic question. Therefore capacity credit, whilst limited in its applicability in that it ignores environmental outcomes, primary energy consumption, and other important aspects of energy provision, can provide a useful insight to part of the energy system puzzle.

In essence, capacity credit is a measure of the mean level and predictability of aggregate electricity output from a technology, and consequently by how much it reduces the system load met by other generators. In order to improve knowledge regarding the whole-system influence of a new energy technology that has the potential to enter the system on a large scale, it is desirable to estimate capacity credit associated with that technology. Frequent

examples of calculation of the capacity credit of wind power are available in the literature in Anderson (2006), Beenstock (1995), El-Sayed (2002), Gouveia and Matos (2004), Voorspools and D'Haeseleer (2006) and Milborrow (1994). This sub-section develops a methodology for calculation of capacity credit of micro combined heat and power (micro-CHP), and applies that methodology to the UKom to arrive at quantitative estimates. It is of interest to calculate capacity credit of micro-CHP because it is a demand-side technology that, like wind power, is not likely to adhere to conventional dispatch ideals; from the electricity networks perspective it is comparable to an "intermittent" generator as it is likely to operate when the dwelling occupier requires warmth or electricity. The mathematical formulation of the capacity credit calculation is necessarily different from that of wind power, taking into account the decentralised demand-led nature of micro-CHP, but previous studies detailing capacity credit calculation methods are drawn upon to inform this study. Capacity credit is calculated for three micro-CHP technologies; Stirling engine, gas internal combustion engine, and generic fuel cell based systems[21], under three possible operating strategies; electricity-led, heat-led, and a least-cost strategy.

### 7.3.1 Background for Capacity Credit

#### *7.3.1.1 Definition of Capacity Credit*

No generator is available 100% of the time. There will be times when its output is limited due to outages for maintenance, unplanned outages due to failures, or output limited due to lack of the primary energy resource (e.g. a wind turbine cannot generate electricity when the wind is not blowing). On average for conventional power plant planned unavailability (e.g. for scheduled maintenance) is approximately 10-11% and unplanned unavailability between 4 and 6% according to World Energy Council (2008).

Aggregate demand from consumers in the electricity system is also uncertain, depending on a variety of factors including weather, time of year, time of day, weekday versus holiday etc. It follows that total installed capacity in the electricity system must be greater than peak expected demand, to ensure all system electricity requirements can be met, with some known level of certainty.

[21] For the purposes of this study the technical representation of all the micro-CHP systems has been simplified, as discussed later in the sub-section. Particularly, the SOFC and PEMFC systems have been amalgamated to provide a characterisation of a generic fuel cell system with 40% electrical efficiency and 85% overall efficiency.

Capacity credit is defined in a variety of different ways in the literature; for example Voorspools and D'Haeseleer (2006), El-Sayed (2002). The most accepted definition appears to be that of maintaining system loss of load probability[22] (LOLP), where introduction of a less predictable generator results in the displacement of a certain amount of "conventional" generation but the whole system maintains LOLP at previous levels. Therefore it is a measure of the reliability of the contribution made by a type of generator, relative to the generators that already exist on the network. If the aggregate capacity added of the new generator type is greater than the aggregate capacity of conventional generation displaced (in order to maintain the LOLP of the system) that new generator type has a capacity credit less than one. If the amount of new generator capacity installed displaces exactly the same amount of existing generation capacity, the new generator has a capacity credit of exactly one. The reader should note that a generator type could have a capacity credit greater than one if it can be relied upon to generate with more certainty than the existing aggregation of conventional generators (i.e. the addition of x GW of a new generator type displaces more than x GW of existing generating capacity). Therefore, overall, capacity credit is a measure of the capacity contribution made by a generator type in the context of electricity system capacity expansion or change, taking into account predictability of generator availability and uncertainty in demand.

#### *7.3.1.2 Energy Economics, Policy, and Capacity Credit*

Capacity credit is a metric of interest in electricity system planning for a variety of reasons. It also has some important limitations. These aspects are discussed below.

Energy policy makers and regulators are concerned with, among other things, the effectiveness of investment in the energy sector and the security of electricity supply (an aspect of which is reliability of the electricity generation assets on the system). The capacity credit metric speaks to both of these concerns, but the complexities of electricity system investment, market operation, and complimentary and conflicting energy policy aims serve to obscure its direct applicability to either.

It may be argued that if capacity credit for a technology is low, additional reliable generation is required to be available on the system to maintain the reliability of the system. This may be undesirable because it implies that additional investment and/or operation may be required (one could have simply installed the reliable generator, perhaps

[22] Loss of load probability is the probability that demand for electricity will exceed available generating capacity.

resulting in a system with the same LOLP at lower cost). If one takes the view that all costs of the electricity generation system are ultimately borne by the consumer, whether directly or indirectly through taxation, one could conclude that a technology with low capacity credit may be negative from a societal point of view. However this argument over-simplifies the complex reality of factors bearing on electricity markets, where a variety of other aspects such as environmental outcomes and levels of primary energy consumption play a significant role in economics and choice of policy instruments. Capacity credit certainly does not capture the whole picture with regards to efficiency of investment in, reliability of, or the ability to meet environmental goals of the electricity system. Indeed the complexities of such an issue could not be captured by many interconnected indicators. However, capacity credit remains a useful *part* of the whole picture.

Specifically, capacity credit does not capture the economics of the situation in value terms. It measures important technical aspects of generation and not their associated economics. For example, if a generator has a low capacity credit, but is also significantly cheaper than existing conventional generation, it may still represent an economic proposition. Even where addition of a low capacity credit generator results in additional need for balancing actions by the system operator, possibly at higher cost, other policy aims such as greenhouse gas emissions reduction can tip the balance in favour of the low capacity credit systems. Additionally, the capacity credit metric does not capture the frequency, depth, or length of outages, which are important if a holistic picture of electricity system reliability is required, as discussed in Anderson (2006).

Nor does capacity credit capture local network impacts of a technology that may have significant bearing on economically achievable penetration levels. Capacity credit is by definition an indicator that is relevant on the national level, but large scale penetration of micro-CHP may have significant impact at the local network substation level, resulting in voltage sag or over-voltage, excursions in frequency of supply, or reverse flow of energy at the substation transformers (a situation that could require expensive upgrade of many substations). As presented in section 3.4.1, various studies considering local network impact of micro-CHP including Ingram et al. (2003), Mott MacDonald (2004), Peacock and Newborough (2006) who have broadly concluded that around 50% penetration of $1kW_e$ micro-CHP systems is possible without significant local network impact or necessity for network upgrade. An alternative to network reconfiguration is virtual power plant style

control of micro-CHP as suggested in Peacock and Newborough (2007) and van Dam et al. (2008).

Capacity credit, when considered alone, is therefore a metric with specific application, and forms only part of the picture with regards to efficiency of investment and reliability of supply. However, regardless of these limitations, capacity credit remains a useful metric for policy makers and system planners, provided there is an understanding of how to interpret it.

#### *7.3.1.3 Micro-CHP Control Strategies*

Electricity output of micro-CHP is dependent on the control strategy employed in its operation, which in turn means that capacity credit is dependent on control strategy. Micro-CHP could be controlled in order to achieve certain outcomes of benefit to the dwelling occupier, distribution network operator, supplier, or other electricity system stakeholder. Whilst the control response available from each technology differs, and future technologies may be equipped to respond in different ways, a body of research is developing regarding what stakeholder aims are most achievable and desirable.

In general it is desirable for any control strategy to have some economic basis, although the beneficiary of the economic gain often differs between strategies investigated in the literature. Perhaps most importantly the investor in the technology should receive sufficient benefit to justify the investment. Some control strategies in the literature and in commercially available devices are described below.

The most basic control strategy is to attempt to meet the heat load of the dwelling by first dispatching the micro-CHP unit and providing any additional heat required from the onboard supplementary thermal-only system (usually a condensing boiler). This is the most common control strategy, and is the primary strategy used in existing commercial micro-CHP units. The electrical output from the unit is determined by its ability to modulate to meet lower heat demands.

Another possible control strategy is to follow the electricity demand of the dwelling. The unit is dispatched at a set point close to, but not greater than the onsite electricity demand. This may be desirable when electricity prices are very high, and thermal demand can be followed by the combined output from the micro-CHP and supplementary thermal capacity.

Alternatively, a "least cost" control strategy may be synthesised and applied. The author has investigated this possibility in Hawkes and Leach (2007), and concluded that under present price conditions and expected technology characteristics, the least cost operating strategy (where thermal storage is not present) is to follow both heat and electricity demand, whichever is greater at any one moment.

A number of more complex control strategies, in terms of communication and/or computing power required, have been investigated in the literature. These involve applying fuzzy logic described in Entchev (2003), attempting to modulate electrical load profiles at the local area level as per Peacock and Newborough (2007), and attempting to minimise aggregate cost to the supplier through simultaneous control of a large number of micro-CHP units as per van Dam et al. (2008). Control to provide ancillary services on the local network level has also been investigated in Schaeffer et al. (2006). All central control strategies designed to achieve certain aims for Distribution Network Operator (DNO) or Supplier are necessarily constrained, as the most important aspects of micro-CHP control must be to provide low cost warmth to the dwelling occupier.

Heat following, electrical load following, and a "least cost" control strategy are investigated here, each of which is likely to exhibit different capacity credit. The reader should note that each control strategy is associated with different economic and environmental outcomes and different outcomes for DNO and Suppliers. All these factors must be taken into account to achieve a balanced perspective of the relative merits of the available options. The basis for strategies chosen for this investigation is that;

1. they can meet the dwelling's thermal demand,
2. they can achieve a reasonable cost to the dwelling occupier when compared with using grid electricity and a condensing boiler (the baseline case), and
3. they are likely to achieve a reasonably low greenhouse gas emissions outcome (with respect to a grid/boiler baseline[23]), with the possible exception of electrical load following as concluded in Hawkes and Leach (2007).
4. they do not require communication between the micro-CHP units and a centralised controller.

[23] Baseline emissions scenario for the referenced study was were the dwelling met electricity demand with average CCGT centralised generation, and heat demand with a condensing boiler.

### 7.3.2 Mathematical Formulation to Determine Capacity Credit for Micro-CHP

As noted above, there are several examples of the treatment of capacity credit for unpredictable renewable generators such as wind power in the literature (for example, *Voorspools and D'Haeseleer*, *Milborrow (1980)*, *Milborrow (1994)*, *Gouveia and Matos* (2004), Dale et al. (2004), Beenstock (1995), Anderson (2006)). However, the mathematical formulation to determine capacity credit of micro-CHP is necessarily different from that of wind power. With wind power, supply and demand are assumed to be normally distributed independent continuous random variables. Therefore power output from an aggregation of all wind turbines in a country is generally assumed to have no time dependence and no seasonal dependence. Under this assumption, the capacity credit of wind power can then be calculated as per Anderson (2006).

The mathematical formulation for the capacity credit of micro-CHP is more complicated, because of one or more of the following factors;

a. it may not be appropriate to assume that demand is independent from aggregate micro-CHP output,

b. there is a dependence between time-of-day and aggregate micro-CHP output, and

c. aggregate micro-CHP output depends on the designer/manufacturer's control strategy, which in turn usually depends on demand in the dwelling.

Therefore the general mathematical treatment applied by Anderson (2006) is adopted, and alterations are made to that treatment to account for the inherent differences between intermittent renewable resources and micro-CHP.

It is assumed that the national electricity system is made up solely of a number of identical large dispatchable plants, a number of identical micro-CHP units, and demand. These three elements are modelled by three continuous random variables;

1. F – aggregate available capacity from a number of large dispatchable plant,

2. mCHP – aggregate output from a large number of micro-CHP units, and

3. D – aggregate national demand.

F and D are independent, F and mCHP are independent, but mCHP and D may have some correlation. This is because micro-CHP is a demand-driven technology, where a unit's

output is linked to the actions of the dwelling occupants. All three random variables are assumed to be characterised by normal distributions, based on the central limit theorem.

A fourth random variable, M, is defined as the margin between available supply and national demand. The expected value of M is defined as:

$$E(M) = E(F) + E(mCHP) - E(D)$$

**Equation 29**

Therefore the margin, M, is also normally distributed, with mean $\mu_m$ and standard deviation $\sigma_m$.

The capacity credit definition applied is as follows; capacity credit is given by the ratio of the amount of "conventional" centralised generation (in MW) displaced by the introduction of a certain amount of an alternative technology divided by that amount (in MW) of the alternative introduced, under the requirement that loss of load probability remains the same before and after introduction of the alternative technology. This definition is reflected in Equation 30.

$$CC = \frac{c_f (n_0 - n)}{c_{mCHP} p}$$

**Equation 30**

Where $n_0$ is the number of large dispatchable units before introduction of the alternative technology, and $n$ is the number after such introduction. $p$ is the number of micro-CHP units introduced. $c_f$ and $c_{mCHP}$ are the capacities of the large dispatchable generators and micro-CHP units respectively.

It is assumed that loss of load probability (LOLP) before (and after) introduction of the new technology is approximately 2.3%. This corresponds with the average margin being two standard deviations above zero, as indicated in Figure 40.

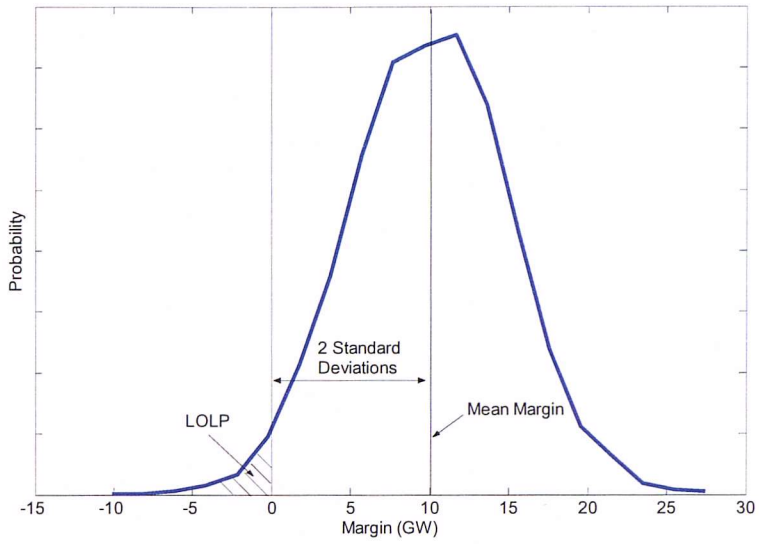



**Figure 40: Conceptual Probability Density Function for the Margin, showing the mean margin ( $\mu_m$ ), 2 standard deviations below the mean margin ( $2\sigma_m$ ), and the LOLP area.**

Therefore the relationship expressed in Equation 31 must hold before and after the introduction of the alternative generator, for loss of load probability to remain constant:

$$\mu_m = 2\sigma_m$$

**Equation 31**

From Equation 29 an estimate of the mean margin is given in Equation 32:

$$\mu_m = \mu_f + \mu_{mCHP} - \mu_d$$

**Equation 32**

And where all large dispatchable units are identically sized, Equation 32 becomes Equation 33,

$$\mu_m = n\mu_{fi} + \mu_{mCHP} - \mu_d$$

**Equation 33**

where *n* is the number of large dispatchable units, $\mu_{fi}$ is the mean output of a single large dispatchable unit and $\mu_{mCHP}$ is the average aggregate output from the set of micro-CHP units.

The variance of the margin is given by Equation 34;

$$\sigma_m^2 = \sigma_s^2 + \sigma_d^2 + A$$

**Equation 34**

where $\sigma_s, \sigma_d, A$ are the aggregate supply standard deviation, demand standard deviation, and a term to account for covariance between mCHP and D respectively. The variance of supply is the linear sum of the variances of F and mCHP:

$$\sigma_s^2 = \sigma_f^2 + \sigma_{mCHP}^2$$

**Equation 35**

Substituting Equation 35 into Equation 34 gives Equation 36:

$$\sigma_m^2 = \sigma_f^2 + \sigma_{mCHP}^2 + \sigma_d^2 + A$$

**Equation 36**

$$\text{where, } A = -2\,\text{cov}(mCHP, D)$$

The variance of individual plant availability cannot be characterised by a normal distribution, but the central limit theorem (as a sample size increases, the means of samples drawn from a population of a binomial or multinomial distribution will approach the normal distribution) can be used to allow estimation of variance of aggregate contribution from each generator type. Because large dispatchable supply is made up of *n* binomial independent units, the variance of an aggregation of *n* plants can be related to the (observable) variance of the existing system that consists of $n_0$ similar plants, as expressed in Equation 37.

$$\frac{\sigma_f^2}{\sigma_{f0}^2} = \frac{n}{n_0}$$

**Equation 37**

Substituting Equation 37 into Equation 36, the following relationship is achieved:

$$\sigma_m^2 = \frac{n}{n_0}\sigma_{f0}^2 + \sigma_{mCHP}^2 + \sigma_d^2 - 2\,\text{cov}(mCHP, D)$$

**Equation 38**

Finally, substituting Equation 38 and Equation 33 into Equation 31, we arrive at:

$$n\mu_{fi} + \mu_{mCHP} - \mu_d = 2.\sqrt{\frac{n}{n_0}\sigma_{f0}^2 + \sigma_{mCHP}^2 + \sigma_d^2 - 2\mathrm{cov}(mCHP, D)}$$

**Equation 39**

For a given level of introduction of the alternative technology, it is possible to solve Equation 39 for *n*. This calculation must be repeated for each hour of the day and for each month (i.e. 12*24 = 288 calculations) to account for hourly and monthly variations in the random variables mCHP and D. The maximum value of *n* from these 288 calculations is substituted into Equation 30 in order to calculate the capacity credit.

All variables required to solve Equation 39 are observable except for the covariance between mCHP and D. This quantity may be estimated by approximating the correlation between mCHP and D for each time period, and multiplying by demand standard deviation and mCHP standard deviation, as discussed below.

### 7.3.3 Input Data and Analysis Method

#### *7.3.3.1 Residential Demand and Micro-CHP Output*

The output from each individual micro-CHP unit is determined by a combination of control strategy, demand in the dwelling and available set-points for operation of the units. Equation 11 requires an estimate of the mean and variance of the output of an *aggregate* set of micro-CHP generators. These parameters can be estimated by determining the output of each micro-CHP unit based on the demand data, and then using basic theory of statistics to determine how a larger set of units would behave. This process and the data it is based on are described below.

This study utilises one of the few data sets available in the UK containing both electrical and heat demand for a large set of dwellings. This data was gathered from the Milton Keynes Energy Park, a set of energy efficient dwellings north of London.[24] Example aggregate profiles of electricity and heat demand for a winter day with an indication of their variability are presented in Figure 41 and Figure 42.

[24] Limitations and sensitivity analysis of results due to quality of input data are presented later in this sub-section.

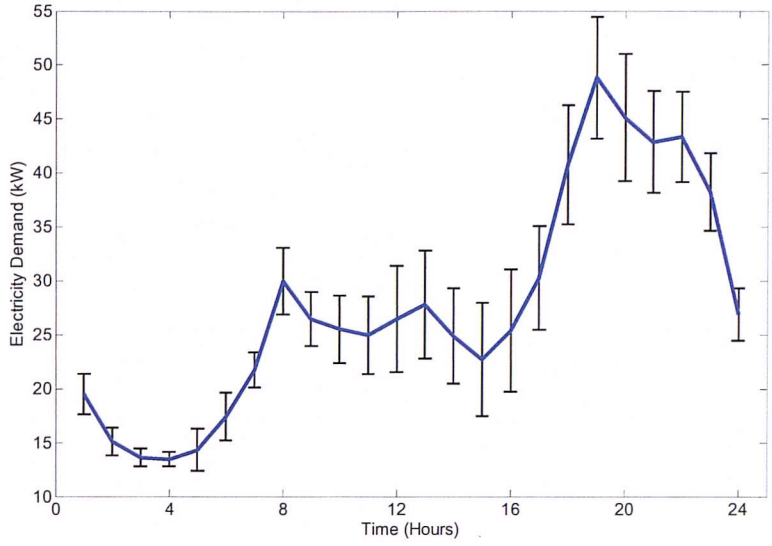



**Figure 41: Average Aggregate Electricity Demand for a Set of Properties in the Milton Keynes Energy Park for a Single Weekday in Winter, with Error Bars Representing 1 Standard Deviation from the Average.**

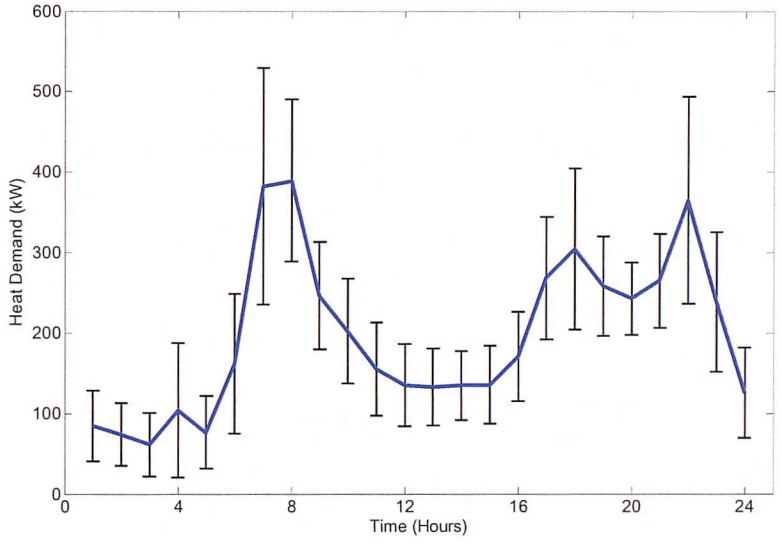



**Figure 42: Aggregate Heat Demand for a Set of Properties in the Milton Keynes Energy Park for a Single Weekday in Winter, with Error Bars Representing 1 Standard Deviation from the Average.**

Demand for each individual property is taken, and micro-CHP set point chosen based on that demand (set point immediately below demand is chosen) for the given control strategy. Therefore, for example, the output for a heat following strategy is determined by assessing the dwelling's heat demand, and choosing the micro-CHP set point that is less than but closest to that demand (additional heat demand requirements are met by the supplementary thermal system in the micro-CHP unit). If a dwelling had a 2.3kW$_{th}$ heat demand, the Stirling engine would be off (minimum set point is 0.5kW$_e$, which corresponds to 3.25kW$_{th}$), the internal combustion engine would be operating at 0.8kW$_e$, and the fuel cell would be operating at the 1.1kW$_e$ set point.

Each micro-CHP unit can be operating in one of four possible discrete states; off, 0.5kW, 0.8kW, or 1.1kW[25]. Each state has a specific probability $\pi_i$. This situation can be modelled using a multinomial distribution as per Berry and Lindgreen (1990). For a set of *p* independent events, where each event has *i* possible outcomes (i.e. states), $A_1, A_2, A_3, \ldots, A_i$, which are mutually exclusive and have probabilities, $\pi_1, \pi_2, \pi_3, \ldots, \pi_i$, respectively. The mean number of events that have outcome *i* is given by Equation 40, and the variance of the number of events that have outcome *i* is given by Equation 41. The covariance between outcomes *i* and *j* is given by Equation 42.

$$\mu_i = p\pi_i$$

**Equation 40**

$$\sigma_i^2 = p\pi_i(1-\pi_i)$$

**Equation 41**

$$\mathrm{cov}(i,j) = -p\pi_i\pi_j$$

**Equation 42**

Equation 40, Equation 41, and Equation 42 give the values of relevant parameters for each possible micro-CHP state, but the quantity of interest in this study is the aggregate output from a set of micro-CHP generators. Therefore the results from these equations for each possible micro-CHP state must be scaled to reflect the output level they correspond to, and added together to form the aggregate output. Mean and variance of the resulting distribution are given in Equation 43 and Equation 44 where $A_1$, $A_2$, and $A_3$ correspond to the three non-zero output states for the micro-CHP unit.

$$\mu_{mCHP} = p(A_1\pi_{A_1} + A_2\pi_{A_2} + A_3\pi_{A_3})$$

**Equation 43**

$$\sigma^2_{mCHP} = p\left(A_1^2\pi_{A_1}(1-\pi_{A_1}) + A_2^2\pi_{A_2}(1-\pi_{A_2}) + A_3{}^2\pi_{A_3}(1-\pi_{A_3})\right) - 2p\left(A_1A_2\pi_{A_1}\pi_{A_2} + A_2A_3\pi_{A_2}\pi_{A_3} + A_1A_3\pi_{A_1}\pi_{A_3}\right)$$

**Equation 44**

Equation 44 gives the variance of aggregate micro-CHP output due to factors within a single day. However, there could be additional variance due to factors between days (notably weather related changes). Using the laws of total variance, it is possible to add the average

[25] See note in "limitation of this study" section for a discussion of the impact of this assumption.

of within-day variance (i.e. unexplained variance) to between-day variance (i.e. explained variance), to arrive at total variance of aggregate micro-CHP output.

### *7.3.3.2 UK National Demand*

National Grid (2006) gives statistics of national demand in the form of the UK National Grid Company's Seven Year Statement. A sample of weekday demand profiles for each month was assembled by choosing the weekdays out of the 2006 demand profile, resulting in approximately 20 to 24 observations for each hour-long period in the day for each month. The average national demand for each hour of the day in January 2006 is displayed in Figure 43, with error bars to indicate one standard deviation either side of the mean demand.

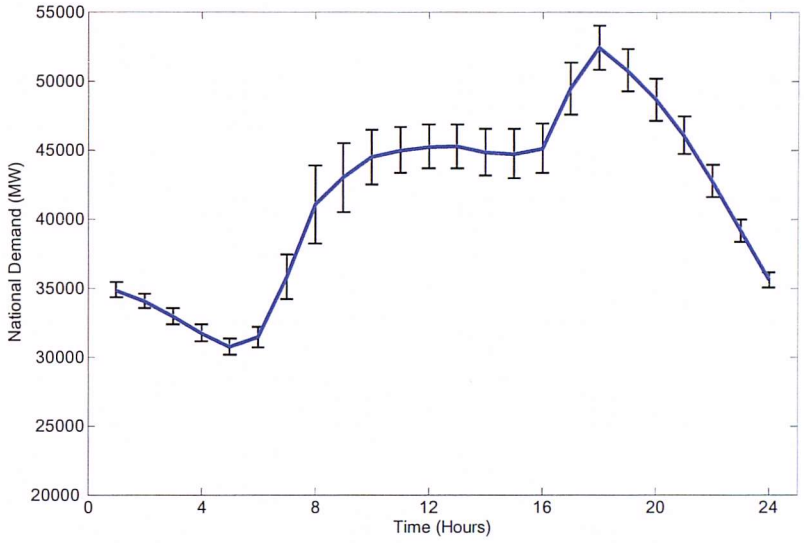



**Figure 43: Average Weekday UK National Demand in January 2006, with Error Bars to Indicate 1 Standard Deviation Either Side of the Average**

This process can be repeated for each hour in the day for each month to calculate the mean and variance parameters for national demand required by Equation 39.

### *7.3.3.3 UK Large Centralised Dispatchable Supply*

In this study it is assumed that conventional supply consists of a number of large dispatchable (e.g. fossil-fuelled) power station units. In the UK the average capacity of these units is approximately 350MW, and there are approximately 220 such units in the original system before hypothetical introduction of micro-CHP. Aggregate installed capacity is approximately 80GW in the modelled system, which is representative of the UK situation. However, only approximately 100 of these power units is above 100MW,

accounting for around 95% of UK generating capacity. Therefore the large dispatchable supply system modelled in this study consists of 100 large power stations, with an average capacity sufficient to achieve a LOLP of 2.3% given variability in supply and variability in demand.[26]

The existing system is modelled as a set of binomial (available/unavailable) units. For a large aggregation of such units, aggregate available capacity can be modelled using the normal distribution, with mean available capacity given by $c_f n\pi_{Available}$, and variance of available capacity is given by $c_f^2 n\pi_{Available}(1-\pi_{Available})$, where $c_f$ is the nameplate capacity, $n$ is the number of generators, and $\pi_{Available}$ is the average availability of each generator.

An estimate of the mean and variance of large dispatchable supply in the original UK system is therefore available for the present estimation of micro-CHP capacity credit, because experience with the UK system has shown that on average approximately 85% of generating capacity is available at any given time. This includes both planned and unplanned outages. In reality power station operators will avoid peak demand times when scheduling maintenance, but as micro-CHP may essentially shift this peak time (see discussion re "critical" time in the Capacity Credit Result section) the operators may not be able to predict this peak time. Therefore both planned and unplanned unavailability are included, and the mean and variance of conventional generation capacity is assumed to be constant throughout the year.

#### *7.3.3.4 Covariance Between mCHP Output and National Demand*

The only piece of data from Equation 39 that is not observable from the available data is the covariance between micro-CHP output and national demand for a given hour of the day in a particular month. This is because the data sets for residential demand (which drives micro-CHP output) and national demand are not available for the same time period.

Covariance is given by Equation 45.

$$\mathrm{cov}(mCHP, D) = \sigma_d \sigma_{mCHP} corr(mCHP, D)$$

**Equation 45**

[26] This is a slight departure from reality, but a necessary simplification to make the problem tractable. The authors believe no significant error is introduced.

Standard deviations of D and mCHP are known from the data described above, so an estimate of the correlation between these variable is required. As an estimate of the correlation for a single hour period for a particular month, the correlation over the entire day between average aggregate micro-CHP output and national demand is used. Sensitivity analysis of the result to standard deviation of aggregate micro-CHP output and national demand is performed to gain an understanding of the impact of this assumption.

#### *7.3.3.5 Micro-CHP Availability and Set-Points*

The availability of the electricity generation system in each micro-CHP unit cannot be established empirically, because insufficient evidence exists to draw broad conclusions. However, it is expected that the systems will have high availability, as dwelling occupiers will not accept the requirement of regular maintenance of the units. The central estimate of availability used in this study is 90% for all technologies, and this is believed to be conservative.

The efficiencies and heat-to-power ratios are as defined in Section 2.2. Each micro-CHP unit has a capacity of 1.1kWe and is able to operate at four possible set-points; 1.1kW, 0.8kW, 0.5kW, or off. The units are able to change between these set points without constraint (i.e. there are no limitations with regards to on/off decisions or ramping).

#### *7.3.3.6 Analysis Method for Capacity Credit*

The following analysis method is applied to arrive at the capacity credit results:

1. Residential demand and national demand are assembled for each hour of the day, for each month of the year.

2. From individual residential dwelling demands, micro-CHP output is determined for each hour, month and year.

3. Mean and variance of aggregate micro-CHP output are determined using Equation 43 and Equation 44 for the multinomial distribution.

4. Mean national demand and variance are determined for each hour of the day, and for each month.

5. Correlation between average aggregate micro-CHP output and national demand is calculated.

6. For each hour of the day, and for each month, above values are substituted into Equation 39, which is solved for n. This results in a vector of 24*12 = 288 values for n.

7. The maximum value of n is taken from step 6, and substituted into Equation 30, resulting in an estimate of the capacity credit.

8. Steps 2 to 7 are repeated for each micro-CHP technology, and each dispatch strategy.

9. Steps 2 to 8 are repeated for each micro-CHP penetration level. Penetration levels range from 1,000,000 units, to the maximum 13,000,000 units.

The key result is a table of capacity credit values for each technology, for each dispatch strategy, and for each penetration level.

### 7.3.4 Analysis Results, Discussion, and Sensitivity

#### *7.3.4.1 Capacity Credit Result*

The results presented in Table 14 indicate the capacity credit of each micro-CHP technology under each control strategy, for each investigated penetration level.

The first broad result of interest is the relative difference in capacity credit between technologies. Fuel cell based micro-CHP has the highest capacity credit, followed by internal combustion engines, and Stirling engines. Like other policy-related results presented in this chapter, this corresponds to the relative heat-to-power ratios of the technologies. Clearly low heat-to-power ratio technologies can achieve higher capacity credit. This is because they are able to continue producing electricity even when heat demands are relatively low.

| | Penetration Level ('000,000 units) | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 |
| **Stirling Engine** | | | | | | | | | | | | | |
| *Least Cost* | 0.48 | 0.48 | 0.48 | 0.48 | 0.48 | 0.48 | 0.48 | 0.48 | 0.48 | 0.47 | 0.46 | 0.44 | 0.42 |
| *Heat Led* | 0.33 | 0.33 | 0.33 | 0.33 | 0.33 | 0.33 | 0.33 | 0.32 | 0.32 | 0.32 | 0.33 | 0.33 | 0.31 |
| *Electricity Led* | 0.26 | 0.26 | 0.26 | 0.26 | 0.26 | 0.26 | 0.26 | 0.26 | 0.26 | 0.26 | 0.26 | 0.26 | 0.25 |
| **ICE** | | | | | | | | | | | | | |
| *Least Cost* | 0.75 | 0.75 | 0.75 | 0.75 | 0.75 | 0.75 | 0.75 | 0.73 | 0.70 | 0.67 | 0.65 | 0.63 | 0.62 |
| *Heat Led* | 0.71 | 0.71 | 0.71 | 0.71 | 0.71 | 0.71 | 0.71 | 0.71 | 0.68 | 0.65 | 0.63 | 0.61 | 0.59 |
| *Electricity Led* | 0.26 | 0.26 | 0.26 | 0.26 | 0.26 | 0.26 | 0.26 | 0.26 | 0.26 | 0.26 | 0.26 | 0.26 | 0.25 |
| **Fuel Cell** | | | | | | | | | | | | | |
| *Least Cost* | 0.92 | 0.91 | 0.91 | 0.91 | 0.91 | 0.91 | 0.91 | 0.87 | 0.84 | 0.81 | 0.79 | 0.77 | 0.75 |
| *Heat Led* | 0.86 | 0.86 | 0.86 | 0.86 | 0.86 | 0.86 | 0.86 | 0.85 | 0.82 | 0.79 | 0.77 | 0.75 | 0.73 |
| *Electricity Led* | 0.26 | 0.26 | 0.26 | 0.26 | 0.26 | 0.26 | 0.26 | 0.26 | 0.26 | 0.26 | 0.26 | 0.26 | 0.25 |

**Table 14: Capacity Credit for Each Technology, Control Strategy, and Penetration**

The second broad conclusion is derived from comparison between operating strategies. The least cost operating strategy achieves the highest capacity credit, followed by heat-led operation. With the exception of the case of the Stirling engine, the capacity credit for following electricity demand is significantly lower than the other strategies, and (by definition) it is identical between technologies. Overall it is apparent that strategies that involve following heat demand result in the highest capacity credit, which follows from the fact that in the UK high national electricity demand occurs at times when residential dwellings are likely to have high heat demand (i.e. a mid-winter weekday).

The final broad conclusion to be made from Table 14 is that whilst capacity credit decreases with increasing penetration of the technology, the decrease is not substantial. For example, even at high penetrations of any micro-CHP technology up to 8,000,000 units, the overall capacity credit of the installations has fallen no more than 7% from a 1,000,000 unit penetration.

It has been noted in some publications that as micro-CHP may not operate as much in summer when heat demand is reduced, it may not displace reserve capacity (for example, Wood (2004) and Voorspools et al. (2001)). This broadly equates with low capacity credit. This argument notes that there is a "critical" time when the maximum amount of conventional generation is required, which is the essential limiting factor for the capacity credit of micro-CHP. The "critical" time concept is an important one for the capacity credit calculation[27], because it represents the point at which output from the micro-CHP units is most important in terms of displacing conventional generation capacity. This may or may

[27] Indeed the "critical time" concept is implicit in "step 7" of the "Analysis Method" presented above. The "maximum value of n" corresponds to the time at which the most conventional generation is required.

not be the time of system peak demand. Indeed it may occur at a time of historically lower system demand, but when aggregate average micro-CHP output is low, or particularly unpredictable, such as in summer. However, the modelling of all technologies and control strategies exhibited a "critical" time at approximately 6pm on a December or January weekday, even when 13,000,000 micro-CHP units are installed. In summer months less conventional generation is displaced by micro-CHP, but this does not influence the capacity credit of the technology up to the penetrations investigated because the time that the peak amount of conventional generation is required remains to be in winter months. This result discredits the argument put forward by Wood (2004) and others for the case of the UK.

#### *7.3.4.2 Sensitivity Analysis for Capacity Credit Results*

In order to analyse the sensitivity of the result to various input parameters, the 2,000,000 unit penetration level was chosen as the basis for comparison because it represents a relatively achievable target in the medium term. Four alternative input data value scenarios were chosen for sensitivity analysis (five scenarios in total to include a reference case):

Scenario 1: Reference case as per Table 14.

Scenario 2: Standard deviation of aggregate micro-CHP output increased to 20% of mean aggregate micro-CHP output.

Scenario 3: Standard deviation of aggregate national demand increased by a factor of 2.

Scenario 4: Standard deviation of aggregate national available centralised supply increased by a factor of 2.

Scenario 5: Micro-CHP availability set to 98%.

Results of this sensitivity analysis are presented in Table 15. Overall it is apparent that the capacity credit of micro-CHP can be influenced by a variety of parameters. If the aggregate output from the micro-CHP units had standard deviation of 20% of the mean aggregate output, capacity credit falls by no more than a few percent. Increasing the standard deviation of national demand has an even more marked influence; capacity credit can be halved. Conversely, if the standard deviation of available supply increased, then capacity credit of micro-CHP increases because it is effectively being compared to the less reliable centralised generation source. Increasing the availability of micro-CHP to 98% (which some may argue is more realistic than the 90% value used in the reference result, because consumers would not accept requirement for frequent maintenance of the systems)

increases the capacity credit as expected. In this case, for fuel cell based micro-CHP operating in the "least-cost" operating strategy, capacity credit exceeds unity, indicating that this technology would displace more capacity of conventional centralised generation than its own installed capacity.

| | Sensitivity Analysis Scenario Number | | | | |
|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 |
| | Reference Scenario | Micro-CHP Standard Deviation Increased | National Demand Standard Deviation Increased | Available Supply Standard Deviation Increased | 98% Micro-CHP Availability |
| **Stirling Engine** | | | | | |
| *Least Cost* | 0.48 | 0.45 | 0.24 | 0.50 | 0.54 |
| *Heat Led* | 0.33 | 0.30 | 0.22 | 0.34 | 0.37 |
| *Electricity Led* | 0.26 | 0.23 | 0.08 | 0.27 | 0.29 |
| **Internal Combustion Engine** | | | | | |
| *Least Cost* | 0.75 | 0.70 | 0.52 | 0.78 | 0.85 |
| *Heat Led* | 0.71 | 0.66 | 0.52 | 0.75 | 0.81 |
| *Electricity Led* | 0.26 | 0.23 | 0.08 | 0.27 | 0.29 |
| **Fuel Cell** | | | | | |
| *Least Cost* | 0.91 | 0.86 | 0.70 | 0.96 | 1.03 |
| *Heat Led* | 0.86 | 0.81 | 0.69 | 0.90 | 0.98 |
| *Electricity Led* | 0.26 | 0.23 | 0.08 | 0.27 | 0.29 |

**Table 15: Capacity Credit for Sensitivity Analysis Scenarios**

Change in the standard deviation of national demand has the most marked influence on the presented results. The standard deviation of national demand used in this study is based on measured national demand data, and therefore represents a good estimate of the actual value. Therefore the doubling of this standard deviation as investigated in this sensitivity analysis is unlikely in reality, and the results presented here should be taken as the outcome in the most extreme scenario. In practice, standard deviation of national demand is mostly influenced (indirectly) by the weather, and extreme changes in weather patterns are unlikely in the medium term. In the future patterns of national demand may change as the electricity system and economy change, but the influence of these factors is beyond the scope of this study.

### *7.3.4.3 Qualitative Comparison with Other European Countries*

A point of interest is comparison of the results presented above with those that might be expected for other European countries based on statistics of national supply and demand. Whilst supply is to a reasonable extent similar in terms of availability (with the possible exception of those countries that have significant penetration of intermittent renewable electricity generation), but demand profiles – both national and residential – are likely to be significantly different.

Northern, colder climate countries are likely to achieve high capacity credit from micro-CHP provided their summertime national demand peak is significantly lower than wintertime national peak. Additionally, high capacity credit relies on wintertime national demand peak occurring at a time when there is likely to be heat demand in a substantial portion of residential dwellings. This in turn implies that if a national demand peak were to occur due to primary or secondary industry demand (e.g. in the early afternoon), micro-CHP capacity credit may be low.

Capacity credit of micro-CHP in southern European countries is influenced by a similar array of factors, with the added complexity that summertime air conditioning load is often responsible for the national demand peak. Without the (possibly expensive) addition of evaporative cooling to micro-CHP systems, or the possibility of dumping significant amounts of heat from the system and meeting an electrical air conditioning load (note that heat dump is associated with possibly poor greenhouse gas emissions performance of micro-CHP systems as discussed in section 7.1.3), micro-CHP would not be able to meet this air conditioning load. Therefore the capacity credit of micro-CHP (without evaporative cooling) in countries with this situation is likely to be low.

#### *7.3.4.4 Limitations of this Capacity Credit Study*

This study incorporates a number of assumptions and other limitations. Any future attempt to estimate capacity credit could try to improve upon this situation, and therefore the authors' analysis of these factors is presented here.

Firstly, the study could be repeated with an improved set of residential demand data. The data set applied consists of approximately 100 dwellings with energy consumption monitored over a three year period. Data points are occasionally missing or inconsistent and recordings were taken from best-practise energy-efficient dwellings more than a decade ago, so a more recent or higher quality data set drawn from a sample of properties including a diverse range of locations/counties could be employed.[28] This, in itself, could represent a significant research effort to understand the depth and breadth of patterns of residential energy use in the UK, and the driving forces and potential for change in these patterns.

[28] In order to circumvent erroneous results due to poor data quality, only dwellings with complete data sets were used. Hourly mean and variance of aggregate micro-CHP output was drawn from samples where at least 70 dwellings had provided consistent readings.

Secondly, the choice of capacity for the units (i.e. 1.1kWe) and the choice of set points for each technology, and indeed whether or not any set points are required for some micro-CHP technologies (full modulation may be possible), have an influence on the results of this study. Capacity choice probably has the most marked influence; for example, if units were $2kW_e$ each, total installed capacity would increase substantially, with an inverse influence on capacity credit. Furthermore, a fully modulating technology is likely to have a slightly higher capacity credit than a set-point limited technology. This is because the unit will not be required to operate at a set point below demand, but may be able to follow load exactly, therefore operating at higher average output. Also, where set points are required, their choice determines what level the unit operates at, thus influencing capacity credit. This influence has not been investigated in detail in this study, but it expected to have more evident influence on capacity credit of high heat-to-power ratio technologies.

Thirdly, technology substitution (i.e. replacement of boiler stock with micro-CHP) will alter the demand profile and subsequent micro-CHP output profile. Indeed micro-CHP could be controlled in a very different way to common central heating boiler controls from which the investigated demand profiles were taken. An example of alternative control methods, such as use of underfloor heating to maintain internal temperature and can provide positive economic and environmental results are presented in Chapter 8 (section 8.2.3).

Fourthly, capacity credit is a measure of the relevance of a particular generation type in electricity system expansion. However, this and other studies calculate capacity credit for the current electricity system. It is of interest to consider how the electricity system could change over coming decades and how this may influence the capacity credit calculation result. For example, substantial increase in air conditioning load could significantly alter the results.

Overall this study would benefit from re-application of the developed mathematical model once empirical evidence from micro-CHP operation has been gathered, and/or when more accurate or larger sample-set of electrical and thermal demand in dwellings are available.

### 7.3.5 Conclusions Regarding Capacity Credit

This sub-section has presented the background, mathematical formulation, and analysis results for the capacity credit of micro combined heat and power (micro-CHP). Capacity credit is an important indicator when considering electricity system expansion because it gives an estimate of how much conventional generation plant will not need to be commissioned for a given penetration of an alternative technology. This in turn provides

useful information regarding the overall economic efficiency of a national electricity system.

The mathematical model of micro-CHP that was developed in this section was applied to the UK situation for three technologies and three control strategies. Technologies investigated were Stirling engine, internal combustion engine, and generic fuel cell based systems. Under central estimates of input data it was found that for a 1,000,000 unit penetration (1.1GW), fuel cell based micro-CHP using a least-cost operating strategy achieved the highest capacity credit of 92%. This implies that 1.1GW of micro-CHP could displace roughly 1.0GW of conventional generation capacity with the resulting system maintaining its probability of demand exceeding available supply. Internal combustion engine based systems achieved 75% capacity credit, and Stirling engines achieved 48% capacity credit for the least-cost operating strategy and 1.1GW level of penetration. These results further reinforce the recurring result in this thesis; that low heat-to-power ratio technologies such as fuel cells perform better. They can achieve high capacity credit because they can continue to operate when there is low heat demand (for heat-led and least-cost operating strategies). As penetration level increases, capacity credit decreased for all technologies and operating strategies, but the decline is not substantial. A further key result of this analysis is that the capacity credit of micro-CHP in the UK is not greatly influenced by the fact that heat demand is low in summer months. This is because national system demand is also lower in these months, and therefore substantial conventional reserve capacity exists, and reliable micro-CHP output is not required to maintain system loss of load probability.

The observed results were shown to be sensitive to changes in some important input parameters, but it is reasonable to conclude that reported capacity credit values are accurate +/- 10%, except in the case where variance of national demand changes significantly, resulting in more than 20% reduction in capacity credit. High quality demand data and/or empirical evidence of micro-CHP operation, including information regarding set points, are required to achieve a greater confidence in the result.

## 7.4 Conclusions Regarding Ability to Meet Policy Objectives

This chapter has investigated the greenhouse gas, energy security, and capacity credit implications of adoption of micro-CHP. Each of these considerations is important for the successful commercialisation of the technology, as they relate directly to concerns

regarding climate change, *perceived* dependence on foreign primary energy sources, and the economic efficacy of micro-CHP in terms of societal investment in energy generation and transmission and distribution infrastructure. Each metric is of added importance if the large potential market for micro-CHP is realised, as this is when the impact of the technologies will be apparent at the national scale.

Greenhouse gas emissions reductions have been shown to be heavily dependent on the heat-to-power ratio of the micro-CHP prime mover technology, the thermal demand of the target dwelling, and the $kW_e$ capacity of each individual installation. Technologies with lower heat-to-power ratios can provide a greater and more consistent $CO_2$ reduction (in comparison to the reference system) than those with high heat-to-power ratio. Very low heat-to-power ratio technologies such as SOFC- based systems provide the best result, and can virtually eliminate the $CO_2$ footprint for energy consumption in a dwelling where large capacities around $4kW_e$ are installed. This raises interesting questions regarding their applicability in the currently-topical zero-carbon housing regulations. Micro-CHP prime movers with mid range heat-to-power ratios (e.g. ICE-based and PEMFC-based systems) are more sensitive to annual thermal demand, where easing thermal constraints (i.e. increasing thermal demand) allow these systems to generate more electricity. Very high heat-to-power ratio technologies appear to be particularly challenged to provide meaningful reductions in any annual thermal demand scenario. None of the technologies achievable $CO_2$ reductions where sensitive to annual electricity demand, because credit for generation is identical regardless of whether it is consumed onsite or exported to the grid.

Electricity buyback prices were found to interact with potential $CO_2$ reductions for micro-CHP in unanticipated ways. Although some form of export or performance-based reward is clearly a good motivator for appropriate operation of micro-CHP systems, high electricity buyback prices may not be the best choice of policy instrument. This is because they can incentivise a dwelling owner/occupier to behave (and operate the system) in a way that wastes heat to generate electricity and profits from high electricity buyback rates. This issue is discussed in more detail in Chapter 9.

Perhaps most importantly, it has been shown that as grid electricity embodied $CO_2$ rate falls, the ability of any micro-CHP systems to provide meaningful $CO_2$ reductions becomes compromised. The critical point appears to be where grid electricity $CO_2$ rate falls below approximately $0.3kgCO_2/kWh$. This suggests that if policy and regulation pushing forward

large scale "centralised" low carbon electricity generation is successful, micro-CHP will be a near to medium term technology from the point of view of plausible $CO_2$ reduction.

The energy security implications of large scale introduction of micro-CHP have also been briefly investigated. It was shown that high penetration of gas-fuelled micro-CHP is likely to increase the reliance of the residential sector on natural gas as a primary energy source. Whilst this is arguably undesirable, the change in level of dependence on gas between cases with and without micro-CHP is relatively small, so this issue is not of great consequence. Indeed questions have been raised regarding the reality of risks associated with gas import dependence, suggesting that they may not be critical. Primary energy consumption mix changes have therefore not been a focus of this thesis.

Finally, it was concluded that capacity credit of micro-CHP is likely to be high, particularly for low heat-to-power ratio technologies. Therefore, if predicted high penetrations of micro-CHP materialise, the technology could form an important part of overall UK electricity supply. The implementation, results and limitations of the capacity credit study have been considered in detail, highlighting possible directions for future research in this area.

These conclusions compound with results obtained in Chapter 6 suggesting that micro-CHP can be cost-effective and environmentally sound, promoting it as a technology solution that can help to meet a number of energy policy aims. However, results from this chapter also suggest that care must be taken regarding where and when micro-CHP installation should be supported. Overall the same thermal constraints versus ability to generate electricity issues that drive a positive economic case also result in superior policy-related performance. The exception to this rule lies in the fact that onsite electricity demand of the target dwelling does no bear greatly upon potential for CO2 reductions, whilst it has significant bearing on the economic case.

Issues arising from results in this chapter are discussed further in Chapter 9, which seeks to outline plausible methods of policy support for the technologies.

# Chapter 8: Impact of Key Technical Parameters on System Performance

This chapter applies the modelling framework developed in section 4.3 to create an understanding of the key technical characteristics for commercially successful micro-CHP. This study is undertaken from the point of view of the technology developer, who requires direction regarding which aspects of system design or control to focus research and development upon. Environmental impact of system changes are also reported here, because it is assumed that positive environmental credentials, in addition to attractive economics, will be required if technologies are to be successful.

For this exercise all modelling input parameters are as per their central estimate values as presented in section 2.2, except for the parameter under scrutiny in each sensitivity analysis. The range and values investigated for each parameter are discussed in each corresponding section. The building variant investigated is that of an existing terraced dwelling, with energy consumptions as per section 2.1.5 (except the case of sensitivity to thermal demand load factor as discussed below), with a 1kW$_e$ micro-CHP system installed.

## 8.1 Description of Key Technical Parameters

The developed modelling framework is capable of analysing a vast array of sensitivities related to prime mover or balance of plant design, system control, or thermal delivery and storage arrangements. A subset of these options is chosen to arrive at a tractable set of parameters for investigation.

Broadly speaking, the technical characteristics that relate to economic and environmental results are efficiency, utilisation, and system dynamics related. Simplistically they relate to how much fuel is consumed and how often the prime mover is used. However, as this section reveals, the interaction is much more intricate than this, with a number of interrelated factors combining to bear upon economic and environmental performance. Table 16 briefly lists and explains the parameters studied, but detailed explanation is included in each sub-section below.

| Parameter | Definition | Ranges Explored |
|---|---|---|
| **Overall Efficiency** | Overall Efficiency is a proxy for thermal efficiency. Overall Efficiency = Power Efficiency + Thermal Efficiency. Thermal efficiency is the efficiency with which waste heat is captured for use in space and DHW heating | Approx 50% - 100%, depending on system |
| **Part-load Efficiency** | Part-load efficiency relates to the performance of the system at loads less than its nameplate capacity | Various according to system, see below. Fuel cell systems typically have higher part-load efficiency |
| **Thermal Demand Load Factor** | Thermal demand load factor relates to the hardware and control used to deliver space heating | Four specific thermal load profiles from building simulation package |
| **Ramp Rate** | The rate at which electrical output can be changed, in $kW_e$/minute. | 0.025kWe/minute to no ramp rate limit |
| **Start-Up Cost** | The amount of electricity and gas used to start the system over and above that used by the reference system. It is the cost of this start-up energy. | 0 to 5.5p/start (engines)<br>0 to 8p/start (fuel cells) |
| **Turndown Ratio** | The minimum operating point for the system ($kW_e$). Most systems are not designed to operate below a certain limit. | $0kW_e$ to $1kW_e$ |
| **Minimum Up-Time** | The minimum amount of time the system must stay on for once it has been turned on, in minutes. | No min up-time, to 120 minutes (engines) or 240 minutes (fuel cells) |
| **Degradation** | The rate of reduction in electrical efficiency, for fuel cell systems3 | 0 to $1x10^{-2}$%/kWh |
| **Thermal Energy Storage** | Gives the micro-CHP system the option to store thermal energy for use in a later time period, subject to some losses | 5 litres to 200 litres of water-based storage |

**Table 16: Overview of Technical Parameters Investigated**

System developers can consider the cost and potential for success in attempting to improve performance regarding each of the parameters in Table 16, and focus on the elements of system design or control that speaks to that parameter.

## 8.2 Sensitivity of Micro-CHP Performance to Key Technical Parameters

### 8.2.1 Overall Efficiency

In this research the micro-CHP systems are considered with respect to their relative advantages over the competing reference system. In the case of the UK, that competing reference system is a condensing boiler and grid electricity, as described in section 3.2. In general boilers are mature technology, benefiting from several decades as a mainstream commercial product. Particularly condensing versions exhibit exceptionally high seasonal efficiencies, often exceeding 100% (LHV efficiency, where condensing models can recover the latent heat of vaporisation via condensation of the exhaust stream) in standardised laboratory tests. Such efficiency levels make this technology very difficult to compete with,

and potentially make the overall efficiency of micro-CHP systems an important concern for system developers. Therefore the first metric chosen for analysis in this study is **system overall efficiency.** The overall efficiency is defined as the combination of electrical and thermal efficiency, and in a practical sense corresponds to the thermal aspects of the micro-CHP system such as heat exchanger, manifolding, and system insulation design. Analysis of sensitivity of model outputs to changes in overall efficiency could therefore be interpreted as sensitivity to changes in thermal efficiency, because electrical efficiency is held constant at central estimate values during study of this parameter. Note that this implies that the systems produce very little useful heat in some circumstances; for example the case of SOFC-based micro-CHP with 50% overall efficiency would produce only approximately 0.1kW$_{th}$ at 1kW$_e$; maximum rated power.

Figure 44 and Figure 45 show the economic and environmental result for the four micro-CHP systems across a range of overall efficiency values. Overall efficiencies investigated range from approximately 50% up to 100%, depending on the technology under consideration. For example, the fuel cell technologies are assumed to be more limited in terms of overall efficiency because of more complex balance of plant such as fuel reformers, as described in section 2.2.3.

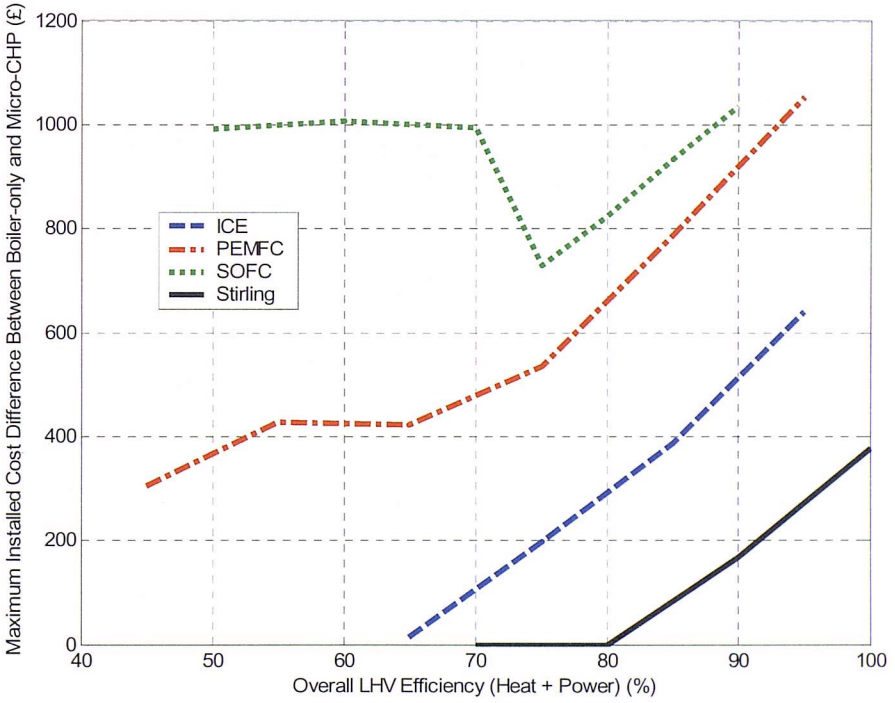



**Figure 44: Sensitivity of Maximum Installed Capital Cost Difference Between Boiler-only System and Micro-CHP Systems (£) to Overall Efficiency (Net Heat + Power) (%)**

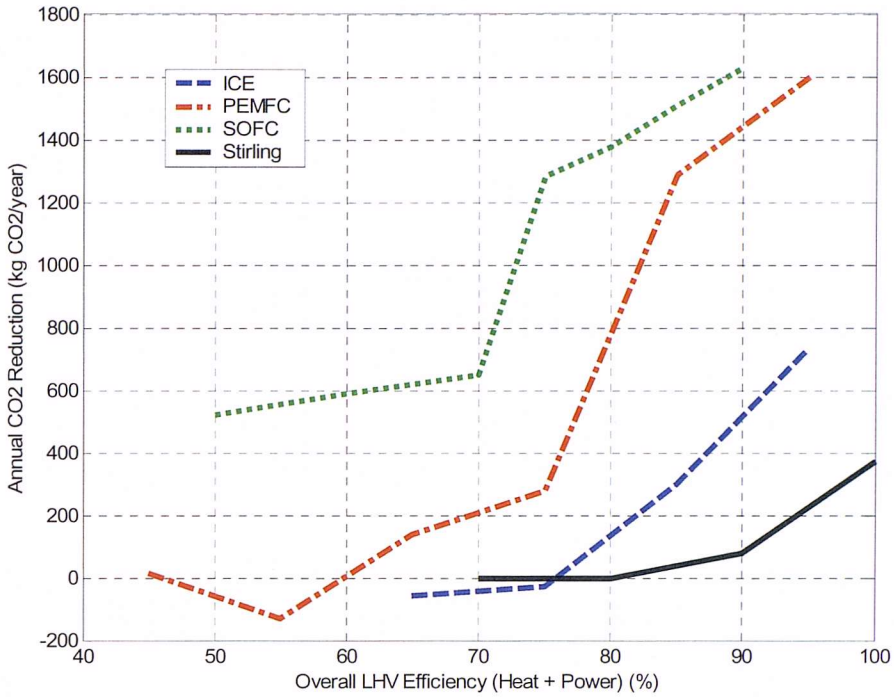



**Figure 45: Sensitivity of Annual $CO_2$ Emissions Reduction (kg $CO_2$/year) for Micro-CHP Systems to System Overall Efficiency (Net Heat + Power) (%)**

Figure 44 shows the dependence of the relative value of the micro-CHP systems on overall efficiency. In general the plots within Figure 44 confirm the expected upward trend in system value as overall efficiency increases. However, the SOFC-based system exhibits an interesting anomaly to the trend, which is discussed below. In all cases in Figure 45 increasing overall efficiency improves the annual $CO_2$ reduction significantly. Interestingly, the SOFC-based micro-CHP can deliver an emissions reduction even when overall efficiency approaches 50%, whereas all other technologies will actually increase emissions when compared to the reference case at this point.

In the case of SOFC-based micro-CHP, as overall efficiency increases, the relative value of the SOFC-based micro-CHP system stays constant, dips in the range of 75% to 85% overall efficiency, and then increases again. This can be explained through examination of the optimal operating strategy displayed in Figure 46 (for the cases of 50% and 90% overall efficiency). A clear difference exists between the low and high overall efficiency cases in Figure 46 in terms of the tension between thermal production and thermal demand. The low overall efficiency (i.e. lower thermal efficiency) system is able to generate electricity because it does not generate much heat and is subsequently rarely constrained by producing too much heat for the thermal demand. It can essentially follow the electricity load, which is the most profitable strategy in this case. Conversely, the high overall

efficiency system (i.e. higher thermal efficiency) is more constrained in this sense because it produces more heat for a given amount of electricity and (according to the technical constraints on dumping heat) it is required to have a demand sink for that heat. When no such heat sink exists, the system must modulate or switch off. This reduces the value of the system as a whole because it is able to operate less frequently. Hence the economics of the low overall efficiency SOFC-based case is less dependent on thermal demand, and more dependent upon the tension between the cost of electricity from the grid versus the cost of electricity from the SOFC. The other micro-CHP systems do not have sufficient electrical efficiency to provide electricity-only at lower cost than grid electricity, so they do not exhibit the relationship between overall efficiency and system value of SOFC-based systems.

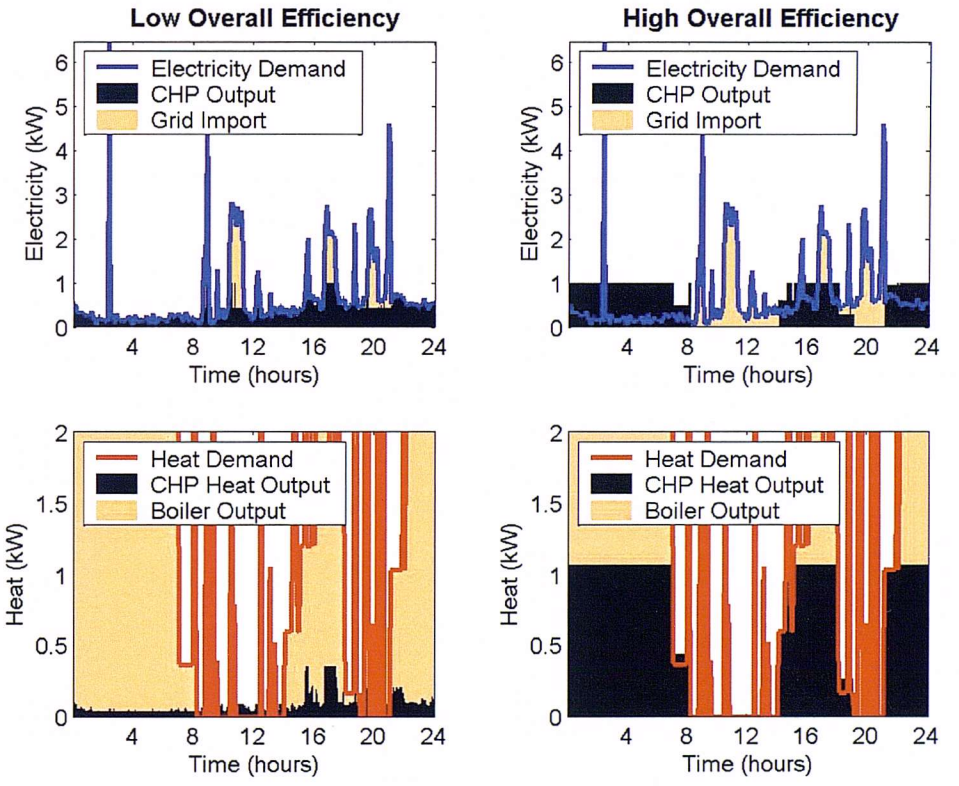



**Figure 46: Comparison of Low and High Overall Efficiency System Optimal Operation Schedule for SOFC-Based Micro-CHP**

On the whole the three lower electrical efficiency micro-CHP systems exhibit predictable sensitivity with regard to changes in overall efficiency. The highest electrical efficiency system (SOFC-based micro-CHP) responds quite differently. Its economic case is hindered by the increased thermal output associated with high overall efficiency just as much as it is helped by it, because it is able to profit when producing electricity only. It can also continue to deliver emissions reductions across the range of overall efficiencies, although

these are significantly reduced at low overall efficiency values when compared to what is possible at high overall efficiency.

Regardless of this anomaly, arguably the best SOFC-based system is the one with highest overall efficiency because it presents high economic value and admirable emissions reduction. This result is consistent across all technologies, and system developers should usually aim for best possible thermal design to maximise thermal and overall efficiency. Methods such as pinch technology can be employed to study and optimise heat exchange arrangements to achieve this high thermal efficiency, as demonstrated in Wallmark (2004), but such studies are beyond the scope of this thesis. The fact that very high electrical efficiency systems can continue to present reasonable economic value at low overall efficiency (and subsequent sub-optimal emissions reductions) is a concern for policy makers, and it may be possible that minimum standards regulation are employed to ensure high overall efficiency systems. This issue is discussed in relation to policy support in Chapter 9.

### 8.2.2 Part Load Efficiency

A similar issue to overall efficiency is that of **part load efficiency**. Part load efficiency could be important for micro-CHP systems for a number of reasons. Firstly, the competing boiler system is assumed to be fully modulating. This means that it is assumed to be able to reduce its $kW_{th}$ output down to close to zero thermal power in an efficient manner. Through inspection of the nature of residential demand (see section 2.1) it is apparent that demanded heat or power is often at low $kW_{th}$ levels, indicating that an optimal operating strategy could entail frequent part load operation. This raises questions about the importance of the ability of micro-CHP systems to modulate efficiently.

For this study, part-load efficiency is defined as electrical and overall efficiencies over the load range of $0.2kW_e$ to $0.5kW_e$. Efficiencies over the upper load range (i.e. $0.5kW_e$ to $1.0kW_e$) are held constant at central estimate values in this analysis. Technically, this translates to varying the ability of the micro-CHP system to modulate efficiently. If the system is required to operate frequently over this range of outputs, the ability to do so efficiently could be valuable and result in environmental benefits.

There is significant differentiation between technologies in terms of part load operation. Electrical efficiency for the engine-based technologies is highest at close to full throttle, at an output called the "design point". Departures from this design point can result is significant reductions in performance, as is apparent in the internal combustion engine

steady-state electrical efficiency curve in Figure 6. On the other hand fuel cells have relatively high part load electrical efficiency. Indeed the net direct current output of a fuel cell stack (without any balance of plant) typically exhibits higher part load electrical efficiency than full load electrical efficiency. The addition of balance of plant, which usually has predominant effects at low output levels, can reduce the system part load efficiency. Nevertheless the fuel cell systems investigated in this research have higher part load efficiency than the engine-based systems. Part load thermal efficiency is also potentially an important technology characteristic although the technologies do not differ so much in this regard, with all systems being subject to the losses associated with heat exchangers etc. The relative temperature of operation of each technology type does impact upon thermal efficiency, but this issue is better captured in the analysis of overall efficiency of section 8.2.1.

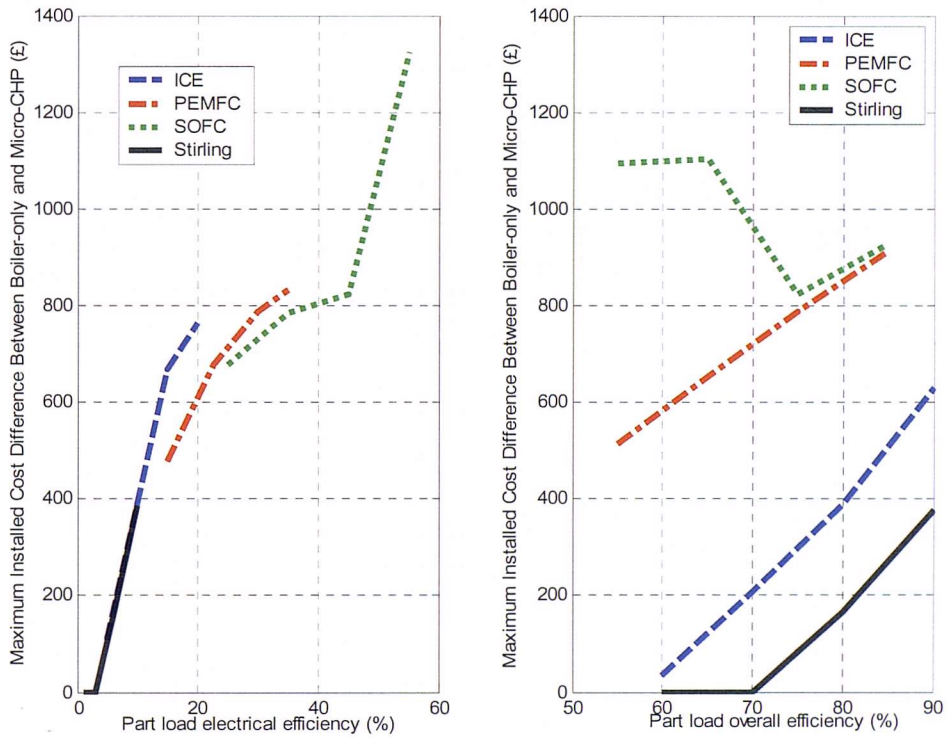



**Figure 47: Sensitivity of Maximum Installed Capital Cost Difference Between Boiler-only System and Micro-CHP Systems (£) to Part Load Electrical and Thermal Efficiencies**

Inspection of Figure 47 reveals a strong dependence of system value on part-load electrical efficiency, and a similar result between part-load overall efficiency and full load overall efficiency (investigated above). The economic result is largely mirrored in the $CO_2$-related result presented in Figure 48.

In the part-load electrical efficiency curve, relative value increases rapidly in the range of 5% to 20%, levels out somewhat, and then increases rapidly again for values above 45%. Notwithstanding the influences of technical difference between investigated systems (i.e. up-time, start cost, etc), this situation corresponds to the trade off between thermal constraints and the ability to access value by producing electricity. For example, as part-load electrical efficiency decreases, more heat is produced by the system, resulting in rapid decline in system value. At the other end of the curve, where part-load electrical efficiency values above 45% result is significantly better performance, similar factors are at work. In this case the high electrical efficiency implies a larger portion of the input thermal energy (i.e. fuel) is converted to electricity, and therefore a smaller portion is converted to heat (i.e. a lower part-load heat-to-power ratio). Overall this corresponds to previous results presented in Chapters 6 and 7; the lesser heat output implies the system is not so constrained regarding its operation. This, combined with the ability of the system to produce electricity at a cost competitive with that of centralised electricity (i.e. the residential tariff or buyback price), translates to rapidly increasing system value.

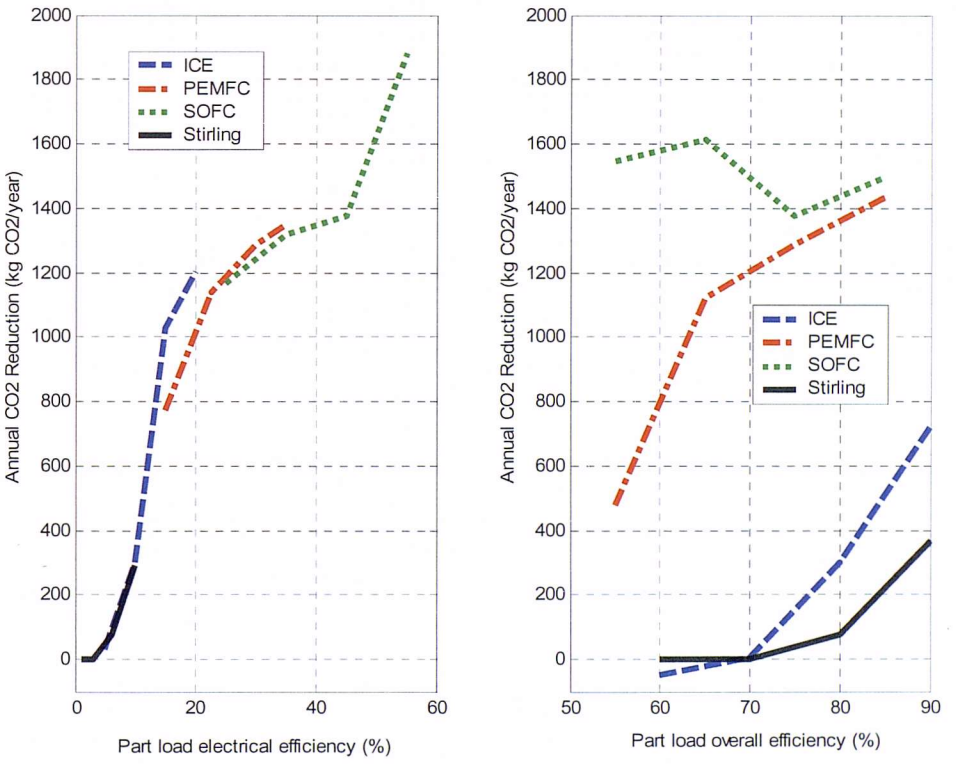



**Figure 48: Sensitivity of Annual $CO_2$ Reduction to Part Load Electrical and Thermal Efficiencies**

The economic result regarding part-load overall efficiency in Figure 47 closely mirrors the result for full load overall efficiency, and the reader is directed to section 8.2.1 for a

discussion of the reasons driving this outcome. The $CO_2$-related result, however, exhibits some difference in sensitivity to part-load and full-load overall efficiency. Whilst the engine-based systems are somewhat similar to the full-load overall efficiency result, particularly the SOFC-based system $CO_2$ result does not appear to depend upon part-load overall efficiency. The reason for this result is that the SOFC-based system is able to operate more frequently in the upper load region (i.e. 0.5$kW_e$ to 1.0$kW_e$). It is able to do this because it has relatively lower thermal output than the other technologies, and is therefore not so constrained at times of low thermal demand and can continue to operate (i.e. the now-familiar low heat-to-power ratio advantage).

In general it is clear that high part load electrical efficiency is a very important characteristic for all micro-CHP technologies, and part load thermal efficiency is very important for all systems except those with very low overall heat-to-power ratio (i.e. SOFC). This result indicates an engineering challenge regarding improving the performance of prime mover and particularly balance of plant components at extremely low output levels. Many engineering approaches focus on optimising operation of a system at a "design point" or at nameplate capacity. Whilst such approaches are also important, these results suggest that there may be a trade-off between efficiency at peak load and part load (with regard to system design) that could increase the value and reduce environmental impacts of micro-CHP systems.

### 8.2.3 Thermal Demand Load Factor

The method of delivery and control strategy for space heating could also have a significant impact on micro-CHP economic and environmental performance. Results relating to this issue presented here have been published by the author in Hawkes et al. (2007).

Thermal delivery systems differ amongst dwellings and between countries. In the UK the vast majority of central heating is hydronic (i.e. based on heated water circulation). Heat is often delivered to a space via wall-mounted radiators at relatively high temperatures around 75°C, and sometimes via underfloor heating systems at around 40°C. Radiator-based systems are typically faster at heating a space, although this depends on the nature of the space. Underfloor systems are slower, and a designed to operate more continuously, resulting in a smoother heat demand profile. Other countries such as the USA and Canada employ arrangements such as forced air systems which use a blower to force air over heated components and then through ductwork to deliver it to the space. Forced air systems are not considered in this thesis because they are rare in the UK

residential sector. The differences between radiator and underfloor heating, in terms of the impact on thermal demand profiles, can be explained by way of a **thermal demand load factor** over the heating season. Thermal demand load factor is defined as the average thermal demand divided by the peak thermal demand for space heating, and is a measure of the smoothness of thermal demand. Because each micro-CHP system has different thermal characteristics and response speed, thermal demand load factor is likely to be an important aspect of design. Whilst this parameter is not in itself an obvious aspect of micro-CHP system design (it relates more to dwelling's thermal delivery system), it does have important ramifications for their design and control. For example, micro-CHP systems may be designed to deliver thermal energy at a particular temperature, or with specific ramp characteristics, and control systems may be designed to interact with particular heat emitters within the dwelling.

Micro-CHP systems can be differentiated according to how appropriate they are for particular thermal demand profile shapes. Engine-based systems are generally able to start rapidly, but have a higher heat-to-power ratio than most fuel cell systems. Solid oxide fuel cell systems operate at high temperatures, and thermo-mechanical issues (e.g. mismatch of thermal expansion coefficients at the interfaces of materials within the stack) may require controlled or infrequent heat-up/cool-down operations. However, once they have completed a controlled start-up, they have lower heat-to-power ratio. These technical issues suggest that each type of micro-CHP system may be appropriate for particular control strategies and further warrants an investigation of thermal demand load factor. Therefore a variety of thermal demand profiles, corresponding to various thermal demand load factors as discussed in the following section, are chosen for investigation herein. These space heating demand profiles must be generated for this analysis, and the method by which this is achieved is described below, followed by dissection of results.

#### *8.2.3.1 Generating Space Heating Profiles with Different Load Factors*

A dynamic building simulation computer program, TAS from EDSL (2004) was applied by Croxford in Hawkes et al. (2007) to generate detailed demand profiles for a nominal home heated with different methods. These heat demand profiles are used herein as inputs for this sensitivity analysis.

Hawkes et al. (2007) investigated a design of home that was considered to be widespread in the building stock and also that had sufficient demand to merit the use of micro-CHP technology was chosen. The characteristics of this house can be seen in Table 17.

Aggregate thermal demand of this home is approximately equivalent to the existing terrace house in Table 1.

| | |
|---|---|
| Ground floor | Kitchen, 2 reception rooms, 1 toilet |
| First floor | 2 Bathroom, 1 toilet, 3 bedrooms |
| Roof | Pitched roof, with unheated attic space |
| Material description | Each room is considered as a zone |
| | Each major room has at least one window |
| | Each internal door considered as open with a fraction 0.1 |
| | Air infiltration throughout = 1.0 air changes per hour |
| | Single glazing throughout |
| | No curtains throughout |
| | Walls are cavity walls( with 50mm air gap) |
| | Roof space heavily insulated (200mm of insulation) |

**Table 17: Building Description based on Hawkes et al. (2007)**

To model a slow response heating system such as underfloor heating an extra zone was used underneath the floor and the heat load required to keep the room above at the resultant temperature of 20°C was registered as the heat demand.

The English House Condition Survey (ODPM (2003)) indicates that the national average floor area is 85 $m^2$, with nearly half of the southern England housing stock containing three bedrooms. The dwelling model assumes two storeys with three bedrooms and a floor area (ground and first floors) of about 75 $m^2$. The dwelling was assumed to have the living room and main bedroom facing south. The living room had a floor area of almost 16$m^2$ and the main bedroom of 9.4$m^2$. The infiltration rate was assumed to be 1 air change per hour, which corresponds to a typical house with original single glazing. In all cases the heating was assumed to provide a resultant temperature of 20°C during heating hours. The second reception room, the lobby and corridor areas were considered unoccupied and unheated. In reality the heating might be on at similar levels to the sitting room but at different occupancy levels. The overall effect on energy consumption was considered appropriate in this case. Internal heat gains are based on occupancy at 2.5 persons, lighting set to be on in the late evenings and early mornings with the exact heating and occupancy schedules available in Hawkes et al. (2007). The assumed dwelling and occupancy profiles remain the same for all four cases considered in this analysis.

The resulting base model can then be compared with models employing different types of heating system which in turn will generate different thermal demand profiles. The four models developed in Hawkes et al. (2007) were:

1. Case 1: base model with assumed ideal central heating operating at the hours specified in Hawkes et al. (2007).
2. Case 2: Base model with ideal underfloor heating operating in the same hours as case 1.
3. Case 3: Base model with ideal underfloor heating operating constantly in winter.
4. Case 4: Base model with 3k$W_{th}$ underfloor heating system operating constantly in winter.

The base case has been deliberately modelled as a typical example of what might be found in the housing stock of the UK. There are many homes that are better insulated and better maintained, but the model considered here is an example of slightly above-average efficiency, with annual space heat demand at approximately the UK average. New or refurbished energy efficient homes could be expected to have a similar profile of energy use but of a different magnitude.

Examples of the resulting space heating demand profiles are displayed in Figure 49 for one day in winter, for cases 1 and 4. The "slow" nature of heating in case 4 is apparent, as this case requires more constant heating with relatively small peak demands as opposed to heating with significant thermal capacity demands in case 1. Domestic hot water loads are assumed to be fixed throughout this investigation, and are not included in Figure 49. Note that DHW contributes to significantly more volatility in overall thermal demand than is displayed in Figure 49.

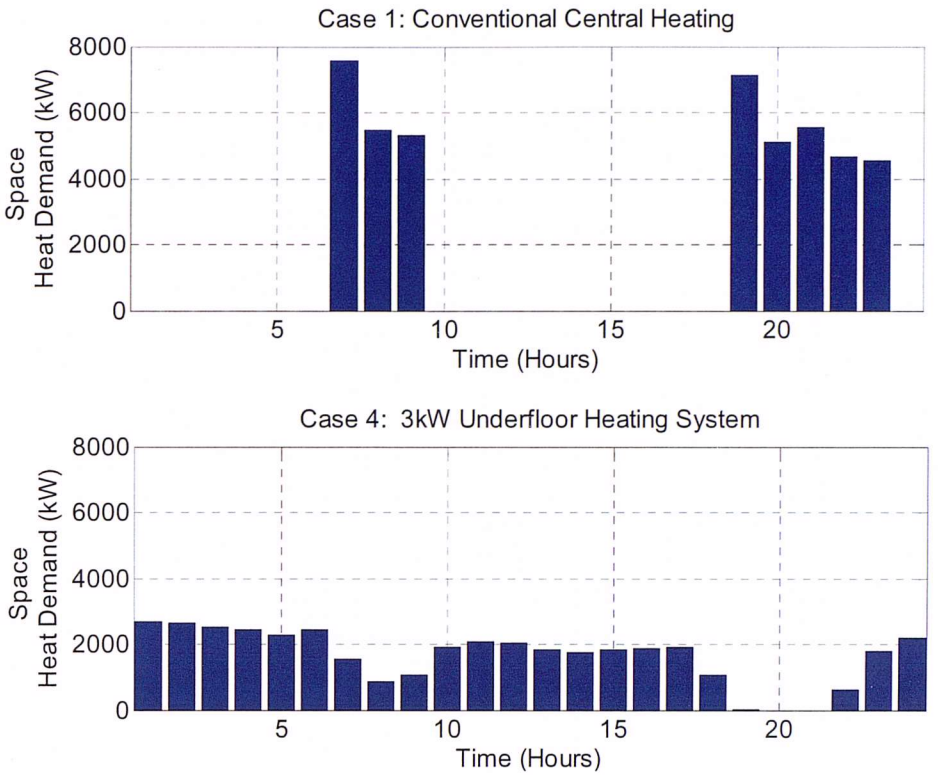



**Figure 49: Comparison of Two Generated Space Heating Demand Profiles – Case 1 Low Load Factor Heating and Case 4 High Load Factor Heating**

### *8.2.3.2 Results of Thermal Demand Load Factor Sensitivity*

The four space heating demand profile cases described above are used as input to the modelling framework (after disaggregation to 5-minutely values, and addition of volatile DHW components). Electricity consumption was assumed to be identical to an "existing terraced house" as per Table 1, and all other parameters were as per their central estimate values. The model is used to determine the primary economic and environmental metric; relative economic value, and annual $CO_2$ emissions reduction in comparison with the defined reference system. Results from this analysis are discussed below.

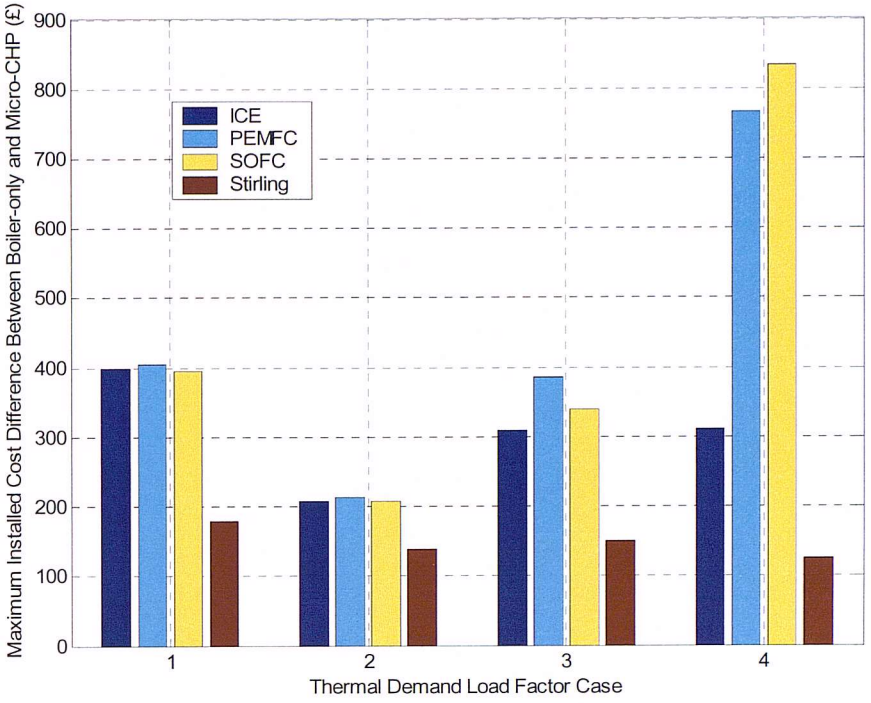



**Figure 50: Sensitivity of Maximum Installed Capital Cost Difference Between Boiler-only System and 1kW$_e$ Micro-CHP Systems (£) to Thermal Demand Load Factor**

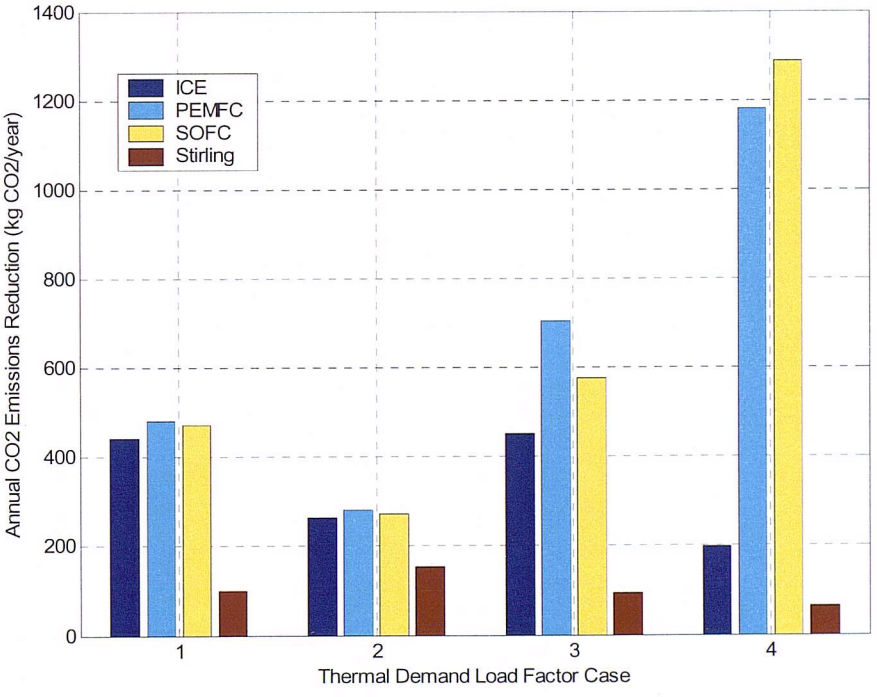



**Figure 51: Sensitivity of Annual $CO_2$ Emissions Reduction (kg $CO_2$/year) for 1kW$_e$ Micro-CHP Systems to Thermal Demand Load Factor**

Figure 50 shows the relation between each space heating case and relative economic value for each of the four micro-CHP systems. For fuel cell-based systems, whilst the first three

cases are somewhat comparable, "case 4" (the $3kW_{th}$ underfloor heating system) shows far-and-away the best economic result. For the engine-based systems, "Case 1" (conventional radiator heating) is the best economic match, although the difference is only marginal for the case of the Stirling engine, and the ICE performs almost as well in cases 3 and 4. Overall this indicates that engine-based systems are slightly better suited to low thermal load factor situations, and fuel cell-based systems are considerably better suited to high thermal load factor situations.

Figure 51 displays the relation between annual $CO_2$ reduction and the thermal demand load factor. This largely reflects the economic result, with the fuel cells performing well at high load factor and the engines exhibiting a more mixed results, with the ICE-based system performing well in case 1 and 3, whilst the Stirling engine provided a consistent result across the cases.

Overall a "slow" space heating demand, based on a $3kW_{th}$ underfloor heating system running constantly in winter (i.e. case 4 heating scenario), is most suitable for coupling with the fuel cell micro-CHP systems. This is because it provides a better economic result, and substantial $CO_2$ emissions reduction when compared with the scenario where thermal demand load factor is lower. Additionally, the slower heating demand is a better technical match for the fuel cell technologies, which could benefit from avoidance of load and thermal cycling. Therefore, from an economic, environmental, and technical point of view, fuel cell systems (or any low heat-to-power ratios system) are better suited to meeting smooth thermal demand profiles. This is because they are able to operate consistently under such demand profiles, because their thermal output is not so large as to require modulation.

The engine systems exhibited a more mixed result. In general their performance is better when coupled with a volatile low load factor thermal demand, but only marginally. Technically the engine-based systems are probably better suited to the low load factor situation. This is because existing systems are designed for on-off operation only, and will therefore benefit from sufficient instantaneous thermal demand to justify operation at nameplate capacity. A low thermal demand load factor offers such opportunities.

### 8.2.4 Ramp Rate

Following on from the issues discussed above, there is another technical characteristic that could be related to the ability of a micro-CHP technology to efficiently meet a given energy demand profile. The rate at which the prime mover can alter its output level, or **ramp rate**,

influences the ability of a unit to meet volatile electrical or thermal demands, and has important control implications. For example, if thermal and electrical demand occur simultaneously it would be beneficial for a SOFC-based micro-CHP to respond as indicated by the analysis in section 5.2.1 (Table 10). However, a constraint on ramp rate may prevent this response, thereby reducing the value of the micro-CHP system. Additionally, likewise to the issues associated with thermal demand load factor discussed above, ramp rate can relate to mechanical stresses caused by thermal gradients across technology components. This reinforces the proposition that maximum ramp rates could be an important micro-CHP constraint.

Appropriate ways in which to characterise ramp varies between engine-based and fuel cell based technologies. In order to furnish comparison a universal metric is adopted here; rate of change of electrical power output in $kW_e$ per minute. Whilst this is a reasonable metric for assessment of the engine-based systems, the fuel cell systems design and development focus around another metric; current density. A relatively simple relationship between current density ($Amps/cm^2$) and load factor[29] (i.e. power) can be formulated. An example of such a relationship is displayed in Figure 52 from Hawkes et al. (2006). This curve may be utilised to interpret ramp-related results for the anode-supported SOFC micro-CHP system described in Hawkes et al. (2006), but individual developers, including PEMFC developers, should formulate their own relationship for their specific technology in order to ensure relevance of results.

[29] Load factor is defined as the instantaneous output divided by the rated nameplate capacity of the prime mover. For example, if a prime mover of $2kW_e$ capacity were operating a load factor of 0.6, its output would be $1.2kW_e$.

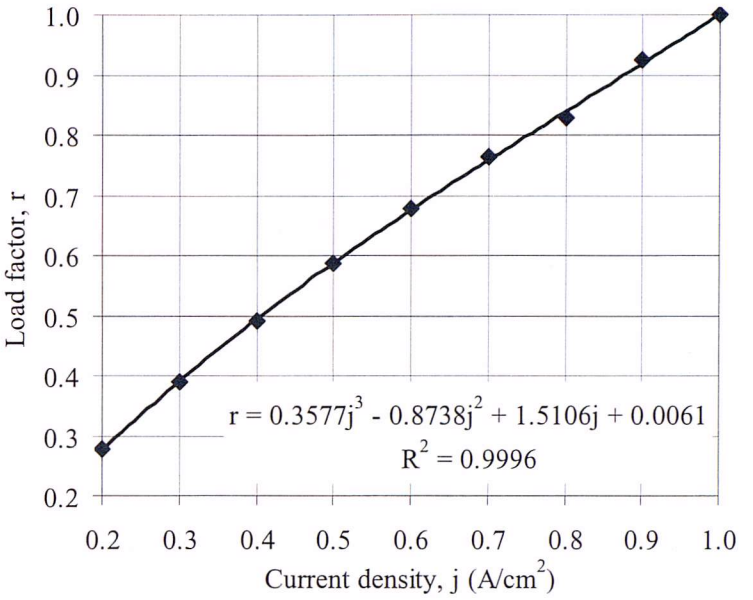



**Figure 52: Relationship Between Current Density and Load Factor[30] for SOFC Stack from Hawkes et al. (2006)**

The range of ramp rates investigated range from 0.005 to 0.2kW$_e$/minute. As the time-step employed in these studies is 5-minutes per period, these limits correspond to a range of 25W$_e$/period through to 1kW$_e$/period. Therefore the largest ramp limit imposed is essentially the situation where the system is unconstrained in terms of ramp. Ramp limits are imposed in both direction (i.e. ramp upward is constrained to the same extent as ramp downward).

Figure 53 and Figure 54 display the sensitivity of the economic and environmental result to a range of ramp rates. Both of these figures plainly indicate that variation in the maximum ramp rate of the micro-CHP system does not have a significant influence on either the economics or the environmental credentials for any of the investigated micro-CHP systems. Only at very low maximum ramp rates below 0.02kW$_e$/minute is any influence discernable, and even then it is minor, corresponding to less than 5% of the value of the fuel cell based micro-CHP systems.

[30] Load factor is defined here as the instantaneous output of the stack (kW$_e$) divided by its nameplate capacity (kW$_e$).

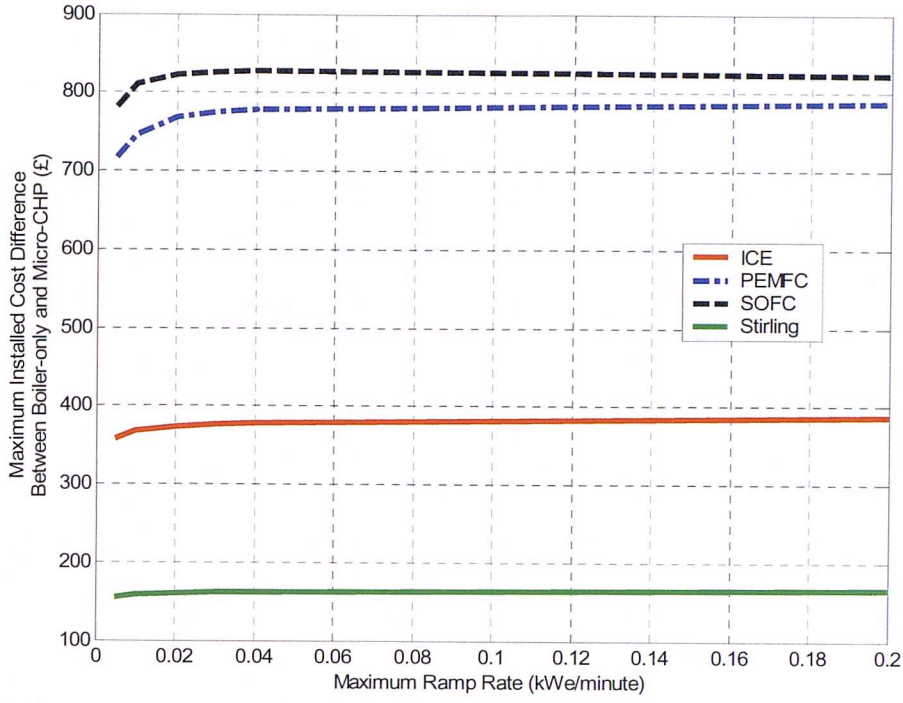



**Figure 53: Sensitivity of Maximum Installed Capital Cost Difference Between Boiler-only System and Micro-CHP Systems (£) to System Maximum Ramp Rate ($kW_e$/minute)**

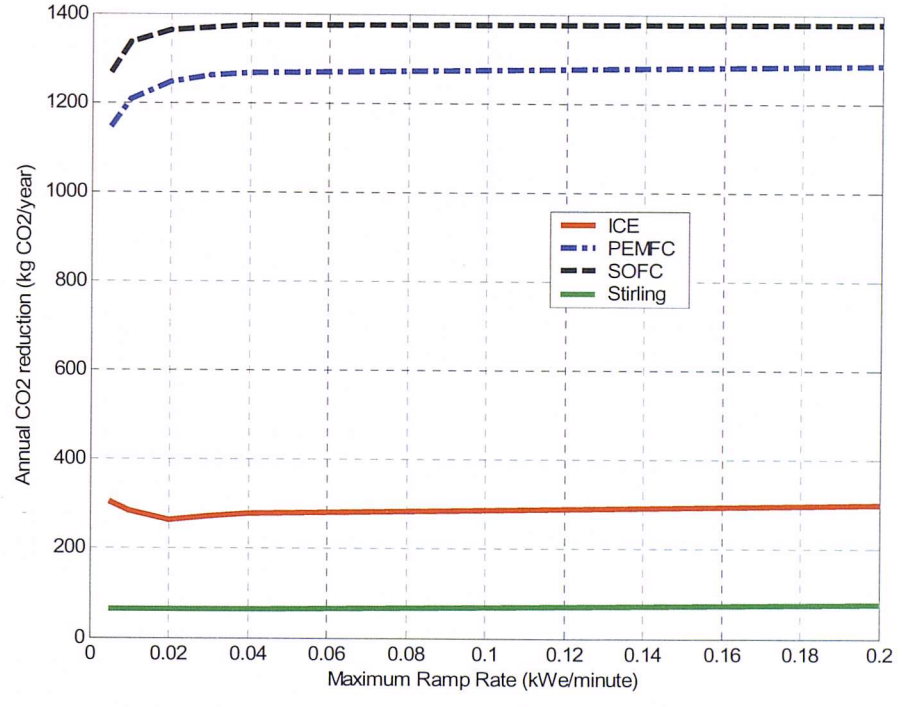



**Figure 54: Sensitivity of Annual $CO_2$ Emissions Reduction (kg $CO_2$/year) for Micro-CHP Systems to System Maximum Ramp Rate ($kW_e$/minute)**

This result indicates that system developers should not be concerned about creating systems that can ramp up or down rapidly. As long as systems can ramp up and down at

greater than 25$W_e$/minute, and an intelligent control system is in place, the actual maximum rate of ramp is largely irrelevant. It should be noted that this result is a product of the unit commitment optimisation method employed, which implicitly has future knowledge of demand. Therefore a system with a tightly constrained ramp limit can begin to ramp up well before the demand occurs, and will do so if such action is economically beneficial. For space heating demands this artefact of the modelling approach is justifiable because space heating typically operates on a predefined schedule, implying that the system can prepare to respond in good time. In further defence of the modelling outputs, the operational strategy of the unit for one tight and one loose ramp limit for a SOFC-based micro-CHP system is displayed in Figure 55.

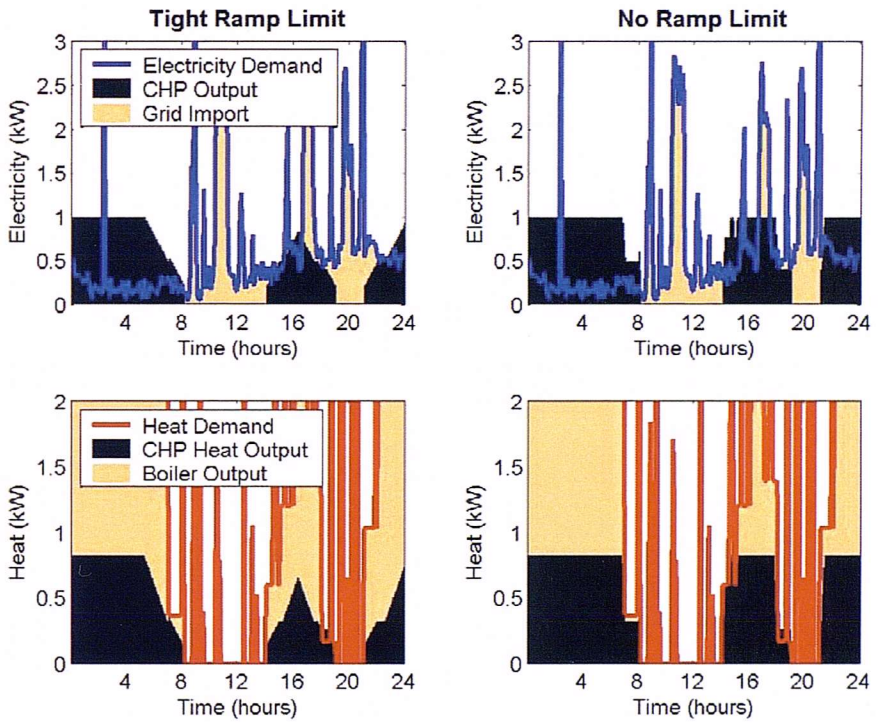



**Figure 55: Optimal Operation Schedule for 1k$W_e$ SOFC-Based Micro-CHP Showing Generator Response for Tight Ramp Rate Limits Versus No Ramp Rate Limits on a Shoulder Season Day**

The optimal operating strategy indicated in Figure 55 for each maximum ramp rate limit appears achievable where simple learning/predictive control is applied. For example, where tight ramp limits are imposed the system responds slowly during prolonged thermal demand, but the dispatch signal could still plausibly be based on thermal demand alone. This situation is identical for the case of no ramp rate limits in that the system responds to prolonged thermal demand, which could be relatively easily predicted via external temperatures (which can be measured), and household U-value (which can be learned by an adaptive control system), and desired internal temperature which is set by the dwelling

occupier. In both cases the peaky demands (which are DHW demands) are ignored. Overall the implied control strategy for the unit is relatively simple and achievable, and the optimisation routine is therefore not producing results that are unattainable in practice.

### 8.2.5 Start-up and Shutdown Cost

All existing micro-CHP systems use electricity and/or fuel to start or stop operation. For example, energy can be used to prime and heat the generation device and to power up balance of plant (BoP) components prior to prime mover start-up. Likewise, micro-CHP systems must be stopped in a managed fashion, and balance of plant such as extraction fan and hydronic system pump will keep running for some time after prime mover stop in order to deliver remaining thermal energy to the space or domestic hot water tank. These start-up and shut down loads are expected to be larger than equivalent loads for the reference boiler system due to higher thermal mass and greater interdependency between BoP components in micro-CHP systems. For all micro-CHP, electricity and fuel are usually consumed during start-up and electricity is consumed during shutdown. Fuel cell based systems start/stop procedures could be more complex and may involve the consumption of additional fuel and electricity because BoP components are required to start/stop in a particular order, and rapid thermal cycling of the fuel cell stack may be undesirable.

Very little reliable data exists regarding the characteristics of system start/stop across a range of micro-CHP devices. A recent field trial of primarily Stirling engine based micro-CHP in the UK by the Carbon Trust (2007) found that these devices consumed roughly 100 Watts of electricity for a few minutes for start-up, and around 100 Watts for several tens of minutes during shutdown. A report of the IEA Annex 42 on residential cogeneration by Arndt et al. (2007) presented an experimental investigation into micro-CHP performance including a set of power consumption/production curves for cold and warm starts of Stirling engine, ICE, and PEM fuel cell systems. Table 18 presents estimates of start/stop energy consumptions based on the Carbon Trust field trial and Annex 42 reports. Start-up consumptions are based on a cold start.

| | Start-up Electricity Use (Wh) | Shutdown Electricity Use (Wh) | Start-up Gas Use (Wh) | Shutdown Gas Use (Wh) |
|---|---|---|---|---|
| **1kW$_e$ Stirling Engine** | 8.3 | 25 | 500 | 0 |
| **4.6kW$_e$ ICE** | No data | No data | 1667 | No data |
| **4.6kW$_e$ PEMFC** | No data | No data | 6000 | No data |

**Table 18: Start-up and Shutdown Electricity and Gas Consumption for Key Micro-CHP systems**

As data is limited, where specific data is not available estimates are used in this analysis, and where necessary start-up/shutdown consumptions for larger capacity prime movers (i.e. 4.6kW$_e$) are scaled to be more applicable to the systems analysed (i.e. 1kW$_e$). It is assumed that start-up electricity consumption is small for all systems, although slightly larger for fuel cell based systems due to greater complexity of their BoP (e.g. start-up of fuel reforming or sulphur/CO removal systems). Shutdown electricity consumption is assumed to be more substantial, based on the premise that the BoP continues to run in order that the energy stored in the thermal mass of the device can be (partially) harvested. Based on Table 18, estimates of start-up gas consumption (i.e. fuel energy used to heat up the prime mover and BoP that cannot be recovered when the system is shut down) are 500W$_{th}$h for the engine-based systems and 1500W$_{th}$h and 2000W$_{th}$h for the PEMFC and SOFC-based systems respectively. Shutdown gas consumption is assumed to be zero for both engine-based devices and approximately 500$_{th}$W for fuel cell based devices, reflecting the fact that fuel cell system balance of plant may require controlled consecutive shutdown, resulting in additional consumption. As these estimates are recognised to be approximate, wide margins of sensitivity are investigated.

Start-up and shutdown costs utilised are based on the electricity and gas tariffs presented in section 3.2 combined with the energy consumption estimates presented above. It is assumed that if a system starts, it must also shut down, so start-up and shutdown costs are combined into one value, which is referred to as the "start-up" cost in the rest of this analysis. It is also assumed that start-up and shutdown energy consumptions are in addition to corresponding energy consumptions experienced by boiler-only systems, which are in turn assumed to be subsumed in the electricity and thermal demand profiles utilised. Values and ranges energy consumptions and associated costs are displayed in Table 19. All values are relative to the start-up/shutdown consumption of the reference boiler system.

| | Range of Start-Up/Shutdown Electricity Consumption (W$_e$h) | Range of Start-Up/Shutdown Gas Consumption (W$_{th}$h) | Range of Start-up/Shutdown Costs (£) |
|---|---|---|---|
| **Boiler** | - | - | - |
| **1kW$_e$ ICE** | 8.3 - 50 | 200 - 2000 | 0.005 - 0.055 |
| **1kW$_e$ PEMFC** | 16 - 100 | 400 - 3200 | 0.01 - 0.08 |
| **1kW$_e$ SOFC** | 16 - 100 | 400 - 3200 | 0.01 - 0.08 |
| **1 kW$_e$ Stirling** | 8.3 - 50 | 200 - 2000 | 0.005 - 0.055 |

**Table 19: Ranges of Energy Consumption and Corresponding Start/Stop Cost for Key Micro-CHP Technologies**

The modelling framework is applied to consider each micro-CHP system under the energy consumption/cost combination ranges presented in Table 19. The results of this

investigation are presented below in Figure 56 and Figure 57 which map the case of $1kW_e$ systems operating in the median existing bungalow of Table 1.

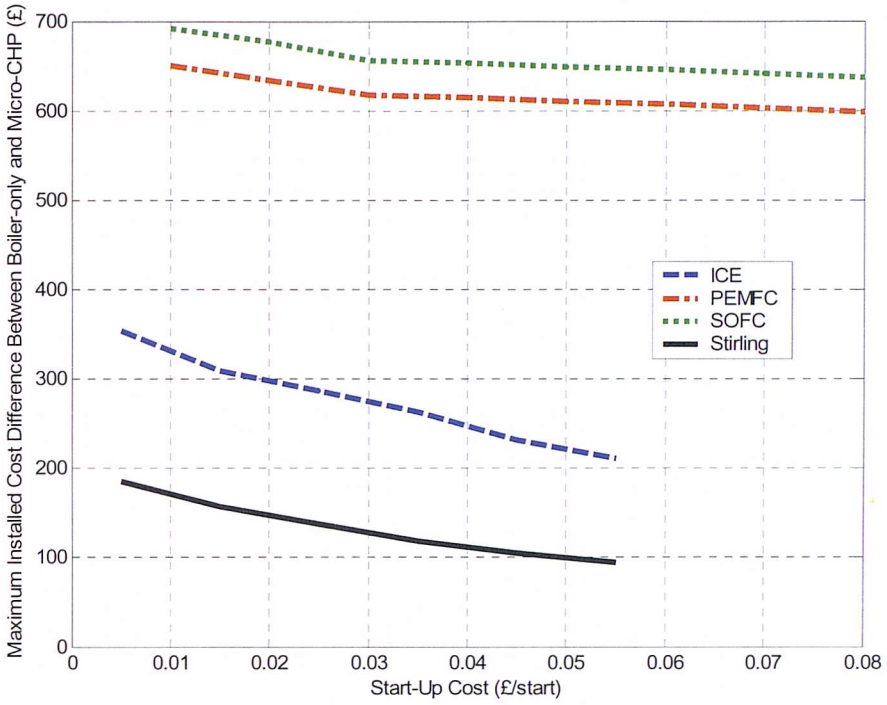



**Figure 56: Sensitivity of Maximum Installed Capital Cost Difference Between Boiler-only System and Micro-CHP Systems (£) to System Start-Up Cost (£ per start)**

Figure 56 indicates that the relative value of engine-based micro-CHP systems is influenced to a greater extent by changes in start-up cost than the fuel cell based systems (i.e. the engine-based systems plot gradients are larger than that of the fuel cell systems). Each engine-based system loses more than a half of its value between the very low and maximum start costs investigated. Likewise, in Figure 57, annual $CO_2$ emissions reduction achieved is more adversely affected in the case of engine-based systems.

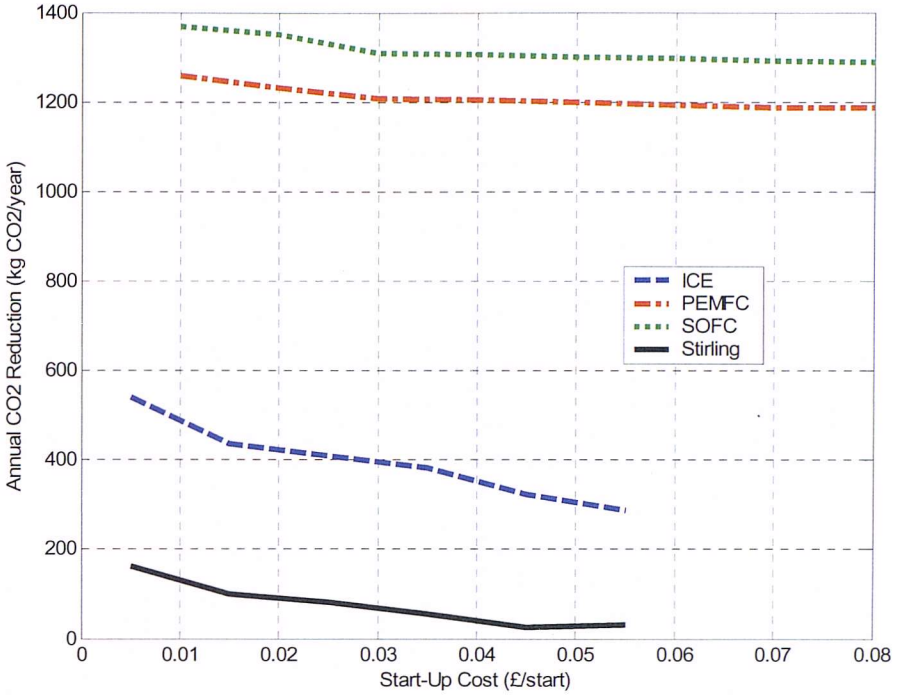



**Figure 57: Sensitivity of Annual $CO_2$ Emissions Reduction (kg $CO_2$/year) for Micro-CHP Systems to System Start-Up Cost (and associated energy consumption) (£ per start)**

In order to better understand the reasons behind this result, the number of start/stop operations per year under the minimum and maximum start-up cost scenarios are explored in Table 20. The influence of increasing start-up cost is apparent; all systems reduce the number of start/stop operations in response to increasing cost of such actions. Once again a difference between engine-based (higher heat-to-power ratio) and fuel cell based (lower heat-to-power ratio) technologies is clear. The low heat-to-power ratio systems are more able to avoid start/stop cycling because they are less thermally-constrained. This means they can turn down output to a sufficient degree such that thermal output does not impinge upon thermal demand constraints, and therefore the system can remain on.

| | ICE | PEMFC | SOFC | Stirling |
|---|---|---|---|---|
| **Number of Cycling Events at Minimum Start/Stop Cost** | 487 | 183 | 244 | 426 |
| **Number of Cycling Events at Maximum Start/Stop Cost** | 121 | 61 | 61 | 121 |

**Table 20: Number of Start/Stop Cycling Events per Year for Each Micro-CHP Technology, with respect to the Minimum and Maximum Start/Stop Costs Investigated**

Based on the assumption that start-up and shutdown energy consumption is greater in the case of micro-CHP systems than the reference boiler system, it is obvious that operating

strategy should attempt to avoid start/stop operations for better economic and environmental results. The extent to which this is possible depends upon the thermal demand in the dwelling, the heat-to-power ratio of the prime mover, the thermal capacity of the micro-CHP system, the turndown ratio of the system, and the predictive abilities of the operating strategy of the micro-CHP system. Whilst the information presented above is a useful guide to the influence of start-stop costs, and can inform system developers regarding the importance of producing systems with low start/stop costs, it is only one of several interrelated variables that bear upon the necessity to cycle the system. The following section investigates one of these related variables; turndown ratio.

### 8.2.6 Turndown Ratio

As discussed above in section 8.2.5, the importance of turndown ratio is linked to energy consumption during start-up and shutdown in the sense that a system that can turn down thermal output to a low level is more likely to be able to avoid switching off. In addition to this interaction, turndown ratio is also important in an operational sense; a system that can modulate is more likely to be able to match thermal or electrical demand, and thus it will have more options in terms of operating point with subsequent benefits to system value and possibly to $CO_2$ emissions reduction.

Figure 58 and Figure 59 present the sensitivity of case for investment and annual $CO_2$ emissions reduction to minimum operating point (i.e. a proxy for turndown ratio) for the four micro-CHP systems. Once again a clear differentiation is apparent between the technologies. The low heat-to-power ratio fuel cell based systems are much more resilient to poor turndown characteristics than the higher heat-to-power ratio engine-based systems. For example, the Stirling engine based system is unable to provide a positive case for investment if it cannot turn down below 0.4kW$_e$, whilst the fuel cell based systems retain marginal value above £600 even where they cannot turn down at all. The fuel cell based systems both exhibit relatively flat plots, with only very low turndown delivering significantly greater value and $CO_2$ reductions.

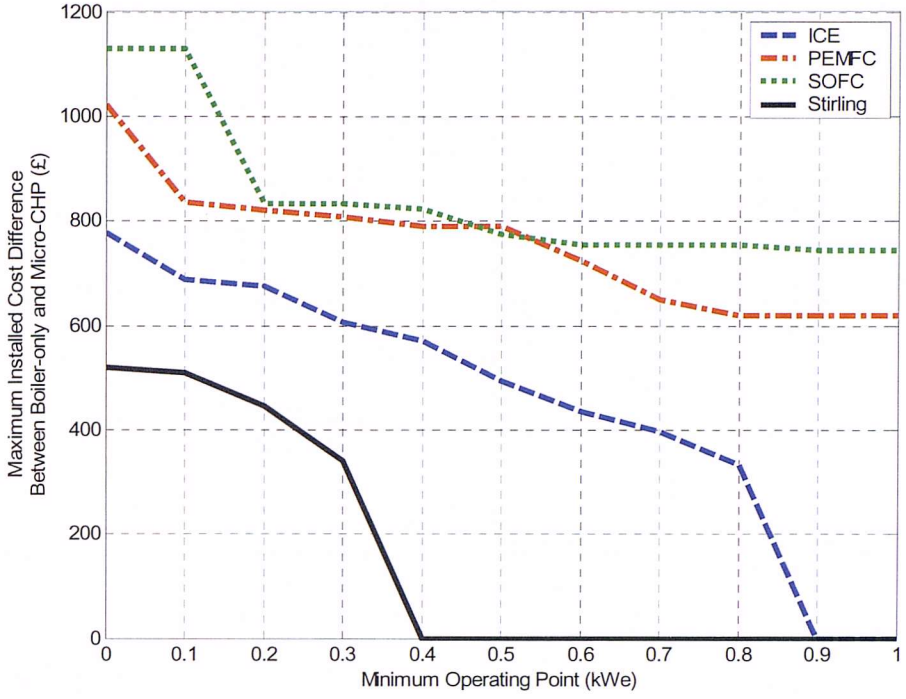



**Figure 58: Sensitivity of Maximum Installed Capital Cost Difference Between Boiler-only System and Micro-CHP Systems (£) to Turndown Ratio (kWe)**

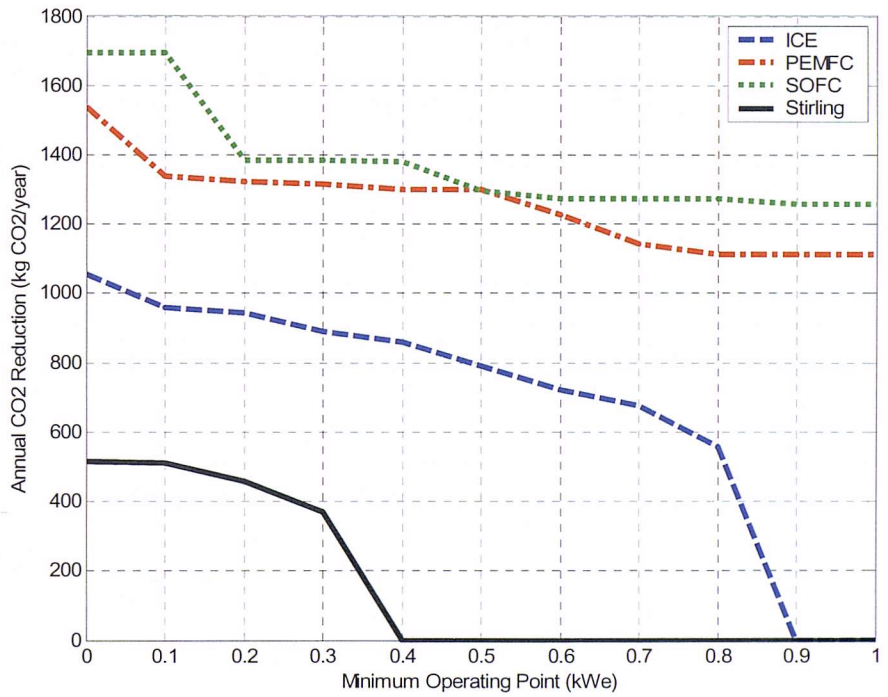



**Figure 59: Sensitivity of Annual $CO_2$ Emissions Reduction (kg $CO_2$/year) for Micro-CHP Systems to Turndown Ratio (kWe)**

The importance of turndown ratio apparent in Figure 58 and Figure 59 raise questions regarding the ability of micro-CHP systems to operate at low output power levels, and what

efficiency characteristics each prime mover type could exhibit during turndown. These questions are identical to those posed by results from the part-load efficiency study in section 8.2.2. Indeed turndown ratio and part-load efficiency are clearly closely related technical characteristics in terms of economic and environmental credentials of micro-CHP systems.

The majority of $1kW_e$ engine-based units in field trials and commercially available (in Japan) are not able to turn down at all. They offer on/off operation only. Whilst this engineering decision could have been taken for a variety of possible technical reasons, the results of this analysis suggest turndown should be considered as a valuable system characteristic, even if that turndown involved operation at a few selected set-points. It is an engineering challenge to produce systems capable of efficient turndown to extremely low output levels, where the conventional wisdom is that balance of plant (BoP) energy consumptions become dominant and system efficiency drops off rapidly. Should BoP components be improved to the point where turndown to near-zero output whilst maintaining efficiency is possible, particularly for fuel cell based systems, substantial additional value would become available to the owner/operator, arguably increasing the value of the unit to the developer. A corresponding $CO_2$ reduction result would also be achieved.

### 8.2.7 Minimum Up-Time

A further technical parameter that relates to start-stop control decisions is the minimum up-time of the prime mover. This is defined as the length of time, in minutes, that the prime mover must stay on for if it switches on. Technically it relates to durability of the system, where rapid thermal cycling can cause damage and should generally be avoided where possible, particularly for the case of fuel cell based systems. Minimum up-time constraints could also be imposed as a means of addressing other technical issues: For example, to prevent the owner/operator from cycling the unit because this can have negative economic and environmental consequences as discussed in section 8.2.5. This section considers sensitivity of performance to minimum up-time. Ranges of minimum up-times investigated relate to anecdotal evidence regarding the relative ability of each system to switch on/off rapidly. The engine-based systems are assumed to be able to cycle rapidly with minimum up-time between 5-minutes and 2-hours. Fuel cell based systems are assumed to cycle more slowly, with the range investigated being 5-minutes to 3.5-hours.

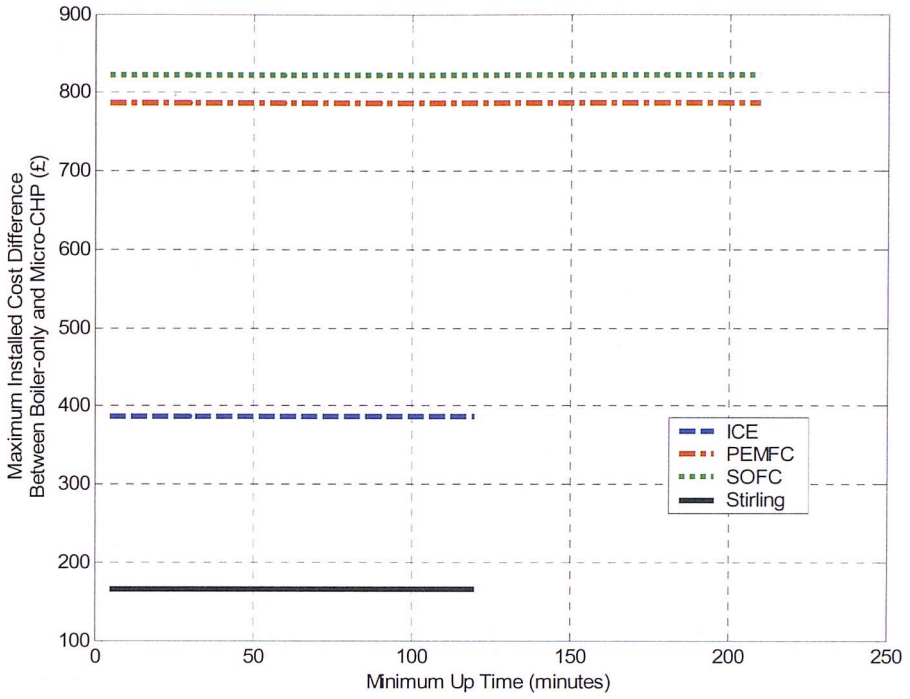



**Figure 60: Sensitivity of Maximum Installed Capital Cost Difference Between Boiler-only System and Micro-CHP Systems (£) to Minimum Up Time (minutes)**

As with other constraints contemplated in this chapter, minimum up-time imposes limits on the operating strategy options under the cost minimisation. Therefore one would expect a reduction in value of the systems as minimum up-time increases. Figure 60 and Figure 61 show the sensitivity of the primary economic metric and the $CO_2$ related result to variation in minimum up-time. Clearly this constraint has no impact at all on either performance metric; minimum up-time is irrelevant over the ranges investigated.

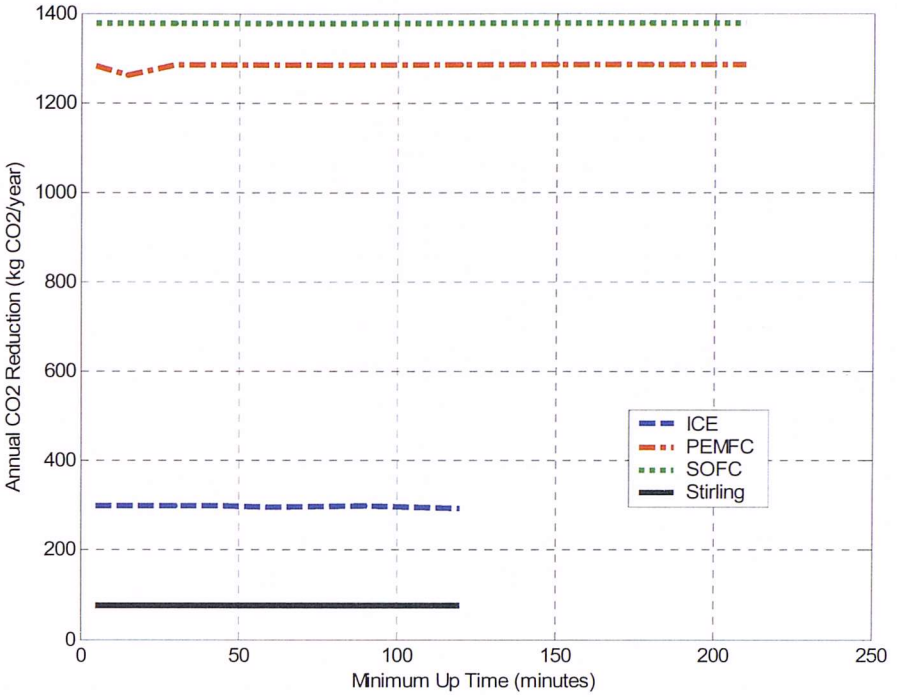



**Figure 61: Sensitivity of Annual $CO_2$ Emissions Reduction (kg $CO_2$/year) for Micro-CHP Systems to Minimum Up Time (minutes)**

To better understand the cause of this result the optimal operating strategy under very short and very long minimum up-time constraints is presented in Figure 62. In this case the minimum up-time for an ICE-based micro-CHP is plotted, and the longest minimum up time considered is extended to 5-hours in order to produce a discernable effect. When minimum up-time is greatly extended (to 5-hours) the system no longer switches on at approximately 16:00 hours, but otherwise the operating strategy remains the same. Even under this change, the marginal value of the micro-CHP system reduces by only £10.

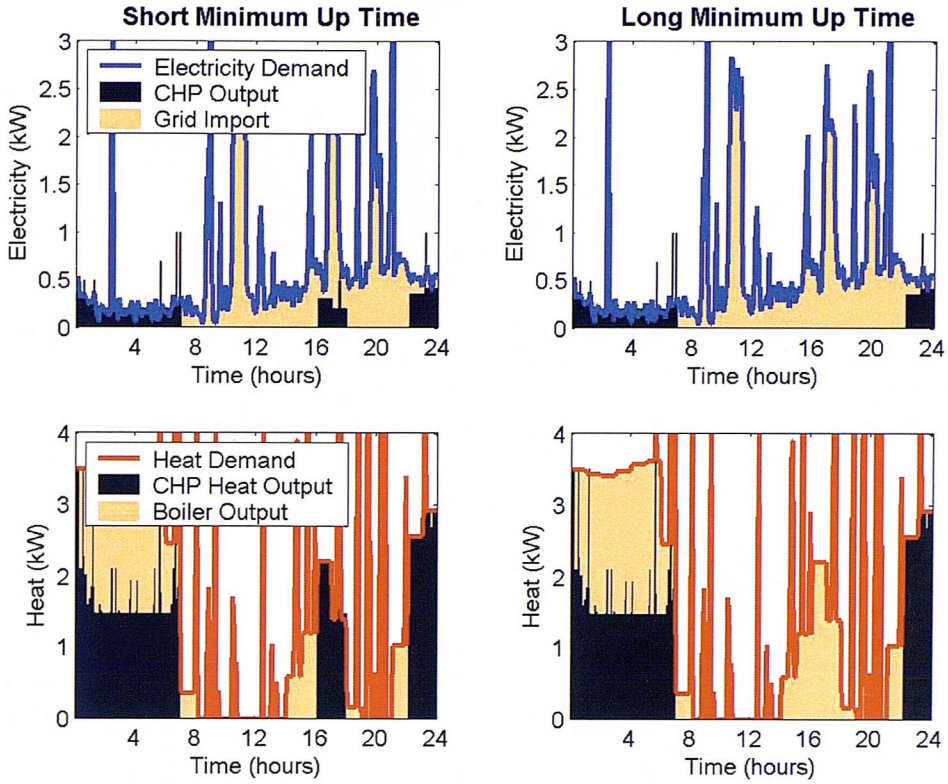



**Figure 62: Optimal Dispatch of an ICE-based Micro-CHP Under Short and Very Long Minimum Up-Time Constraints**

The reason for the lack of influence of minimum up-time can be further understood through consideration of the other constraints, and interactions between constraints. Foremost among these is the start-up cost of the prime-movers. The start-up cost was held constant at the non-zero central estimate values across this analysis of minimum up-time. Therefore the systems already had motivation to avoid start-up and shutdown, and the minimum up-time constraint did not add significant weight to this. To illustrate this point Figure 63 plots the primary economic metric for the case where start-up cost is set to zero. In comparison with Figure 60, this shows a more marked influence of minimum up-time, although overall impact is still very small.

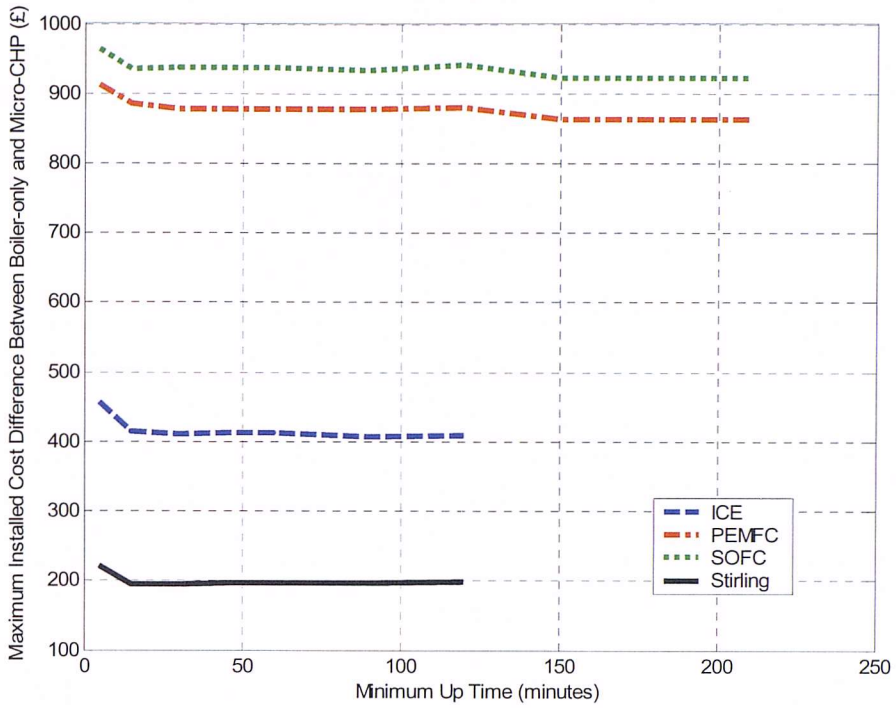



**Figure 63: Sensitivity of Maximum Installed Capital Cost Difference Between Boiler-only System and Micro-CHP Systems (£) to Minimum Up Time (minutes) for the Case of No Start-Up Cost**

Based on these results it may be concluded that achieving a short minimum up-time is unimportant in terms of either economic or $CO_2$-related performance. However, deliberately incorporating a significant minimum up-time into a systems control strategy could still be desirable due to its interaction with other technical aspects. Notably among these is avoiding the user rapidly cycling the unit, which could be associated with poor performance due to start-up/shutdown energy consumption, and could damage some systems.

### 8.2.8 Degradation

This sub-section investigates the potential for operational and thermal cycling damage to a fuel cell based micro-CHP system via "degradation" mechanisms.

Degradation is a characteristic of fuel-cell stacks. It is related to the electrochemistry of materials used in the stack and the fuel employed. Therefore it is a feature unique to fuel cells, once again setting them apart from engine-based micro-CHP, although this time in a negative sense. Whilst it is true that engine-based systems also lose efficiency with time, regular tuning can for the most part rectify this problem. Fuel cells, on the other hand, can experience permanent performance degradation, making it an important feature to consider in techno-economic analysis designed to identify key technical features of the

systems. This section sets out a sensitivity analysis of the impact of degradation on the case for investment and environmental performance of PEMFC-based micro-CHP as defined in section 2.2.

Fuel cell degradation is usually reported as a voltage reduction per 1000 hours operation. According to Brett (2008) it is the product of a variety of mechanisms related to all the main components of the stack and is often specific to the type of fuel cell technology. Degradation mechanisms may be:

- Reversible (e.g., flooding, flow channel blockage, electrolyte membrane dehydration).
- Partially reversible (e.g., poisoning by fuel impurities, SOFC anode oxidation).
- Irreversible (e.g. sintering of electro-catalyst, electrolyte decomposition, catalyst support corrosion).

Some mechanisms of degradation may be exacerbated or remedied by excursions from steady state operation, such as cycling of temperature, electrical load, humidification level, electrode oxidation state, etc. Degradation will always be a feature of fuel cell performance and will be a function of cell/stack design and fabrication methods, materials, operating mode and the fuel used.

As presented in the modelling framework presented in section 4.3.2, degradation has been characterised as a linear reduction in net AC electrical efficiency of the micro-CHP system, with respect to either $kW_eh$ output (i.e. output-based degradation), or per thermal cycle (i.e. thermal-cycle-based degradation). Empirical evidence for degradation rates at different load levels does not exist in the literature, so assumptions must be made here regarding the range of rates to investigate. Empirical results do exist in the literature for steady-state operation of PEMFC systems operating on reformate, with ranges from Cleghorn et al. (2006) reporting voltage degradation of just over 1% per 1000 hours to Hinds (2004) reporting more than 6% per 1000 hours. Given an initial electrical efficiency of 30% (and assuming a linear relationship between voltage and efficiency), this translates to a range of electrical efficiency degradation rates between 0.3% and 1.8% per 1000 hours. Translating from steady-state data to dynamic data, this becomes 0.0003% to 0.0018% per $kWh/kW_{installed}$. This range was initially adopted for this sensitivity analysis, but was reduced to 0.0 to 0.0006% per $kWh/kW_{installed}$ to ensure validity of results (i.e. to prevent negative efficiency values near the end of the system's life which do not reflect the

physical reality). Degradation rates for thermal-cycling related mechanisms are unknown, and a range of values is investigated here. A system developer can inspect this range and choose the appropriate value for their system.

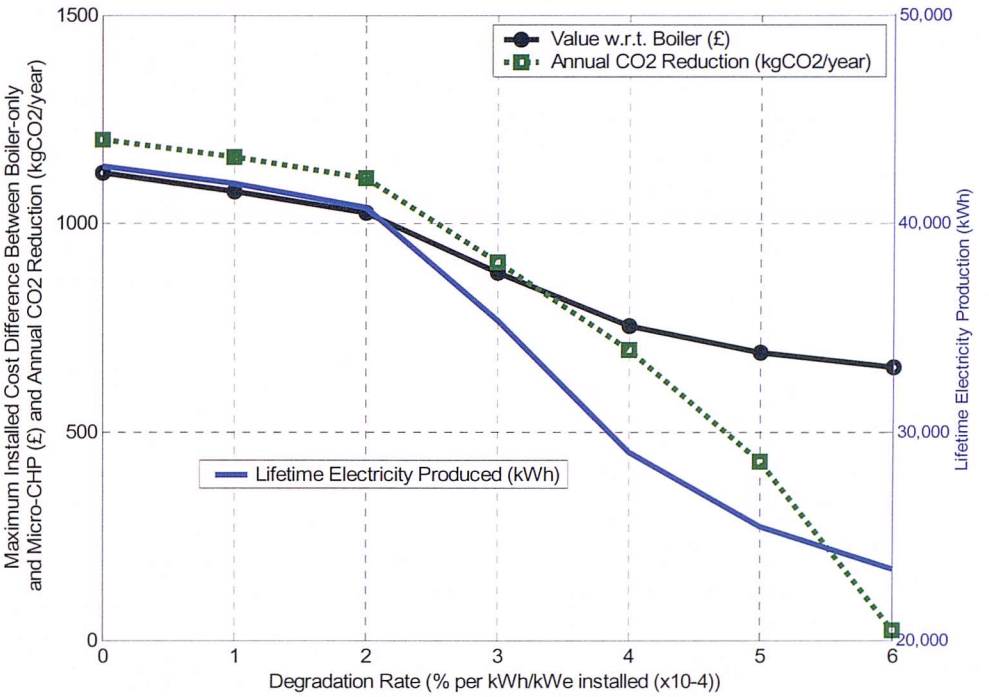



**Figure 64: Sensitivity of Maximum Installed Capital Cost Difference Between Boiler-only System and PEMFC Micro-CHP Systems (£) and Lifetime $CO_2$ Reductions to Output-Based Degradation Rate (Electrical Efficiency %/kWh/$kW_{installed}$ x$10^{-4}$)**

Figure 64 displays the results of the sensitivity analysis for output-based degradation. It is clear from inspection that degradation rates within the range of those observed for existing systems seriously impacts performance. Between the zero and 0.0006% rates £500 is wiped off the value of the micro-CHP system. Likewise $CO_2$ emissions reduction drops from above 1 tonne per year to zero. Additionally, the operating strategy changes such that the system produces less electricity over its lifetime (indicated by the blue line in Figure 64), reflecting operational disincentives created by degradation (i.e. operation at time t=1 makes operation at time t=2 until end of life less efficient) and increasing thermal constraint on the system as more of the fuel energy is recovered and utilised as heat. In essence the heat-to-power ratio of the system is increasing, because overall efficiency remains constant.

Figure 65 displays the sensitivity analysis for thermal-cycling based degradation. Over the range of values investigated thermal cycling is also an important consideration regarding performance, although only at higher degradation rates above 0.006% per cycle when the

$CO_2$ emissions reduction decreases noticeably and above 0.008% when the case for investment is affected. At lower degradation rates influence is still apparent, but is less critical. The operating strategy response of the system is apparent in the blue line in Figure 65, indicating that the system operates in a manner that avoids thermal cycling as degradation rates increase.

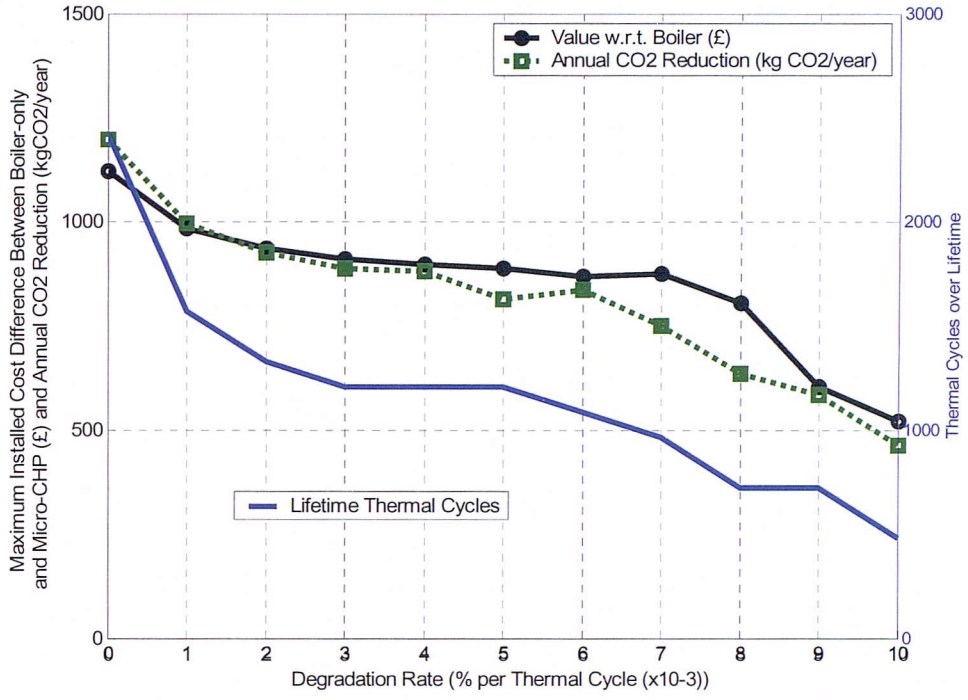



**Figure 65: Sensitivity of Maximum Installed Capital Cost Difference Between Boiler-only System and PEMFC Micro-CHP Systems (£) and Lifetime $CO_2$ Reductions to Thermal-Cycling-Based Degradation Rate (Electrical Efficiency % per Thermal Cycle x$10^{-3}$)**

Thermal-cycling related degradation differs from output-based degradation in that it can be more easily avoided; it is possible to avoid cycling the system, whilst it is not possible to avoid using it. Notwithstanding operating strategy related approaches to avoid degradation, propensity of a system towards degradation is also related to cell/stack/system design, fabrication methods, materials employed in the stack, and the fuel used. Trade-offs between these factors, capital cost, operating strategy and potential gains should be considered together to determine a way forward regarding system design to maintain acceptable performance at minimum cost.

### 8.2.9 Addition of Thermal Energy Storage

The final technical parameter investigated in this chapter relates to the key conclusions that have been drawn in this research so far; that thermal constraints can have a strong bearing on the economic and environmental case for micro-CHP. This conclusion suggests

that any change that can relax thermal constraints will create value. Thermal energy storage (TES) is the obvious choice to achieve flexibility on the thermal side of the system.

In this analysis it is assumed that various sizes (in litres) of thermal storage capacity are added to the micro-CHP system. Stored energy can be used to meet either space heating or domestic hot water loads, which is an unusual arrangement for the UK but not uncommon in continental Europe. As per the formulation of the modelling framework in section 4.3.1, thermal storage is assumed to be linear (i.e. constant turnaround efficiency, with charge and discharge efficiency both set to 90%). Furthermore, as the opportunity to install TES in a dwelling is space-dependent, a variety of sizes of storage are investigated ranging from 5 litres to 200 litres[31]. Finally, to avoid transfer of thermal energy between seasons via storage (which is unrealistic for energy stored in a typical insulated cylinder), the modelling approach requires that the storage system is completely discharged within each set of sample days representing a season. Overall it is recognised that this is a basic representation of TES in comparison with (for example) 3-dimensional modelling of stratified storage as can be found in the literature (e.g. Rosen et al. (2004)), but such simple representation is required here to perform a basic investigation of the impacts of relaxation of thermal constraints using storage in a computationally tractable manner.

[31] As the modelling framework requires TES capacity to be expressed in energy terms rather than volume, the following method is used to convert between the two: Storage medium is assumed to be water, and volume in litres is converted to mass (1litre = 1kg), followed by determination of energy content based on mass x specific heat of water (4.186 joules/gram) x temperature change. Temperature change between dwelling inlet and the centre of the storage tank is assumed to be 65° Kelvin.

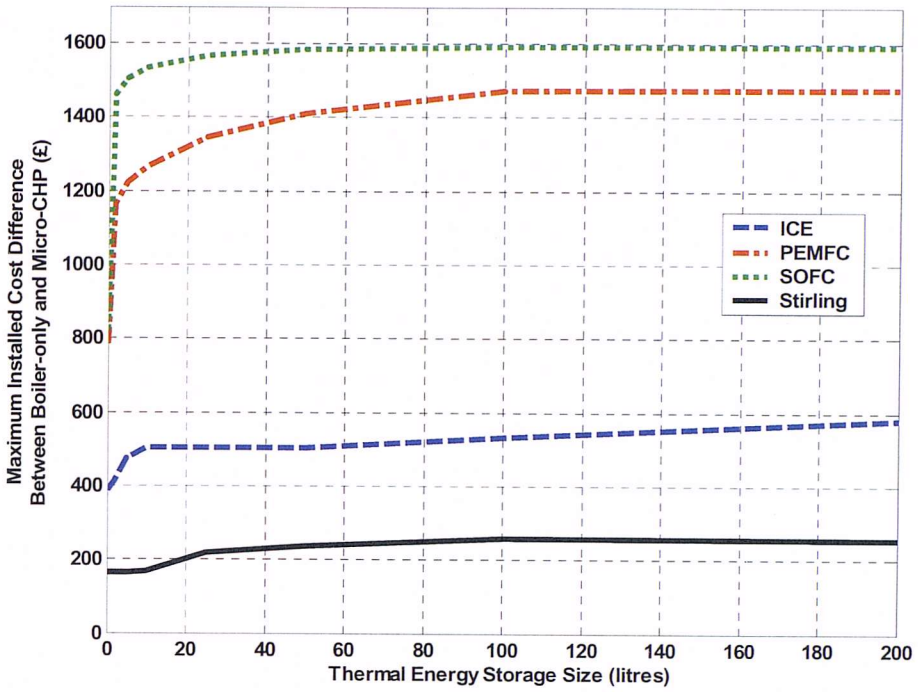



Figure 66: Sensitivity of Economic Performance of the Four 1kW$_e$ Micro-CHP Systems with respect to Capacity of Thermal Energy Storage Available

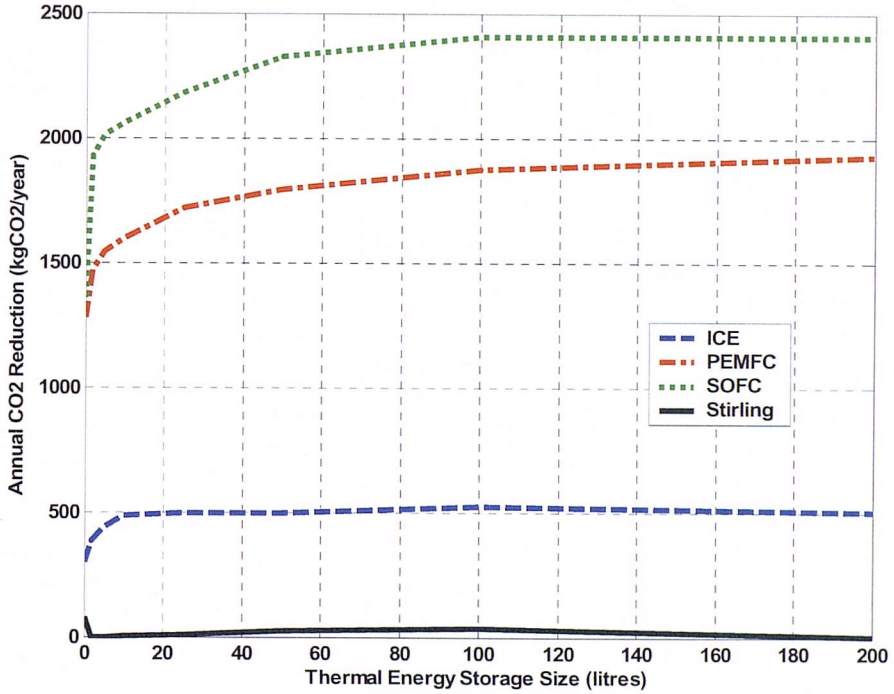



Figure 67: Sensitivity of $CO_2$ Performance of the Four 1kW$_e$ Micro-CHP Systems with respect to Capacity of Thermal Energy Storage Available

The results of the sensitivity analysis are presented in Figure 66 and Figure 67. Undoubtedly TES has strong synergies with micro-CHP. Even additions of very small capacities of TES (e.g. small "onboard" thermal buffer tank between the prime mover thermal outlet and demand) can create extensive additional value, particularly for the case of fuel cells.

Once again technologies can be differentiated by heat-to-power ratio; those with low heat-to-power ratio benefit much more from TES than those without. The reason that high heat-to-power ratio systems do not benefit so much is that they must push a lot of energy through that buffer to attempt to gain any value (from generating more electricity). Where a system does this, the losses associated with turnaround efficiency of the buffer bears negatively upon overall performance. Conversely, for the case of low heat-to-power ratio systems, relatively minor utilisation of the thermal buffer creates a lot of potential for additional electricity generation. Turnaround efficiency of the buffer does not impact upon performance in this case because the buffer is required to store less energy resulting in reduced losses.

However, the reader should note that capitalising on the presence of thermal storage required a more intelligent control strategy for the device. This is because the decision to charge/discharge storage is intimately linked with predictions of future demand. This issue would become more critical as the size of the thermal storage decreases, with (for example) a poor storage decision potentially resulting in the micro-CHP prime mover having to switch off. Whilst it has been shown that TES is clearly an important consideration for technology developers, detailed investigation of the tension with operating strategy and improved characterisation of thermal storage (discussed above) are beyond the scope of this thesis.

## 8.3 Conclusions Regarding Key Micro-CHP Technical Characteristics

This chapter has investigated nine high level technical characteristics of micro-CHP systems to gain understanding of their respective influence on economic and environmental performance. This can serve as a guide to focus R&D, but final decisions about which technical characteristic is the most important is not possible without an assessment of a) the likely R&D effort to improve a feature inter-related with b) the cost of manufacturing systems with the improved feature, and c) the price a potential investor is willing to pay for

a system with the feature (or the presence of regulations requiring it). The results obtained in the chapter are summarised in Table 21.

| Characteristic | Prime Mover Technology | Range Investigated | Range of Performance (primary metric (£),$CO_2$ reductions (kg$CO_2$/year)) |
|---|---|---|---|
| **Overall Efficiency** | ICE | 70%-95% | £0-£600 (-50-700kg $CO_2$) |
| | PEMFC | 45%-95% | £350-£1100 (-100-1,600kg $CO_2$) |
| | SOFC | 50%-95% | £750-£1,000 (550-1,700kg $CO_2$) |
| | Stirling | 70%-100% | £0-£400 (0-400kg $CO_2$) |
| **Part Load Electrical Efficiency** | ICE | 5%-20% | £100-£750 (0-1,200kg $CO_2$) |
| | PEMFC | 15%-35% | £500-£850 (800-1,350kg $CO_2$) |
| | SOFC | 25%-55% | £700-£1,350 (1,200-1,900kg $CO_2$) |
| | Stirling | 1%-10% | £0-£400 (0-350kg $CO_2$) |
| **Part Load Overall Efficiency** | ICE | 60%-90% | £50-£600 (0-1,200kg) |
| | PEMFC | 55%-85% | £500-£900 (800-1,350kg) |
| | SOFC | 55%-85% | £800-£1,100 (1,400-1,600kg) |
| | Stirling | 60%-90% | £0-£400 (0-350kg) |
| **Thermal Demand Load Factor** | ICE | "Fast" vs "Slow" Heating | £200-£400 (200-450kg) |
| | PEMFC | | £250-£750 (250-1,200kg) |
| | SOFC | | £200-£850 (250-1,300kg) |
| | Stirling | | £100-£200 (50-150kg) |
| **Ramp Rate** | ICE | 0.005$kW_e$/min to No Ramp Limit | £350-£400 (300kg) |
| | PEMFC | | £700-£800 (1,150-1,300kg) |
| | SOFC | | £800-£850 (1,250-1,400kg) |
| | Stirling | | £150 (50kg) |
| **Start-Up Cost** | ICE | 0.5p-5.5p | £150-£300 (200-400kg) |
| | PEMFC | 1p-8p | £600-£650 (1,200kg) |
| | SOFC | 1p-8p | £650-£700 (1,300-1,400kg) |
| | Stirling | 0.5p-5.5p | £50-£200 (0-150kg) |
| **Turndown Ratio** | ICE | 0$kW_e$ – 1$kW_e$ | £0-£800 (0-1,050kg) |
| | PEMFC | | £600-£1,000 (1,100-1,550kg) |
| | SOFC | | £750-£1,150 (1,300-1,700kg) |
| | Stirling | | £0-£500 (0-500kg) |
| **Minimum Up Time** | ICE | 5min-120min | No influence |
| | PEMFC | 5min-210min | |
| | SOFC | 5min-210min | |
| | Stirling | 5min-120min | |
| **Degradation w.r.t. Energy Output** | PEMFC | 0-6E$^{-4}$%/kWh/$kW_e$ | £650-£1,100 (0-1,200kg) |
| **Degradation w.r.t. Thermal Cycles** | PEMFC | 0-10E$^{-3}$/Cycle | £500-£1,100 (500-1,200kg) |
| **Thermal Energy Storage** | ICE | 0-200 litres | £400-£600 (300-500kg) |
| | PEMFC | | £800-£1,500 (1,300-1,900kg) |
| | SOFC | | £800-£1,600 (1,300-2,400kg) |
| | Stirling | | £200-£250 (200-0kg) |

**Table 21: Abridgement of Results in Chapter 8**

Many of the more critical parameters in Table 21 relate to efficient low energy consumption operation at very low load levels. Three closely related characteristics; part load efficiency, start-up cost, and turndown ratio, are all very important for economic and environmental performance. They all point towards the necessity to incorporate balance of plant components that all able to maintain efficiency whilst modulating to very low output levels. Likewise the prime mover itself must also maintain high efficiency at part load. Creation of such components is an engineering challenge.

Interestingly neither ramp nor minimum up time had a significant influence of micro-CHP system performance. Application of a reasonably intelligent and possibly adaptive control strategy designed to predict when space heat demands are likely to occur can eliminate the need for systems that can change output levels rapidly. Minimum up time was relatively unimportant because space heating demands are typically long cycles of demand, so a system naturally switches on/off infrequently regardless of imposition of a minimum up time.

As expected, the addition of thermal energy storage (TES) to a system was found to influence economic and $CO_2$-related performance. It has a very strong positive influence for fuel cell based systems, which can almost double in value with the addition of a very small thermal buffer. Likewise, fuel cell based systems $CO_2$ performance showed very strong synergies with presence of TES. Engine based systems were less predisposed to benefit from TES because the high heat-to-power ratio of these systems implies that more energy must be passed through storage, resulting in large turnaround losses. In contrast, low heat-to-power ratio systems gain a great deal of flexibility from the storage because a small amount of thermal flexibility results in large potential to generate more electricity. Turnaround losses are not important for these systems because a relatively small amount of energy needs to be stored to provide flexibility. Overall it is again possible to differentiate between micro-CHP prime movers based on heat-to-power ratio. A caveats to this conclusion is that representation of TES applied here is rather simplistic, and further investigations would improve appreciation of the potential of this feature to aid commercialisation prospects of micro-CHP. Furthermore, the interaction of TES with all of the other technical parameters investigated in this chapter is warranted given the fact that it alleviates thermal constraints, which have been shown in chapters 5 and 6 to be a key element of performance.

As expected degradation of PEMFC based systems was found to be a significant factor impacting performance, justifying the focus of fuel cell developers on durability issues. However, degradation (over the ranges investigated) is not more important than (for example) part load efficiency, suggesting that balance of plant design and part load operation could benefit from more attention. Thermal cycling based degradation of PEMFC was found to have less impact than output-based degradation, primarily because it is possible to avoid cycling the system through a smart operating strategy.

All but two of the technical characteristics investigated have been found to be very important for the economic and environmental performance of the systems. The decision regarding which of them should be pursued in order to improve performance of systems is up to the technology developers, and beyond the scope of this thesis.

# Chapter 9: Residential Sector Energy Policy and Potential for Support of Micro-CHP

Based on results presented in previous chapters, this chapter seeks to define plausible policy instrument structures to support adoption and appropriate utilisation of micro-CHP in the UK residential sector. It first reviews energy policy instruments at work in the UK sector, and provides a critique of their influence, noting which instruments currently support micro-CHP and which instruments could support the technology with minor modification. Based on this context of recent policy developments and details of support afforded to other microgeneration[32] technologies, the basis for upfront capital investment support for stakeholders purchasing micro-CHP systems is discussed with reference to the key market drivers and policy-related outcomes presented in Chapters 6 and 7. Finally, it presents and examines a variety of performance-based support instruments for micro-CHP, highlighting shortcomings in the approach adopted in the recent Energy Act (HM Government (2008c)) for microgeneration support, and exploring alternatives.

## 9.1 Review of Energy Policy for the UK Residential Sector

### 9.1.1 Background for Energy Policy in the UK

Spurred by international concern regarding climate change, the UK government indicated an aspiration to achieve a 60% reduction in greenhouse gas emissions by 2050 in the 2003 Energy White Paper (DTI (2003)). This target was increased to 80% and became a requirement in law when the recent Climate Change Act (HM Government (2008a)) achieved royal assent. The higher target is believed to be more appropriate for a developed country such as the UK to do its part in limiting atmospheric greenhouse gas concentration at levels required for climate stabilisation. As more than 25% of current UK greenhouse gas emissions derive from heat and electricity use in the residential sector, and this sector is seen as an area where substantial emissions reduction can be made at low cost (IPCC (2007)) with appropriate intervention, it has become a focus of policy and regulation. Amongst a variety of measures that could make an impact, microgeneration is seen as one class of technologies that can aid in meeting the ambitious emissions reduction

[32] Microgeneration is defined as any non-conventional energy generation technology applicable to single residential dwellings. This includes solar thermal, solar PV, biomass boilers, heat pumps, micro wind turbines, micro-CHP, and micro-hydro systems.

targets, whilst also providing a measure of energy security through diversity of primary energy sources and geographical distribution.

Over the past decade there have been substantial developments in both broad national energy policy and specific policy and regulation relating to microgeneration, complemented by significant technical advances in microgeneration systems. A critical review of current and proposed policy and regulation relating to microgeneration in the UK is presented here. A wide range of measures exist, some with obtuse relationship to benefit or detriment of microgeneration uptake and/or appropriate installation and operation. Only those measures perceived to have direct bearing on commercial adoption of microgeneration by owner/operators are presented. Further support measures such as academic and commercial research and development funding are not covered.

### 9.1.2 Microgeneration Strategy and the Low Carbon Buildings Programme

The UK Microgeneration Strategy was launched in March 2006 with the intention of realising potential reductions in greenhouse gases from microgeneration, engaging people directly on energy issues to "win the battle for hearts and minds", to improve reliability of energy supply, and to tackle fuel poverty (DTI (2006b)). The primary instrument of the strategy is £86 million of treasury funding over 3 years to be applied to support microgeneration installations through the Low Carbon Buildings Programme (HM Government (no date)). £18 million was available for the "households" stream of the programme, beginning in March 2006.

Technologies supported by the Low Carbon Buildings Programme (LCBP) include those that supply heat only (e.g. solar thermal water heating, heat pumps, biomass boilers), in addition to those that supply electricity. The current installed base of microgeneration equipment is therefore dominated by solar water heating, accounting for more than 95% of total installations. Micro-CHP is currently not supported by the programme, but may be added with appropriate constraints given the recent interim results of the Carbon Trust micro-CHP field trial in Carbon Trust (2007), although relatively few commercial products exist and there is still uncertainty regarding realisable greenhouse gas emissions savings. The level of grant funding per installation under the programme varies by technology, from £400 for solar hot water to up to £2,500 for solar PV, micro-wind and micro-hydro. At the time of writing just under 6,000 new microgeneration installations had been supported by the programme, at a cost to the treasury of just over £8 million.

| Technology | No. of supported installations March 2006 to May 2008 | Average grant amount (£/installation) | Estimated kW of Installations Supported by Grants ($kW_e$) | Estimated Lifetime $CO_2$ Savings per Installation (tonnes $CO_2$) | Estimated cost to taxpayer of $CO_2$ savings (£/tonne $CO_2$) |
|---|---|---|---|---|---|
| **Micro-wind** | 600 | 2,200 | 2,200 | 7/$kW_e$ | 86 |
| **Solar-PV** | 918 | 5,100* | 2,200 | 12/$kW_e$ | 178 |
| **Solar Hot Water** | 3,300 | 400 | - | 8/unit | 50 |
| **Ground Source Heat Pump** | 444 | 1,200 | - | 36/unit | 33 |

**Table 22: Cost to the Government of Estimated $CO_2$ Savings under the Low Carbon Buildings Programme (DEFRA (2007a), HM Government (no date)). *Support for solar PV was limited to £2,500 after May 2007.**

Table 22 shows an estimated cost to the taxpayer of $CO_2$ saved for the four technologies that have received the majority of "household" LCBP funding to date, based on estimated lifetime $CO_2$ savings by technology. Clearly a wide range of implied carbon prices are being supported. This can be justified on the basis that additional support for the emerging innovative technologies is desirable as it creates "options" for future low carbon energy systems and other laudable attributes. Additionally, as noted above, the LCB "household" stream at present provides £18 million of grant funding, equating to approximately 45,000 solar hot water installations, or 7,200 solar PV installations[33]. This level of market penetration is a useful first step, but falls well short of what would be required to make significant progress towards reducing overall $CO_2$ emissions of the residential sector.

Overall, the Microgeneration Strategy and associated LCBP is a useful instrument to raise the profile of microgeneration and engage the community at an appropriate level, and provides valuable information regarding what levels of capital cost reduction are required trigger uptake. However, it is rarely economically efficient in terms of reducing greenhouse gas emissions, does not span a sufficient length of time to provide the certainty of ongoing support that is required to foster innovation (as discussed in Allen et al. (2008) and others), and will not fund enough installations to significantly diversify energy supply. Essentially it is a somewhat useful short-term instrument that will provide information to stakeholders, but is unlikely to have any significant long-term impact.

It is instructive to consider if micro-CHP would fit with the LCBP. Carbon Trust (2007) presents results from a UK micro-CHP field trial that has been running since 2003. This report verified the modelling results presented in this thesis in that it broadly indicated that small $CO_2$ emissions reductions are possible in the residential sector using Stirling engine

[33] At £2,500 per installation. LCB Programme initially provided a higher upper limit to solar PV installations, resulting in the £5,100 per installation noted in Table 22. The upper limit per installation was revised to £2,500 in May 2007.

micro-CHP (a high heat-to-power ratio technology). The performance in terms of $CO_2$ reduction was found to be improved by larger annual thermal demand of the property, also confirming results presented in this thesis. The report noted that low heat-to-power ratio micro-CHP could perform better, although no attempt to quantify this was made in the report. The results of the trial indicate that micro-CHP is a candidate for support such as the LCBP, although as the relationship between $CO_2$ saving and support level is indirect, the exact level of appropriate support for micro-CHP (and types of technologies that should be supported) is debatable. It should be noted that the LCBP requires a dwelling to be insulated to a high standard, use energy efficient lighting, and install heating controls in order to be eligible for support. These measures will decrease the economic and $CO_2$-realted case for the technology as discussed in sections 6.1.2 and 7.1 of this thesis, particularly for high heat-to-power ratio technology. Low heat-to-power ratio technology has a better chance of avoiding this drawback.

### 9.1.3 The Carbon Emissions Reduction Target (CERT)

In the UK's liberalised energy market, the retail elements (i.e. suppliers) have been regulated to reduce the energy consumption of their residential customers over two "energy efficiency commitment" (EEC) periods between April 2002 and March 2008 (HM Government (2001), (2004a)). A continuation of this policy instrument changed the focus to carbon emissions rather than energy consumption[34], which will better account for measures such as micro-CHP. The new scheme obliges suppliers to reduce the carbon emissions of their residential customers between April 2008 and March 2011 according to a Carbon Emissions Reduction Target (CERT) (HM Government (2008b)). The increasing target levels of EEC and CERT instruments are displayed in Table 23. Both the EEC and CERT require suppliers to use a set of "qualifying actions", each of which has an associated energy consumption reduction or carbon emissions reduction. A certain amount of these measures must be applied to a group of customers at risk of being "fuel poor"[35]. At the end of the commitment period the cumulative amount of a supplier's qualifying actions must equal or exceed their allocated portion of the total target. Suppliers are allowed trade actions and commitments amongst themselves, and savings in excess of the target carry over to the next commitment period. Therefore it can be argued that the EEC and CERT are

[34] EEC applied "fuel-standardised" energy savings, which adjusted the effect of qualifying actions to account for the carbon content of the fuel saved. Therefore CERT is not particularly different to EEC, but is more convenient where a measure applies to many fuels such as micro-CHP (e.g. electricity *and* gas).

[35] "Fuel poverty" occurs when a customer spends more than 10% of their income on energy bills.

relatively fair measures for the promotion of $CO_2$ emissions reduction in the residential sector. The instrument in some senses emulates a "cap-and-trade" system, allowing Suppliers to find the most cost effective set of actions and/or commitment trading to meet their targets.

| Policy Instrument | Energy Savings Target (fuel-standardised lifetime-discounted TWh) | $CO_2$ Savings Target (lifetime-discounted Mt $CO_2$) |
|---|---|---|
| **EEC1 2002-2005** | 62 | *40* |
| **EEC2 2005-2008** | 130 | *70* |
| **CERT 2008-2011** | - | 154 |

**Table 23: Basic Statistics of EEC and CERT Policy Instruments based on DEFRA (2007a)**

In the second EEC (April 2005 to March 2008), microgeneration was included as a measure that could be applied towards suppliers' targets under an "innovative action" clause, and it attracted a bonus 50% energy reduction credit over standard actions. The new CERT instrument continues this special treatment of microgeneration as a "market transformation" action. Microgeneration actions can constitute up to 8% of a supplier's target, and they additionally receives a 50% uplift on deemed $CO_2$ savings. In effect, this means that microgeneration can contribute up to 12% (i.e. 8% multiplied by 1.5 uplift) of the supplier's CERT. This does not necessarily mean that microgeneration will be employed to help meet CERT targets, as suppliers are free to choose actions and these are the subject of a business offering.

The CERT should deliver approximately 2% reduction in annual $CO_2$ emissions relative to business-as-usual from the residential sector in 2011. The cost to the supplier of actions in CERT was estimated at £97 per household over the commitment period (DEFRA (2007a)), but the carbon and household energy cost benefits persist over a much longer period. If it is assumed that the suppliers' portion of the cost is socialised (i.e. passed on to all consumers equally regardless of whether or not they are directly benefitting from an action) then the cost of emissions saved is approximately £20 per tonne $CO_2$. However, those benefitting from the actions will have substantially lower (and usually negative) net costs, which is consistent with many energy efficiency measures applicable in the residential sector having positive net present value.

Although overall EEC and CERT appear to be effective policy instruments for reducing $CO_2$ emissions from the residential sector, it remains questionable whether or not they provide meaningful support for microgeneration. Table 24 shows cost breakdown for selected qualifying actions, and derived payback based on information in the 2007 CERT

consultation (DEFRA (2007a)), the Energy Saving Trust website (Energy Saving Trust (no date)), combined with the author's estimates based on results presented earlier in this thesis. The key assumption in Table 24, as in this thesis as a whole, is that home heating solutions (i.e. those options that can completely replace the existing or conventional heating solution) should not be evaluated with respect to their total cost versus lifetime carbon dioxide savings. This is because home heating systems are a necessity for every inhabited dwelling in a cold climate. Therefore, as the purchase of some form of heating system is a necessity, the customer considers the *difference between* the cost of a conventional heating system and the low carbon technology alternative, not the total installed cost. This is identical to the primary economic metric reported throughout this thesis – the maximum installed cost difference between the micro-CHP system and the reference boiler-only system. Table 24 takes the economic comparison a step further in that it estimates the total installed cost of various micro-CHP systems. Once this concept is taken into account it becomes apparent that micro-CHP payback period for the customer are not substantially longer than payback periods for conventional energy efficiency measures such as insulation, and substantially shorter than most other microgeneration measures. For example, if a supplier offered a subsidy equivalent to their average cost of carbon dioxide saved (i.e. approximately £20/tonne) for a heat pump installation the owner-operator still faces a long payback period, whilst micro-CHP can offer payback in less than 5 years. This suggests that it may be possible to make a compelling case for consumer uptake of micro-CHP, and the CERT programme could be a reasonably effective vehicle to promote the technology.

Certain caveats do need to be taken in account when interpreting Table 24. Producing accurate estimates of $CO_2$ savings by technology type is challenging due to the diversity of residential energy consumption, as noted in this thesis in section 5.4, and wide variation in performance of microgeneration systems depending on factors such as the specifics of technology design, location, fuel type, and occupant behaviour. For example, as noted in the Carbon Trust micro-CHP field trial, the performance of Stirling engine technology is dependent on annual thermal demand, length of operating cycles, heat-to-power ratio, internal logical control, efficiency of ancillary components, integration with other heating system components, and the ability of condensing operation to be regularly achieved. Furthermore, a very wide range of installed costs are apparent for all microgeneration technologies, with final cost depending on factors such as technology manufacturer, location, access, presence (or not) of compatible heat emitters, connection or facilities for

fuel supply, and metering. Therefore one would expect a wide range of economic and environmental outcomes for each technology type, and Table 24 should be treated only as broadly indicative of the situation. Finally, the implementation of CERT by a supplier is a business arrangement between them and their customer, so the precise level of support offered is not fixed.

Nevertheless, it is apparent that CERT is potentially an effective means of stimulating uptake of micro-CHP systems. This is not only because it serves to reduce the cost differential between micro-CHP and conventional heating systems, but also because it is a convenient and rapid means to reach a large market. For example, if 10% of a notional 2011-2014 300Mt$CO_2$ CERT were met via micro-CHP, around 3,000,000 installations would occur, providing an enormous boost to penetration. In comparison to micro-CHP, other microgeneration systems are unlikely to be supported on a significant scale by CERT, because the value to a supplier of $CO_2$ saved is insignificant in comparison to the installed cost of the devices, and the supplier is therefore less able to influence uptake in a convincing manner.

| Measure | Total Installed Cost (£) | Estimated Lifetime $CO_2$ Saving (tonnes) | Cost Difference of Measure to Customer* (£) | Customer's Operational Savings[$] (£/year) | Simple Payback Period to Customer (years) | Information Source |
|---|---|---|---|---|---|---|
| ***Cavity Wall Insulation*** | 450 | 25 | - | 90 | 5 | CLG (2007b), Energy Saving Trust (no date) and calculation |
| ***Loft Insulation*** | 350 | 12 | - | 90 | 4 | CLG (2007b), Energy Saving Trust (no date) and calculation |
| ***Compact Fluorescent Lights*** | 2.6 | 0.14 | - | 5 | 0.5 | CLG (2007b), Energy Saving Trust (no date) and calculation |
| ***Biomass Boiler, 20-year lifetime, meets all thermal needs, requires 4 tonnes wood/year*** | 10,000 | 76 | 5,980 | 0 | never | CLG (2007b), Energy Saving Trust (no date) and calculation |
| ***Solar Hot Water, meeting 50% of hot water needs, 20-year life*** | 3,200 | 8 | - | 50 | 64 | CLG (2007b), Energy Saving Trust (no date) and calculation |
| ***Ground Source Heat Pump, COP 4:1, powered by grid electricity, 30-year life*** | 10,000 | 36 | 6,780 | 100 | 68 | CLG (2007b), Energy Saving Trust (no date) and calculation |
| ***Micro-wind (1kWe, 10% load factor), 50% onsite, 50% exported, 20-year life*** | 1,800 | 7 | - | 50 | 33 | CLG (2007b), Energy Saving Trust (no date) and calculation |
| ***High Heat-Power Ratio micro-CHP, existing technology, 10-year life*** | ***3,000*** | ***5*** | ***400*** | ***100*** | ***4*** | ***Results from this thesis and capital cost estimate*** |
| ***Low Heat-Power Ratio micro-CHP, near-to-medium term technology, 10-year life*** | ***3,500*** | ***10*** | ***800*** | ***150*** | ***5*** | ***Results from this thesis and capital cost estimate*** |

**Table 24: Payback time for measures with CERT support (DEFRA (2007a), Energy Saving Trust (no date)) and author's estimates**

* Relative to a £2,500 condensing boiler, and accounting for £20/tonne $CO_2$ reduction supplier contribution. [$] From Avoided Electricity/Gas Import and Revenue from Electricity Sales

### 9.1.4 Tax Incentives for Microgeneration

#### *9.1.4.1 Reduced VAT Rate for Energy Saving Items*

The UK has provided Value Added Tax (VAT) relief on residential fuel and electricity bills since 1995. For the majority of goods and services, VAT is charged at 17.5% in the UK, but this has been reduced to 5% for specific services. The 1995 Finance Act (HM Government (1995)) reduced VAT on purchasing energy for residential customers, it was perceived as equitable to charge an equivalent VAT-rate for purchase of equipment to save energy. Statutory Instrument 1998 No. 1375 (HM Government (1998)) created reduced VAT rate rules for installation and supply of energy saving measures:

- central heating and hot water system controls
- draught stripping
- insulation

As microgeneration systems have some desirable characteristics in relation to residential energy provision, there is an argument that it too should attract the 5% VAT rate. Since 1998 various acts and statutory instruments have added microgeneration measures to the schedule of reduced VAT energy-efficient or carbon-saving goods;

- solar panels, wind turbines and water turbines in HM Government (2000)
- ground source heat pumps in HM Government (2004b)
- boilers designed to be fuelled solely by wood, straw or similar vegetal matter in HM Government (2005a)
- air source heat pumps and micro-CHP in HM Government (2005b)

For the case of micro-CHP; for a £3000 installed-cost (including VAT) unit the reduced VAT incentive is worth £357. This represents substantial support, amounting to more per installation than the CERT in many circumstances, although for both VAT-reduction and CERT the value is notational (i.e. support avoids expense, rather than providing cash to a purchaser).

#### *9.1.4.2 Income Tax Exemption for Microgeneration Electricity Export*

In addition to reduced VAT rates, the UK Government has exempted the owner-operators of domestic microgeneration from income tax on revenue from electricity export and on Renewable Obligation Certificate (ROC) income in HM Government (2007b), (2007c). If income from these sources was (for example) £150 per year, this incentive is worth

between £33 and £60 per year for the 22% and 40% personal income tax rates respectively. However, if an owner-operator were to be taxed on revenue from electricity export, it follows that they could claim expenses on the initial investment through depreciation, maintenance, and on the cost of any fuel consumed. Therefore calculating the true value of this incentive to the owner-operator is convoluted, and its net effect on public revenue through taxation is likely to be small. Nevertheless, it is arguable that this is a less equitable method of financial support for microgeneration because it may favour owner/operators with particular taxation circumstances.

This measure is more important in terms of simplifying the ownership of microgeneration, avoiding the need for every UK microgeneration owner/operator to file a self-assessment tax return and reimburse or receive refunded tax at the end of each financial year, which could be seen as cumbersome to the majority of potential owner/operators who may prefer a fit-and-forget home energy solution.

#### *9.1.4.3 Stamp Duty Exemption*

Where a dwelling achieves "zero carbon" status according to the Standard Assessment Procedure for energy consumption (see Section 9.1.5.2), it has been made exempt from stamp duty charged when it is sold in HM Government (2007d). This exemption is limited to the time period from October 2007 to October 2012. Electricity-producing microgeneration is currently an indispensable element for achieving zero carbon status, when combined with a variety of other measures. This incentive is worth up to £15,000 (for a dwelling sold for £500,000). The incentive is only available to the buyer when the dwelling is sold, and the sum spent on achieving zero carbon status by the seller may well exceed this amount, resulting in this measure being relatively ineffectual. See Section 9.1.5 for a more detailed discussion of zero carbon homes as they relate to the Standard Assessment Procedure and the Code for Sustainable Homes.

### 9.1.5 Building Regulations, Standard Assessment Procedure, and Labelling

#### *9.1.5.1 Part L of the Building Regulations*

The development of stringent building regulations to reduce the energy demand of residential dwellings may influence the commercialisation of micro-CHP. Over the past several decades, minimum requirements for insulation in various building elements have increased dramatically. These changes are enforced through part L of the building regulations, relating to conservation of fuel and power (ODPM (2006a), (2006b)).

The influence of the building regulations in improvement of insulation, glazing, and reduced electrical loads does not improve the commercialisation prospects of any microgeneration technology: Lower annual thermal demand and reduced length of the heating season degrade the economic case for thermal microgeneration (e.g. micro-CHP), and reduced electrical loads degrade the economic case for electricity microgeneration as less onsite load is met by the generator (and more electricity is exported, attracting lower value than displaced onsite generation). However, this adverse interaction between microgeneration and energy efficiency may not persist as the driving forces of the regulations evolve, as discussed below.

The future of the building regulations is entwined with the recent Code for Sustainable Homes (CLG (2006)) which introduced a new rating method and format for new dwellings, presenting a points system for a variety of aspects of sustainability including those related to energy use, although assessment against this code is currently optional. The government has stated that assessment against this code is to become mandatory for all new dwellings (CLG (2007b)) with the energy aspects implemented via part L of the building regulations, possibly from 2010. The code incorporates six levels (from one to six stars), with the five star level indicating "zero carbon" for heating, hot water, ventilation and lighting according to the current 2005 Standard Assessment Procedure (SAP) calculation method, and the six star level relating to a "truly zero carbon" home in terms of all energy use. All new homes built after 2016 are required to meet the six star level truly zero carbon standard (CLG (2007a)), although serious questions exist regarding whether or not this is achievable given the lack of a workforce with the relevant skills and general confusion regarding how targets would best be met.

### *9.1.5.2 Standard Assessment Procedure*

Until recently a wide variety of proprietary assessment procedures were used to determine the energy performance of residential dwellings, resulting in a wide range of possible outcomes and interpretations. Implementation of the Directive on Energy Performance in Buildings detailed in EU (2002) required Member States to adopt a standard methodology for calculating building energy performance. In the UK the Standard Assessment Procedure (SAP) has been chosen to fulfil this requirement. The full version of the SAP is used to assess new dwellings, and a Reduced Data SAP (RDSAP) is used for assessment of existing dwellings. SAP 2005, available in BRE (2005), is the current version of this procedure, and includes microgeneration as a measure that can be used towards reducing the Dwelling Emissions Rate (DER) through $CO_2$ credit for electricity generated. Indeed microgeneration

is currently virtually the only method by which a dwelling could achieve "zero carbon" status relevant to level 5 of the Code for Sustainable Homes and the exemption for stamp duty discussed in Section 9.1.4.3.

The calculation method for $CO_2$ reduction when considering microgeneration adopted in SAP 2005 has been broadly applied in this thesis. As discussed in section 3.2, the reference system provides for different embodied carbon rates for grid electricity, depending on whether it is consumed onsite or exported to the grid. In SAP 2005, when calculating microgeneration impact on $CO_2$ emissions for a dwelling, where a unit has net output of electricity, the assumed emissions rate for the "grid-displaced" electricity is $0.568kg_{CO2}/kWh$. Conversely, grid-supplied electricity is assumed to embody only $0.422kg_{CO2}/kWh$. These differential grid $CO_2$ rates favour microgeneration, but there is little empirical evidence that they are accurate.

However, SAP does not incorporate the majority of electricity use in a dwelling (it only includes electricity related to heating devices, circulation pumping, and lighting). Therefore, using the SAP 2005 calculation method means that even gas-fuelled microgeneration could result in zero or negative Dwelling Emissions Rate (DER) (i.e. in cases where the avoided emissions from grid-displaced electricity exceed the emissions related to heating, hot water, ventilation, and lighting, the dwelling has zero or negative DER and is "zero carbon" for building regulation purposes). A low heat-to-power ratio micro-CHP unit would probably be able to displace emissions from all SAP sources and export enough electricity to achieve zero carbon status for the dwelling (similarly to the $4kW_e$ SOFC-based system example presented in Table 12 in section 7.1). However, it is more challenged to reach "truly zero carbon" status if all energy-related sources of $CO_2$ in the dwelling are accounted for as is the case for level 6 of the Code for Sustainable Homes, applicable from 2016.

#### *9.1.5.3 The Merton Rule*

The "Merton Rule" has also proven to be an important aspect of governance related to microgeneration. It is a planning policy requirement imposed by local authorities requiring a certain percentage of renewable energy (or expected $CO_2$ reduction) in any new development above a prescribed size. This translates to a strengthening of the building regulations in specific developments in that they must meet certain additional criteria. The Merton Rule was initially imposed by the London Borough of Merton, which requires 10% of energy in new developments of 10 or more units (or above 1000 $m^2$) to come from

renewable sources. Very similar approaches have since been adopted by a significant portion of local authorities, and central government has encouraged its adoption, making renewable energy (often delivered via microgeneration as opposed to community or centralised schemes) a key aspect of many new developments. The relative efficacy of central government versus local or regional approaches has since become an interesting topic of debate, with early indications suggesting that while centralised strategy is necessary, local approaches are potentially much more effective in realising microgeneration installations. The primary criticism of the rule is that some implementations can be technology-deterministic, and may not be the cheapest way to deliver $CO_2$ reductions.

Some implementations of Merton-style rules may trigger uptake of micro-CHP. In general, implementations that require low carbon performance, rather than renewable energy, are more suited to the characteristics of gas-fuelled micro-CHP.

#### *9.1.5.4 Home Energy Labelling*

EU (2002), the EU Energy Performance of Buildings directive, requires Member States to ensure that an energy performance certificate is available when a building is constructed, sold, or rented out. The Article in this directive relevant to labelling was implemented for the UK residential sector through energy performance in buildings regulations (HM Government (2007a)). After some resistance, primarily from real estate agents, energy performance certificates became mandatory for all dwelling sales from December 2007 and all dwelling rentals from October 2008.

The intention of energy labelling for residential dwellings is primarily to raise awareness of energy performance, and make the prospective buyer/tenant engage with this aspect of the decision making process more directly. For example, the energy performance certificate (EPC) suggests actions that the dwelling owner/occupier could undertake to improve the dwelling's performance. The bearing of this measure on uptake of microgeneration is not direct, and the changes of building regulations discussed above are likely to have a much more pointed impact. However, the calculations of current and potential energy performance of the building associated with the EPC could be a useful tool in vetting support for micro-CHP installations, as discussed below in section 9.2 .

#### *9.1.5.5 Safety Requirements of the Building Regulations*

Safety concerns regarding microgeneration installation have also been addressed through the building regulations (ODPM (2006c)) to avoid hazards associated with live electricity generating devices on the customer side of the meter.

### 9.1.6 Connection, Metering, Balancing and Settlement

In 2003 the Electricity Network Association published Engineering Recommendation G83/1 for connection of microgeneration up to 16 amps per phase, which corresponds to just under 4.0kW$_e$ for a single phase connection (ENA (2003)). This was the guide for maximum system capacity investigated in this thesis. The G83/1 guidelines allow a microgenerator to be connected in a private dwelling without the prior consent of the local Distribution Network Operator (DNO), who only needs to be informed after the action. This streamlines the connection process somewhat, but several barriers remain as discussed below.

The ability of microgeneration to meaningfully contribute to meeting national or local electricity demand, and the ability of owner/operators to receive fair reward for electricity fed onto the grid, are largely dependent on a complex set of metering, balancing, and settlement arrangements set out in the Balancing and Settlement Code (BSC) (OFGEM (2001)). Whilst a number of alterations have been made to the BSC to allow stakeholders to capture the "embedded benefits" of decentralised generation, these changes still result in a system that is difficult to access for microgenerator owner/operators. It is widely recognised that a successful balancing and settlement system at the residential level must not impose any significant burden on residential owner/operators.

A few changes have been made to the BSC in an attempt to alleviate complexity for the microgeneration owner/operator, but challenges still remain at the time of writing. Modification P81 to the Balancing and Settlement Code (BSC) has removed the requirement for half-hourly metering of microgeneration export (Elexon (2003)); a requirement that previously required all generators that participate in settlement to provide generation volume data for each half hour period of every day. Modification P81 resolves the problem of a mandatory, and possibly expensive metering arrangement for microgenerators, but does not resolve the difficulty the lack of this metering imposes on electricity system stakeholders: In order to balance and settle the electricity system, the system operator/s need knowledge of the export profile of each demand class and generator class, and provision of this information is challenging for large numbers of microgenerators at the residential level.

Options exist for balancing and settlement of microgeneration. These generally fall into two categories;

1. use of "profile classes" with or without deemed output from the microgenerator,
2. real-time metering and reporting of microgenerator output.

Where profile classes are used (as is currently the case under modification P81), export from microgenerators would be submitted for balancing via a set of standardised export profiles that are assumed to reflect the real export of the generators. This is similar to the process currently in place for residential demand[36] or other non half-hourly metered generation. Export profile classes could also be used by suppliers to determine the level of export reward applicable to each type of microgenerator (based on likely time of generation versus time-based price process). However, creating standardised export profile classes for each type of microgenerator represents a significant and expensive challenge, particularly because each "dispatchable" (e.g. micro-CHP) product may have a unique operating strategy and some renewable products are intermittent by nature. Regardless of these difficulties, the Climate Change and Sustainable Energy Act 2006 has made provision for the Secretary of State to require suppliers to offer terms for electricity buyback from customers in HM Government (2006). If followed through, this requirement may accelerate activity on export profiling arrangements (or motivate faster introduction of smart metering, discussed below).

The alternative to the use of standardised profile classes is where the export of microgenerators is metered in real time by "smart meters", which provide this information to microgeneration owner/operators and could relay it to other stakeholders for use in balancing and settlement. This has the advantage of allowing real-time system balancing, and settlement could be performed directly on metered output. Discussion of further benefits of smart metering can be found in Porter (2007). However, substantial data exchange is required between potentially millions of meters and supplier's or aggregator's systems. Additionally, smart meters with universal capabilities would be required in all dwellings hosting microgeneration. Whilst activity regarding smart metering is apparent in the UK and elsewhere, the inclusion of services in devices to enable relevant data transfer etc appears to be a low priority. Therefore, whilst smart metering is a promising solution

[36] Aggregate residential load is extremely predictable. It follows that aggregate output from some types of microgenerators would also be very predictable, and therefore standard profile classes could be effective.

to enable access to the true value of microgeneration (and a variety of other laudable goals), it is less likely to be realised in the near-term.

Another significant unresolved issue, which is intertwined with BSC issues, is that an acceptably simple and robust meter registration arrangement does not yet exist. For an arrangement to be acceptable, a customer wishing to install microgeneration should have one point of contact for generator/meter installation and their registration with supplier and local Distribution Network Operator (DNO). Likewise, a robust system is required to handle change of supplier, change of owner/operator, meter reading, and decommissioning scenarios. The supplier is the residential customer's conventional point of contact, but questions remain as to whether this should remain the case, and what data flows are required to capture relevant information.

Notwithstanding the possible resolution of the issues discussed above, the cost of balancing and settlement to suppliers, supplier agents, DNOs, meter operators, and data collectors remains a contentious issue, where some argue that the additional costs microgeneration imposes outweighs any financial benefits customers are likely to gain from electricity export. The alternative to metering, balancing and settlement of microgeneration export is spill onto the network (with no financial reward), which in significant quantities also imposes a burden on stakeholders. Moreover, the absolute number of customers that electricity system stakeholders have to deal with does not change with the introduction of microgeneration (although the number of meters and the complexity of settlement increases), and practical data flow issues should be resolvable. Existing commercial structures may need revision, and a simple yet fair and effective system for dealing with a large number of microgenerators should be developed.

### 9.1.7 The 28 Day Rule

Initially the UK liberalised energy market provided protection for residential consumers via a mechanism known as the "28 Day Rule". This rule enabled a customer to switch suppliers with 28 days notice, and was based on the justification that it would incentivise competition because a supplier with low prices was likely to be favoured over one with high prices. However, the 28 day rule was criticised because it inhibited suppliers from offering arrangements to customers involving installation of capital-intensive products such as energy efficiency measures or microgeneration because that customer could switch supplier 28 days later.

Whilst it is debateable whether or not this is actually a barrier to such arrangements (e.g. a supplier could offer the product in a contract separate to energy supply, and still have access to repayments of any finance involved if that customer switched suppliers), the regulator (OFGEM) suspended the rule in August 2007. Suppliers can now tailor offerings to customers and lock them in to longer term contracts. This may increase the prevalence of "energy service" type offerings in the market, and could aid the "company control" pathway to installing micro-CHP, but evidence of any change is yet to be observed on any significant scale.

### 9.1.8 Critique of Existing Microgeneration Policy Instruments

As is apparent from the above discussion, a wide variety of current and proposed policy instruments apply to the commercialisation of microgeneration in the UK. Financial instruments include capital grant support, energy efficiency improvement regulations aimed at suppliers, tax incentives, building energy performance regulations and planning policy, and home energy labelling. At the same time a number of actions are being taken to simplify and support the inclusion of large numbers of microgenerators in electricity system balancing and settlement, and to streamline meter-related issues and microgeneration connection. However, co-ordination between instruments is often confused, resulting in an array of overlapping and occasionally conflicting policies, spread between a number of different government departments and agencies. Whilst application of a variety of types of policy instrument could be effective in terms of appealing to the widest possible audience, a simplified set of instruments with clearly defined and joined-up goals could benefit the prospects for commercialisation of microgeneration greatly.

Despite shortcomings, it is clear that there is an impressive range of activity to encourage microgeneration, with substantial financial backing as summarised in Table 25 which estimates total support afforded by policy instruments to various types of microgeneration. Two clear conclusions may be drawn from Table 25. Firstly, once again it is clear that the combination of policy instruments is supporting a wide range of carbon prices. This range is due to the LCBP, and VAT relief. As discussed in section 9.1.2 the LCBP is not a measure specifically directed at achieving $CO_2$ emissions reduction, and is more a platform to raise the profile of the technologies, kick-start the market, and attempt to signal developers that the government is serious about supporting these technologies. Likewise, VAT relief is indiscriminate in terms of support for $CO_2$ reduction, providing approximately 12% capital cost reduction regardless of performance. It could be argued that the LCBP is more directed than VAT relief, as the LCBP process represents a form of vetting of applications

(external benefits are gained through LCBP in that in order to be eligible for support a dwelling must be well insulated, install quality heating controls, and efficient lighting). The second conclusion to be drawn from Table 25 is that micro-CHP systems can benefit greatly from support, with immediate payback to the supported owner-operator for a hypothetical £3,000 installed cost high heat-to-power ratio technology.

In comparison to the LCBP and VAT reduction, the CERT is a much more $CO_2$ savings oriented mechanism, providing a fixed reduction target, and flexibility regarding how to meet it. In the sense that qualifying actions compete with one another the CERT should provide an economically efficient overall solution. Possibly the biggest deficiency in the CERT is that $CO_2$ savings are measured with respect to a business-as-usual scenario, and therefore do not necessarily provide an absolute $CO_2$ reduction. Therefore, although CERT emulates a cap-and-trade system as discussed in section 9.1.3, the lack of a hard cap on emissions suggests it would be more accurate to term it "restrain-and-trade". There is no simple solution to this problem as there is no simple way to measure absolute $CO_2$ reduction at the individual residential level. Most possibilities involve metering dwellings benefiting from an action, and adjusting it for a variety factors that are difficult to quantify (i.e. behavioural, temperature, etc.). Nevertheless, development of a cap-and-trade system like CERT but which provides absolute emissions reduction is an interesting possibility for future policy development efforts.

| Technology | Estimated Total Installed Cost, including VAT at 5% (£) | Estimated LCBP Grant Support (£) | Estimated CERT Support assuming £20/tonne $CO_2$ value to Supplier (£) | VAT Reduction from 17.5% to 5% (£) | Total Public Support (£) | Estimated Lifetime $CO_2$ Emissions Reduction (tonnes $CO_2$) | Public Cost of $CO_2$ Saved (£/tonne $CO_2$) | Simple Payback Period for Owner-Operator with Government Support (years) |
|---|---|---|---|---|---|---|---|---|
| 1kWe Solar PV[$] | £6,000 | £2,000 | £240 | £714 | £2,954 | 12 | £246 | 58 |
| *Micro-wind (1kWe, 10% load factor), 50% onsite, 50% exported, 20-year life* | £1,800 | £540 | £140 | £214 | £834 | 7 | £128 | 22 |
| *Biomass Boiler, 20-year lifetime, meets all thermal needs, requires 4 tonnes wood/year* | £10,000 | £1,500 | £1520 | £1,190 | £4,210 | 76 | £55 | 8 to ∞[♦] |
| *Ground Source Heat Pump, COP 4:1, powered by grid electricity, 30-year life* | £10,000 | £1,200 | £720 | £1,190 | £3,110 | 36 | £86 | 56 |
| *Low Heat-Power Ratio micro-CHP, near-to-medium term technology, 10-year life* | £3,500[*] | £500* | £200[#] | £476 | £1,176 | 10[#] | £112 | 2 |
| *High Heat-Power Ratio micro-CHP, existing technology, 10-year life* | £3,000[*] | £500* | £100[#] | £417 | £1,017 | 5[#] | £191 | 0 |
| *Solar Hot Water, meeting 50% of hot water needs, 20-year life* | £3,200 | £400 | £160 | £381 | £941 | 8 | £118 | 53 |

**Table 25: Total Societal Cost of Policy Instruments for Key Microgeneration Technologies[&] (* indicates author's estimate, [#] indicates result from this thesis)**

[&] All economic estimates made using a current residential energy tariff offered by a major supplier, for energy consumption corresponding to a UK "existing terrace" dwelling. Exported electricity is assumed to attract 4p/kWh payment. All carbon calculations based on assumed embodied $CO_2$ of 0.422kg/kWh for electricity, 0.19kg/kWh for gas. It is recognised that all results are estimates, and substantial variation exists from installation to installation. Both CERT support and VAT reduction are notional amounts; the level of CERT support provided by a supplier is dependent on a business offering and therefore challenging to quantify, and VAT reduction is not seen by the owner/operator, it is an avoided expense rather than cash support.

[♦] Payback and $CO_2$ savings for biomass boiler depends on the fuel used.

At the other end of the policy spectrum are minimum standards regulations such as the building regulations and local planning policies. At the national-level, proposed direction for building regulations (e.g. the Code for Sustainable Homes) is a powerful tool that could effectively mandate the introduction of substantial microgeneration including micro-CHP. The details of implementation of such policies require careful consideration. For example, the current assumption within SAP methodology is that microgeneration benefits from a higher displaced $CO_2$ rate than onsite consumption. This is questionable as it implies that energy efficiency measures have less $CO_2$ per kWh displaced value than microgeneration. Indeed the current distinction between a zero dwelling emission rates as calculated by SAP, and "truly zero carbon" level 6 of the Code for Sustainable Homes requires attention. The final point regarding regulation relates to local versus national approaches, and the need to effectively link these. Devolved approaches such as the Merton rule appear to be a powerful tool for realising national direction, and clear distinction of the role of local, regional, and national policy and regulation could aid certainty and provide opportunities to the microgeneration industry.

Overall probably the most grounded existing measures in terms of achieving $CO_2$ emissions reduction are the changes in the building regulations (i.e. the Code for Sustainable Homes) and the Carbon Emissions Reduction Target, which when combined provide a useful "push" through minimum standards regulation with a complimentary "pull" of investment incentives based on an implied carbon price. Another complimentary aspect of these two measures is that CERT could potentially incentivise actions that are typically outside the realm of the building regulations, such as community heat schemes. Neither of the measures necessarily "picks winners", and can thereby be perceived as solutions appropriate to a competitive market. However their combined effect is relatively slow, providing perhaps 3% per year emissions reduction over business-as-usual. This is probably short of what is required to achieve a 60% or 80% absolute reduction by 2050 given projected increases in aggregate demand over this timeframe. Notwithstanding the shortfall, the measures should be able to provide significant support for microgeneration. For example, as presented in section 9.1.3, if 10% of the next CERT were to be achieved through uptake of low heat-to-power ratio micro-CHP, the 2011 to 2014 commitment period could result in 3,000,000 installations[37]. Similarly, if all new build dwellings were required to be zero carbon from 2016 as per the Code for Sustainable Homes, an identical

[37] This figure is supplied for comparison purposes only. In reality such a large uptake is very unlikely as it implies almost all boiler installations are replaced with low heat-to-power ratio micro-CHP installations over the commitment period.

three year period would result in at least 500,000 microgeneration installations[38]. Conversely, the grant support funding under the Low Carbon Buildings Programme will provide support for of the order of only 20,000 microgeneration installations over a three year period.

The Low Carbon Buildings Programme grant support mechanism is still a useful tool to raise the profile of microgeneration, and will provide valuable data for analysing take-up and (possibly) performance. It is aimed at awareness-raising and kick-starting the market, with the goal of creating possibilities for longer term emissions reduction should any technologies be successfully launched. However, given the short timeframe of support and the low total number of installations, unqualified achievement of these aims seems questionable: The lack of longevity of the instrument may prevent it from achieving anything meaningful in the long term. These problems also mean that it is relatively ineffective for supporting commercial investment in manufacturing capacity for the sector. Finally, from an environmental point of view, the programme supports microgeneration installation over a wide range of carbon prices, suggesting that it is not an instrument designed specifically with immediate $CO_2$ emissions reduction in mind, but is more focused on supporting technologies that may have an impact in the long term.

VAT and stamp duty tax relief provided for microgeneration have strong parallels with grant support, albeit with arguably lower value to the owner/operator, but without the confusing application process and compliance rules. Some aspects of these measures have little basis in robust energy policy, indiscriminately supporting various actions regardless of their effectiveness, as many microgeneration technologies have varying impact on realised emissions reduction. Actual impact of a measure depends on many factors including fuel type being replaced, annual heating and electricity demand in the dwelling, presence of other measures, availability of renewable resources, etc. Therefore blanket support measures such as VAT relief provide poor incentive to achieve emissions reduction, and the revenue forgone by this measure could be more usefully applied within a grant programme or other managed framework where applications can be vetted. It is more justifiable to support energy efficiency measures with VAT and stamp duty relief, because many of these are virtually guaranteed to be economically effective and have lower risk of poor $CO_2$ savings outcomes. The basis under which VAT relief was extended to micro-CHP appears somewhat flawed.

[38] Based on construction rate of 167,000 dwellings per year in Boardman, B., Darby, S., Killip, G., et al. (2005), 40% House. Oxford University Environmental Change Institute: Oxford, UK.

Personal tax exemption of revenue from microgeneration export is a simplifying measure, having little financial effect on the treasury, and should remain for the sake of simplicity of microgeneration ownership. If in the future significant quantities of microgeneration are installed, this issue may need to be revisited. In this scenario long term solution may lie in mechanisms such as those currently in place for taxation of UK personal bank accounts, where tax is taken at source with relatively little involvement of the income earner.

A number of practical issues regarding market structures and metering, balancing and settlement data flows remain, although many of these should be solvable given some effort and expense. The creation of credible standardised export profiles and import profiles for dwellings with microgeneration is probably the most significant challenge in this area in the near term, where a simple, robust and fair solution appears difficult to achieve. The alternative smart metering solution offers many advantages over profile classes, but it remains to be seen if these will be adopted and adapted for use with microgeneration.

A primary question regarding how these policy instruments relate to microgeneration is "how predictable is the $CO_2$ savings for each microgeneration technology?" Any $CO_2$ saving item, including energy efficiency measures, has some uncertainty with respect to actual $CO_2$ savings. For example, savings attributable to cavity wall insulation are roughly dependent on the annual thermal demand of the dwelling, but are influenced by other factors such as the behaviour of the owners, etc. Likewise, as suggested by results in this thesis, $CO_2$ savings from micro-CHP technology is correlated with annual thermal demand. In the past the EEC has attributed average savings to each measure, relying on the large number of installations to provide the correct aggregate savings. This assumption could still function reasonably well when microgeneration is added to the list of supported measures, but nonetheless probably does not provide the optimum $CO_2$ savings for the given public or private investment. Stakeholders may be better encouraged to incentivise effective investment if they were required to estimate $CO_2$ savings and meet a certain standard before providing support, although such as approach could be overly onerous in an administrative sense and thus entail high transaction costs.

For this thesis it is of interest to consider how these issues bear upon the provision of support for micro-CHP. From Table 25 it is apparent that existing financial support mechanisms could be a powerful influence on adoption of micro-CHP. This is because comparatively modest support levels result in relatively short payback periods for the technology, making it an option that is competitive with boiler systems and other

microgeneration measures. Therefore it is of interest to consider how and when support should be offered in order to improve the predictability of $CO_2$ savings achieved. The following sections investigate these issues.

## 9.2 New Policy Instruments to Support Micro-CHP

A few recent efforts, such as Element Energy (2008) and Energy Saving Trust (2007), have outlined potential policy support for microgeneration in the UK. The most recent study by Element Energy considered the growth potential for microgeneration (including micro-CHP) in the UK and suggested a range of policy interventions. Leading amongst these is a feed-in tariff, which would reward electricity generation from the micro-CHP unit. This mechanism appears to be under consideration by the government in that such an approach can be implemented under provisions in the recent Energy Act (HM Government (2008c)). This section investigates policy support mechanisms including a feed-in tariff.

As discussed in section 9.1 a variety of policy instruments relating to microgeneration already exist in the UK. Several of these specifically cover micro-CHP, and others could be easily modified to incorporate it. By far the majority of existing financial policy instruments discussed focus on encouraging uptake of microgeneration technologies, reflecting the fact that most of these are in the early stages of market penetration and are relatively insignificant in terms of contribution to overall energy supply and any associated greenhouse gas reduction. However, should the large potential market for microgeneration (and micro-CHP in particular) materialise, performance-based policy instruments that incentivise appropriate application and/or control of systems will enable their maximum potential to be realised. These instruments could replace or complement the existing upfront investment support instruments. These performance-based instruments should be included in the policy mix from an early stage to ensure the correct message is sent to equipment manufacturers, construction and refurbishment industries, energy market stakeholders, and potential owner/operators. The feed-in tariff incorporated in the recent Energy Act (discussed above) is the first step towards a performance-based incentive.

In order to consider the impact of existing or new policy instruments for the case of micro-CHP, it is necessary to understand what behaviour each of them is likely to encourage, and to consider some basic criteria commonly applied in formulation of energy policy instruments: For example;

1. Feasibility of implementation and workability of the instrument.
2. Effectiveness in achieving policy aims.
3. Cost-effectiveness (public and private).
4. Distributional consequences (particularly relating to fuel poverty).
5. Consistency with free market principles.
6. Flexibility should other policy instruments enter the arena.

One further important element, with particular relevance to the residential sector, is the possibility of a knock-on benefits associated with a policy instrument. Engagement of consumers with their energy supply may encourage further uptake of energy efficiency measures or demand-reducing behavioural changes. For example, Keirstead (2007) reported that installation of PV systems creates a "double-dividend" in that electricity consumption reduces by 6% and owner-operators tend to shift consumption onto times of likely PV generation. Therefore an additional point for residential sector policy instrument assessment could arguably be:

7. Engagement of consumers regarding their own energy provision.

Of the seven listed criteria for consideration, the following sections perform a quantitative assessment of only the greenhouse gas related "effectiveness" and the associated "cost-effectiveness" of a set of investment support and performance-based support instruments to incentivise appropriate uptake and application of micro-CHP technologies. It also makes qualitative comment on the other factors taken into account during policy development with respect to each of the instruments, although it is beyond the scope of this thesis to reach final conclusions on integrated residential sector energy policy. Also, it is important to note that the quantitative elements of the assessment provided here form only a part of the overall assessment of the "effectiveness" of the instrument, which also relates to (for example) behavioural issues which may improve or interfere with the effectiveness or knock-on consequences.

The following two sub-sections discuss justification and methods for upfront investment support and performance-based support, respectively.

### 9.2.1 Upfront Capital Investment Support

Investment support is important where the capital cost of equipment is high. This issue is specifically relevant to the residential sector, where implied discount rates (based on empirical evidence, for example Hausman (1979)) suggest that investment may not occur

even where it is arguably in the best interests of the beneficiary. Examples of this phenomenon include low observed uptake of energy efficiency measures by home owners, even where these investments have fast potential payback. Uptake of micro-CHP may be affected by this phenomenon as it is likely to have a higher capital cost than competing boiler technologies, and therefore potential investors may have high implied discount rates applied to the difference in capital cost. Therefore micro-CHP may benefit from some kind of investment support, reducing the capital cost gap between micro-CHP and the reference system. The same argument applies to the company control model put forward in Watson (2004) and discussed in section 4.1.1.2 of this thesis where the net present value of the investment would increase if capital support were in place. Results reported in this sub-section have been published by the author in Hawkes and Leach (2008b).

In existing UK energy policy investment support for microgeneration is apparent in;

1. The Low Carbon Buildings Programme.
2. The Carbon Emissions Reduction Target.
3. VAT reduction for "energy saving measures" including micro-CHP and microgeneration.

Whilst all of these instruments serve to reduce capital costs, they all act in different ways, as discussed in section 9.1.8. In addition to these existing instruments, a further possible means of providing capital cost support has been discussed in Watson et al. (2008) which suggests that enhanced capital allowances afforded to large centralised generators should also apply to microgeneration. In the case of the "company control" model this is certainly justifiable, and could be a convenient and equitable means of providing upfront support.

Whilst one can be reasonably certain that efficiency measures eligible for support (such as loft insulation) will provide $CO_2$ reductions, the studies presented in this thesis suggest that the same cannot be said for micro-CHP. Therefore it is suggested that support for mature micro-CHP technologies should be differentiated based on their potential to provide emissions reductions.[39] Support could also be differentiated based on the capacity credit of the systems, although indicators of $CO_2$ reduction and high capacity credit may well be

[39] Immediate $CO_2$ savings are certainly not the only policy concern (e.g. support can be provided to address any of a number of barriers to uptake such as to kick-start the market, provide signals and information to consumers and developers, encourage innovation, and point the direction for long term technology development, etc), but they are certainly an important one and are arguably requisite if a new technology is to be supported with the aim of reaching a mass market in the near term.

aligned, as discussed below. The conditions under which micro-CHP is likely to provide $CO_2$ reductions and capacity credit are discussed below based on results presented in Chapters 6, 7 and 8, leading to a set of requirements that could be implemented to target investment support at dwellings with a low risk of poor performance.

For existing dwellings the $CO_2$ result presented in section 7.1 of this thesis is that $1kW_e$ SOFC-based micro-CHP can reduce the "carbon footprint" of residential energy provision by up to approximately 1500kg $CO_2$ per year. This is a substantial reduction, and a defensible reason to offer financial support for investment in the technology should it be required. However, other micro-CHP technologies cannot achieve this level of $CO_2$ savings, and it has been demonstrated that savings are dependent on heat-to-power ratio of the prime mover, and the thermal demand of the target dwelling (as shown in section 7.1.2). It follows that thermal capacity of the unit is also an important characteristic as it also relates to the thermal constraints imposed on the system. Annual electricity demand in the target dwelling is less important as an indicator of likely $CO_2$ savings.

The differentiated performance of micro-CHP systems is further supported by section 7.3 of this thesis, which highlighted the benefits of low heat-to-power ratio micro-CHP technologies in terms of improved capacity credit, adding weight to justification for differentiated support for the technologies. Section 7.3 also noted that capacity credit is closely linked to installed capacity of each system, once again indicating that peak thermal capacity of systems is an important policy metric. Higher capacity credit implies that investment in these technologies means that investment in other "conventional" capacity to meet peak demand may not be required, increasing the efficacy of system capacity investment as a whole.

Therefore, where investment in micro-CHP is supported on the basis that it should provide $CO_2$ emissions reductions and/or have high capacity credit, that support needs to be underpinned by effective minimum standards of performance for micro-CHP systems and vetting of installations to increase the likelihood that policy aims will be met in relation to a specific target dwelling. This could be best achieved by a combination of:

1. Minimum standards regulation to ensure high overall micro-CHP efficiency (both part-load and full load, as discussed in sections 8.2.1 and 8.2.2), similar to arrangements that already exist for boilers in the UK (i.e. SEDBUK rating). Minimum standards could be extended to further technical parameters discussed

in section 8.2, but engineering capability to achieve certain characteristics would need to be assessed beforehand.

2. Classification of micro-CHP systems according to heat-to-power ratio and maximum thermal output capacity, reflecting the common result in this thesis that these thermal constraint issues are key $CO_2$ performance and capacity credit indicators.
3. Provision of financial support based on compatibility of micro-CHP heat-to-power ratio (and thermal capacity) with predicted dwelling thermal demand. Estimation of dwelling thermal demand could be based on Standard Assessment Procedure calculation (BRE, 2005) and/or home energy labelling related energy performance certificate (EPC) assessment.

In addition to these 3 basic requirements for financial support, it is also important to provide information and education to system selectors and installers such that appropriate devices and corresponding heat emitters are chosen, as discussed in section 8.2.3. Such action could also be delivered via dwelling energy assessment procedures (i.e. the Standard Assessment Procedure and/or Energy Performance Certificates) if calculation of dwelling emissions rates incorporates issues of relevance to successful installations. Provision of information regarding efficient operation of micro-CHP devices to dwelling occupiers, combined with "intelligent" integrated control strategies embedded in the systems, could also improve the average performance of installations. Application of these requirements will result in much greater certainty of $CO_2$ reduction, and have the benefit of also being closely aligned with cost-effective micro-CHP applications, according to the requirements presented in section 6.1.

However, even given this framework for supporting installations with potential for high-performance, further issues still exist regarding upfront capital investment support. These relate to concomitant policies. For example, for instruments supporting investment in both micro-CHP and energy efficiency in the residential sector, such as the Carbon Emissions Reduction Targets and the LCBP, the results discussed in this thesis are an important concern. Undifferentiated support of both energy efficiency and micro-CHP may be unwise, because there is an interaction between efficiency (i.e. reduced demand) and micro-CHP performance. Whilst results of analyses in this thesis suggests that micro-CHP can probably provide cost-effective emissions savings in many cases, insulation achieves this in virtually all cases. Therefore, whilst unconditional support of demand side efficiency measures such as insulation or low-energy appliances appears justified, the interaction

between insulation and micro-CHP performance further suggests caveats will be required to prevent support in situations where it would not serve policy aims. Maximum aggregate emissions reduction may be achieved if energy efficiency investment were not supported in the same dwelling in which micro-CHP investment is supported.

Looking into the future as building regulations improve insulation standards and appliance energy efficiency improves it is apparent that adoption of a defensible approach for government support of micro-CHP becomes more important. As building envelope efficiency improves the case for investment and expected $CO_2$ reductions decline rapidly for high heat-to-power ratio technologies, implying that support for their installation could result in outcomes the opposite of policy aims. Low heat-to-power ratio technologies fare much better, but there is still some risk of negative outcomes. This result indicates that low heat-to-power ratio systems are more future-proof in that they can maintain economic and $CO_2$ performance in spite of increasingly stringent building regulations and improving insulation in the existing housing stock. This forward-looking scenario once again reinforces differentiated support for micro-CHP based on the factors listed above and adds the *potential* of a dwelling to be insulated to the list of considerations relevant to vetting financial support. This potential is already assessed in existing Energy Performance Certificate calculations, so access to this information is not problematic.

On the whole upfront investment support, even when properly targeted, is not the only type of support that should be afforded to micro-CHP. As was discussed in relation to Figure 37, $CO_2$ performance is linked to how systems are utilised during their lifetime. Poor $CO_2$ outcomes are still possible, even for targeted installations, depending on *operational* financial incentives. To address this issue, the following section investigates four possible performance-based incentive scenarios in order to understand which ones best motivate operation of micro-CHP to achieve low $CO_2$ outcomes.

### 9.2.2 A Performance-Based Policy Instrument to Support Micro-CHP

Four structures of performance-based policy instruments are investigated. These are chosen based on a) current proposals regarding feed-in tariffs for microgeneration in the UK, b) ability to implement policy instrument with little or no change to current metering requirements, and c) lack of possible negative economic consequences for a dwelling owner-operator who installs microgeneration (because the possibility of negative consequences is likely to be politically unacceptable). An important assumption in the initial analysis is that the fair reward for electricity export is zero, based on the premise that

metering, balancing and settlement costs counter weigh the value of exported electricity. The structure and metering requirements of each of the four instruments is discussed below.

**Policy Instrument 1: Reward for electricity exported to the grid**

The first instrument relates to providing a regulated incentive for the buyback of electricity where a micro-generation owner/operator exports electricity to the grid. This instrument could come in the form of a fixed buyback price for all electricity exported from a dwelling, or a regulated reward price upon which a Supplier could add an additional amount. The instrument can diminish or remove the disparity where the value of displacing import of electricity (approx 10 pence/kWh marginal price) and the value of exporting electricity to the grid (which could be up to 4 pence/kWh - the average wholesale price minus metering balancing and settlement costs).

**Policy Instrument 2: Reward for onsite generation of electricity**

The second instrument provides reward for all electricity generated by the micro-CHP system regardless of whether it is consumed onsite or exported to the grid. This instrument would provide for a minimum payment to the generator per kWh produced, and therefore requires the presence of a meter to measure this contribution. This is identical to the feed-in tariff recently made possible for micro-CHP and other microgeneration in HM Government (2008c).

**Policy Instrument 3: Reward for $CO_2$ reduction**

This instrument is more involved than the previous two in that it straddles both electricity and thermal vectors in the dwelling. It estimates the total $CO_2$ reduction afforded by the electrical and thermal output of the microgenerator, in comparison to a defined baseline consistent with the "conventional alternative". This alternative, as applied in this study, is the case where electricity needs are met via the grid and thermal needs are met via a condensing boiler fuelled by natural gas. Whilst this results in a more complex (and controversial) calculation methodology than the other instruments considered, it is likely to better account for micro-CHP which also straddles electrical and thermal energy vectors. In terms of metering, for approximate calculation of economic benefit, this instrument requires import, export and onsite generation meters, although more accurate (and probably unwarranted) calculation could be achieved through installation of a thermal demand meter.

**Policy Instrument 4: Reward for $CO_2$ Reduction Combined with Export Reward**

The final instrument considered is identical to the 3rd instrument described above, but additionally includes provision for a fair reward for export of electricity. It is assumed that this fair reward entails no additional societal cost, because exported electricity displaces other electricity sources, thereby eliminating "additionality" of the reward (i.e. the micro-CHP generation is treated like any other source of generation in the free market).

### *9.2.2.1 Qualitative Assessment of the Policy Instruments*

A qualitative assessment of feasibility/workability, consistency with energy market policies, and potential for engagement of consumers with their energy provision for each of the four policy instruments is presented in Table 26.

| Instrument | Metering Requirement | Implementation & Workability | Consistent with Free Market | Engagement |
|---|---|---|---|---|
| **Reward for Electricity Export** | Import & Export Meters | Feasible | No | Somewhat |
| **Reward for Onsite Electricity Generation** | Import & Generation Meters | Feasible | No | Somewhat |
| **$CO_2$ Reduction Reward** | Import, Export and Generation Meters | More Challenging | Somewhat | Yes |
| **CO2 Reduction Reward with Reward for Electricity Export** | Import, Export and Generation Meters | More Challenging | Somewhat | Yes |

**Table 26: Qualitative Assessment of the Four Policy Instrument Scenarios**

It is likely, and probably desirable, that any microgeneration installation is equipped with onsite generation and export meters, as these provide flexibility and optionality regarding provision of information and reward. Therefore metering requirements is not seen as a particular disadvantage for any of the policy instruments.

Regarding implementation and workability of the policy instruments, $CO_2$ reduction reward is likely to be the most challenging. This is because it requires estimation of the $CO_2$ emissions that would have arisen had the dwelling used the reference system instead of the micro-CHP system. However, similarly to existing requirements for boilers (i.e. SEDBUK rating), a rating system for micro-CHP is likely to emerge. If such a system includes seasonal efficiency values or seasonal heat-to-power ratios as postulated in section 9.2.1, estimation of the reference system result will become possible. Therefore, whilst administrative burden increases, the instrument is arguably workable.

Like any policy intervention in a market economy, all instruments that interfere with price cannot be considered to be in harmony with free market ideals. Therefore both export

reward and onsite generation reward are not consistent with free market principles. The $CO_2$ reduction reward is more amenable to the free market because it does not act directly on commodity price, although this is certainly debateable as a number of indirect influences may be apparent. Arguably a market for $CO_2$ does exist in the European Emissions Trading System (EU-ETS) and Kyoto-protocol mechanisms (i.e. Clean Development Mechanism, Joint Implementation), although this market is an intervention in itself.

Finally, all instruments serve to engage the owner/occupier with their energy supply, and could motivate knock-on behaviour that further reduces fuel consumption and $CO_2$ production. The $CO_2$ reduction reward was deemed the best of the three because it acts across energy vectors, engaging the consumer with both their electricity and thermal needs, and acts directly on $CO_2$ reduction.

#### *9.2.2.2 Quantitative Assessment of the Four Policy Instruments*

Each policy instrument is now evaluated according to its economic and environmental credentials using the primary economic and environmental metrics applied in this thesis (see section 4.1). Each of the four instruments is analysed across a range of electrical efficiencies of the prime mover. Note that technical characterisations of the micro-CHP technologies have been altered from that presented in section 2.2 to enable this analysis. All characteristics except electrical efficiency are held constant to enable consistent consideration across the range of possible system efficiencies, and to better understand interaction between electrical efficiency and export reward. It is expected that this alteration introduces a small error into the result for some micro-CHP systems, the magnitude of which does not impact upon the conclusions drawn.

The top-left subplot in Figure 68 shows that export reward rate can be a strong incentive for uptake (and use of) micro-CHP; for example, a strong export reward of 10p/kWh can result in an electrically-efficient (low heat-to-power ratio) system having a value of approximately £3,500 more than the competing reference system. In this scenario, if the reference system were a £2,500 boiler, the rational investor would pay up to £6,000 for the $1kW_e$ micro-CHP system. This indicates a strong potential market for low heat-to-power ratio micro-CHP under this type of policy instrument, assuming existing capital cost targets for these technologies can be met. However, the $CO_2$ result displayed in the top-left of Figure 69 indicates an unwelcome corresponding phenomenon.

In the top-left subplot of Figure 69, for low buyback rates, $CO_2$ reduction is substantially lower than for moderate rates (i.e. the front side of the surface exhibits a steep upward slope between 2p and 4p/kWh reward). For moderate buyback rates between 4p and 6p/kWh, emissions reduction is solid, despite a small drop in performance near efficiencies of 20% to 30%. Most importantly, for high buyback rates above 6p/kWh in the efficiency range of 20% to 30%, $CO_2$ reduction collapses. This is because it becomes effective to dump heat from the system, whilst still achieving a positive economic result through selling the electricity generated. For details relating to this phenomenon the reader is referred to section 7.1.3, which discussed this issue in relation to the ability of micro-CHP to meet policy aims.

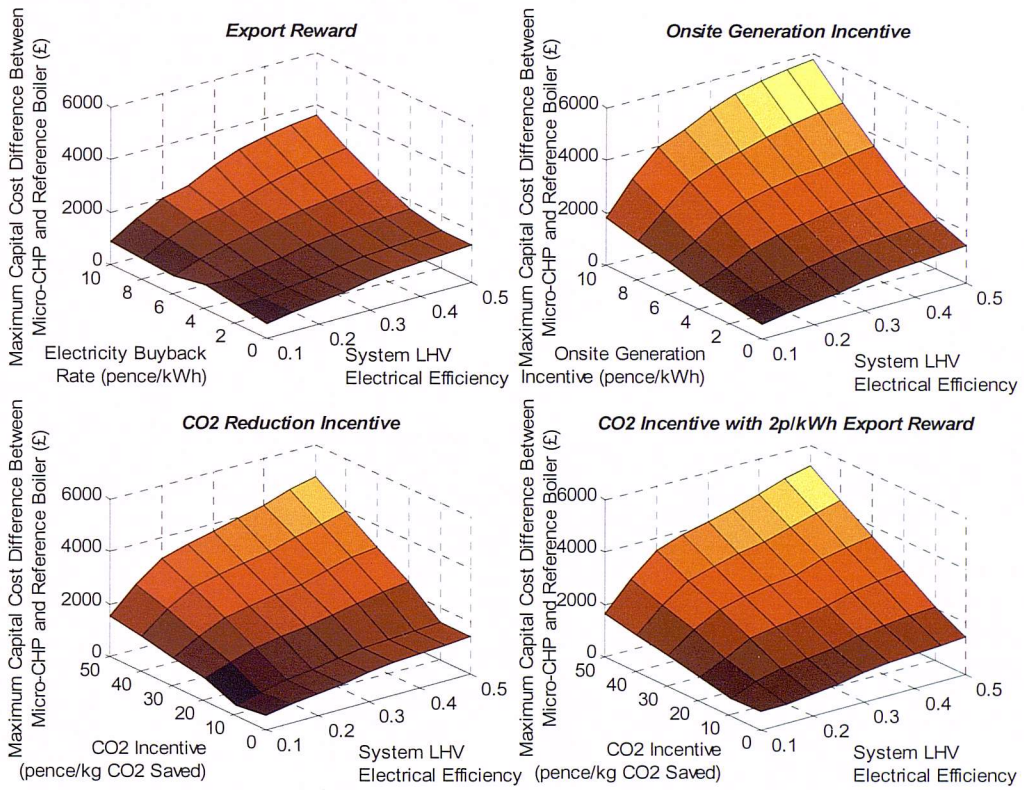



**Figure 68: Sensitivity of Maximum Cost Differential Between Micro-CHP and Reference System w.r.t. Incentive Level and Micro-CHP Prime Mover Electrical Efficiency, for the Four Policy Instrument Scenarios**

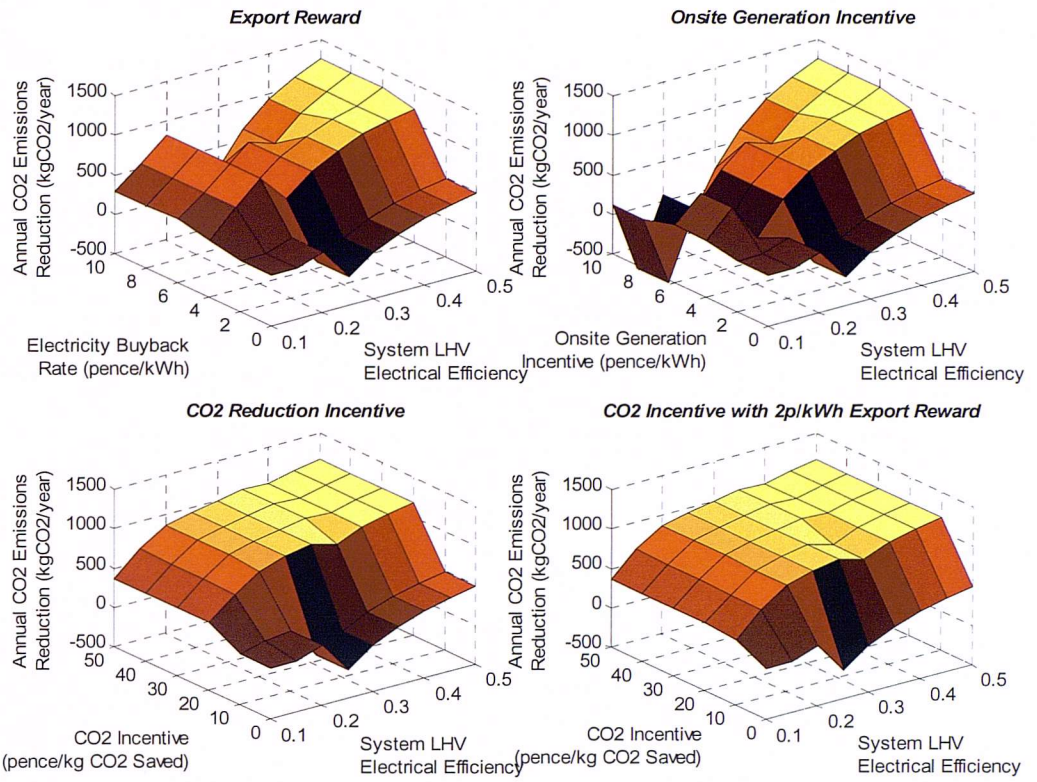



**Figure 69: Sensitivity of Maximum Cost Differential Between Micro-CHP and Reference System w.r.t. Incentive Level and Micro-CHP Prime Mover Electrical Efficiency, for the Four Policy Instrument Scenarios**

This issue presents a challenge to policy makers because a perverse outcome is possible, where substantial "public" investment is made in a technology on environmental grounds, and that investment results in little or no $CO_2$ reduction. Matters are further complicated by the fact that if suppliers offer no reward for export of electricity, $CO_2$ reduction is meagre, and certainly substantially lower than the potential the technologies offer. This creates a two-sided problem for policy makers, where either no support or too much support can yield poor environmental results. Therefore, should an export reward policy instrument be implemented, its performance should be closely monitored to ensure its effectiveness. If it fails to deliver $CO_2$ reductions, the alternative is to regulate electricity buyback price for the residential sector, although such an approach is likely to lack dynamism and conflict with free market principles.

Given the challenges associated with reward for electricity export, the three alternative policy instruments are compared with the export reward instrument in terms of economic outcome and $CO_2$ reduction characteristics. Results of these analyses are displayed in the remaining subplots in Figure 68 and Figure 69. All subplots in Figure 68 are simple to interpret; all four policy instrument scenarios provide a positive economic result for the owner-occupier who installs micro-CHP. The reader should note that these plots are not

intended to allow comparison between instruments, as the financial effectiveness is dependent on a variety of other factors (e.g. the public and private cost per kg $CO_2$ saved, the impact of incentive value on investment attractiveness, etc). Figure 68 simply shows that a negative financial outcome is not possible for the owner-operator, and negative distributional consequences are therefore somewhat mitigated. This is an important aspect of policy instruments that act on the residential sector, which has extremely diverse energy demands from dwelling to dwelling, and is likely to be a politically sensitive area for intervention.

The corresponding $CO_2$ result in Figure 69 is widely varied between the policy instruments. Onsite generation reward (i.e. the 2nd policy instrument – onsite generation reward; top-right subplot in Figure 69), exacerbates the problems experienced by electricity export reward. It effectively increases the motivation to operate the system in a way that discards heat in order to profit from generating electricity. In comparison to export reward, it applies the heat-dumping incentive to all onsite generation, rather than just the component that is exported to the grid. When Figure 68 and Figure 69 are examined together, it becomes apparent that onsite generation reward provides the greatest economic incentive, whilst simultaneously producing the worst (i.e. widely varied, and on-average the least $CO_2$ saving) $CO_2$ result. Clearly this is not a desirable combination from the point of view of public spending with the aim of $CO_2$ reduction, and thus casts doubts on current policy direction in HM Government (2008c). The third policy instrument considered – the incentive for $CO_2$ reduction (bottom-left subplot) – provides a solid $CO_2$ result, with no pitfalls in specific efficiency or incentive level ranges. $CO_2$ reduction is solid between incentive levels of 20 pence/kg $CO_2$ and 50 pence/kg $CO_2$. The final policy instrument – the case where $CO_2$ reduction reward is bolstered by fair reward for export of electricity – also provides a solid $CO_2$ result. It is essentially the same result as the 3$^{rd}$ policy instrument, but solid $CO_2$ reduction is visible down to 10p/kg$CO_2$ incentive level. The pitfalls of export reward alone are not apparent.

In order to conclude the discussion of these policy instruments and improve differentiation between them, one further metric is now considered; the "public" cost per tonne of $CO_2$ reduction. This gives an indication of the effectiveness of the instruments from a societal public spending point of view. This metric is displayed for each of the instruments, across incentive level and micro-CHP system electrical efficiency, in Figure 70. As expected, both $CO_2$ reduction incentive scenarios provide a flat "public cost" surface, as this incentive is

explicitly related to $CO_2$ savings. Both export and onsite generation reward incentives present a much more varied result, with the cost of payouts under the incentives ranging from zero to more than two thousand pounds per tonne of $CO_2$ saved. Clearly, in terms of public cost, the $CO_2$ reduction incentive provides the most consistent result, although this may not always be the best result, as discussed below.

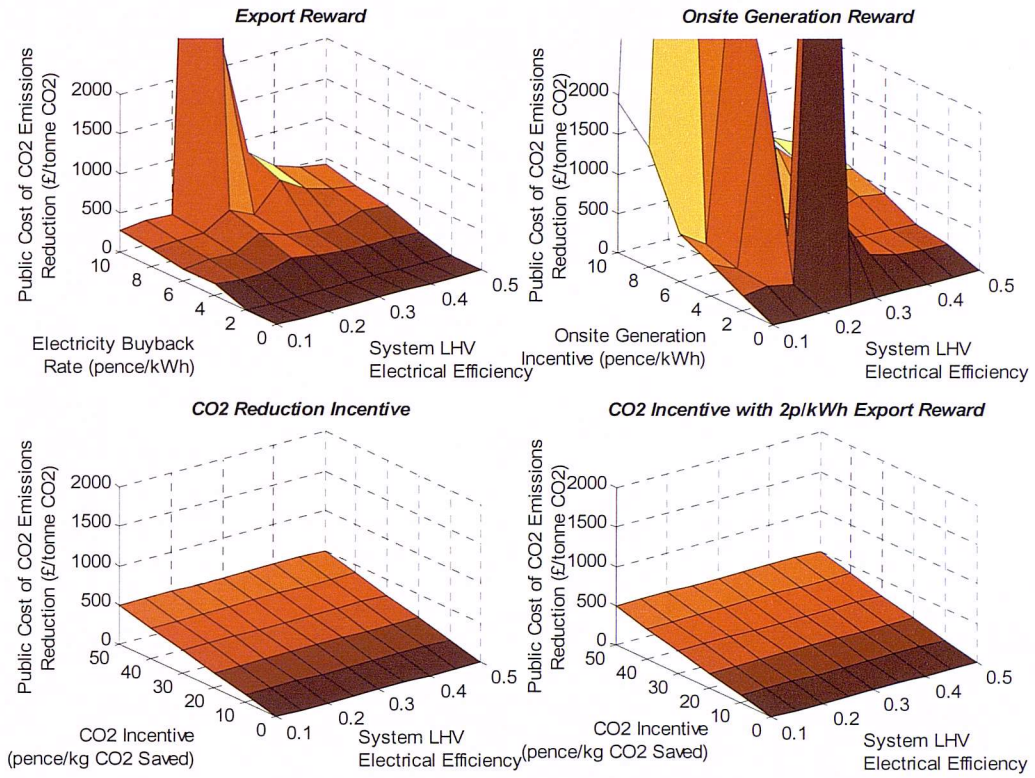



**Figure 70: Sensitivity of Maximum Cost Differential Between Micro-CHP and Reference System w.r.t. Incentive Level and Micro-CHP Prime Mover Electrical Efficiency, for the Four Policy Instrument Scenarios**

There are some cases where the electricity export reward incentive yields lower cost per tonne $CO_2$ saved than the $CO_2$ reduction incentive, notably for low electrical efficiency systems and moderate-to-high incentive levels (i.e. a 10% efficiency system, with 10p/kWh buyback rate or 50p/kg$CO_2$ saved), and for all very high electrical efficiency systems. This outcome is examined in more detail with reference to Table 27, which takes selected results from Figure 69 and Figure 70, and compares them.

| Reward Type | System Electrical Efficiency | Reward Level | $CO_2$ Saved (tonnes/year) | Public Cost of $CO_2$ Saved (£/tonne) |
|---|---|---|---|---|
| **Export Reward** | 10% | 4p/kWh | 0.23 | 150 (75*) |
| | 25% | 4p/kWh | 0.5 | 228 (114*) |
| | 45% | 4p/kWh | 1.1 | 120 (60*) |
| **Onsite Generation Reward** | 10% | 4p/kWh | 0.23 | 400 |
| | 25% | 4p/kWh | 0.5 | 500 |
| | 45% | 4p/kWh | 1.1 | 240 |
| **$CO_2$ Reduction Reward** | 10% | 20p/kg$CO_2$ | 0.36 | 200 |
| | 25% | 20p/kg$CO_2$ | 0.94 | 200 |
| | 45% | 20p/kg$CO_2$ | 1.2 | 200 |
| **$CO_2$ Reduction Reward and Export Reward** | 10% | 10p/kg$CO_2$ & 2p/kWh | 0.36 | 100* |
| | 25% | 10p/kg$CO_2$ & 2p/kWh | 0.94 | 100* |
| | 45% | 10p/kg$CO_2$ & 2p/kWh | 1.2 | 100* |

**Table 27: $CO_2$ Saved and Public Cost of $CO_2$ Saved for the Four Policy Instruments and Selected Incentive Levels (* indicates assumption that 2p/kWh export reward is a fair market reward)**

The first point to be made in relation to Table 27 is regarding the cost of $CO_2$ reduction. Implied $CO_2$ prices to the public revealed in this analysis for all of the efficiency/incentive cases are extremely high when compared to traded prices on the European Emissions Trading Systems (EU-ETS) of €20 to €30 per tonne $CO_2$. This casts doubt on the ability of performance-based instruments supporting micro-CHP to provide economically rational $CO_2$ reduction from a public spending point of view. However, this result is extremely sensitive to a number of factors, as discussed below.

Examination of Table 27 shows that the export reward instrument, at the 4 pence/kWh level, is a good option for high and low micro-CHP system efficiencies, but is less impressive for moderate efficiencies, where the $CO_2$ incentive provides a significantly better result. The onsite generation incentive produces a poor result on all counts, with significantly higher cost for equivalent $CO_2$ savings. The combination of incentives – $CO_2$ reduction incentive and fair reward for export – provides the best result with the highest aggregate $CO_2$ savings and the minimum public cost.

However, this is not a particularly fair comparison, as the 4$^{th}$ scenario assumes there is a 2p/kWh fair value for export reward, whilst the other instruments have not benefited from this assumption. All other scenarios assumed zero fair value of export reward, based on the hypothesis that the costs of metering, balancing and settlement cancel out the value of electricity generated. It should be noted that this assumption is uncertain for existing metering arrangements, and in the near to medium term smart metering and IT solutions may largely circumvent the issue. However, if the export reward scenario included a 2p/kWh fair reward for export, then its public cost of $CO_2$ reduction would be lower than that of the $CO_2$ incentive under equivalent circumstances (see numbers marked by * in Table 27), except in the case of the 25% efficiency micro-CHP system.

It is concluded that whilst performance-based instruments are required to motivate low-carbon operation of micro-CHP systems, it is challenging to differentiate between them before the value of fair reward for export is properly established. This value can be modelled, but will only be proven when large penetration of the technologies are present and aggregate metering, balancing and settlement costs are observed. In the meantime it is arguably appropriate to ensure a modest export reward incentive of the order of around the average wholesale price of electricity. This is provides a signal to stakeholders that performance-based support will be offered to owner/operators of micro-CHP. The impact of this support should be monitored to ensure perverse outcomes are not produced, and adapted according to the characteristics of technologies eventually offered to the market. If metering (etc) issues are addressed in the future, resulting in (for example) fair export reward being approximately the wholesale price of electricity, it is possible that no government incentive will be required to motivate low-$CO_2$ operation of a dwelling's energy production/consumption, and the cost of $CO_2$ reduction to the public would therefore be zero. In the meantime, any reward schemes should be monitored by the regulator to ensure constructive incentives for low-$CO_2$ operation are offered, and perverse outcomes are avoided.

## 9.3 Conclusions Regarding Policy Support for Microgeneration and Micro-CHP

A variety of policy instruments, most of which are focused on upfront capital cost support and removing various non-financial barriers, exist for microgeneration in current UK energy policy. A wide range of implied carbon prices are supported by the existing suite of policy instruments, so clearly other reasons to support measures are at work such as motivating innovation, kick-starting the market, providing a signal of future direction for developers and consumers, and generating information regarding the economic and environmental performance of existing technologies. Looking into the future it appears that increasingly stringent building regulations will promote strong uptake of microgeneration and efficiency measures, with potential for a large number of installations over coming years.

A range of factors are relevant to the success or failure of residential sector energy policy in relation to microgeneration, such as addressing perceived versus bona fide risk, access to information, access to capital and behavioural issues. Amongst these, appropriate metering, balancing and settlement of microgeneration electricity generation/export has been identified as an important factor for many energy market stakeholders including

microgeneration owner/operators, energy suppliers, DNOs, and those involved in metering services. The existing arrangements revolve around aggregate consumption, generation and export metering and the application of profile classes to determine energy balancing requirements and fair settlement. This inhibits constructive and fair access to the benefits of microgeneration. It is a challenging problem to address, although IT and smart metering may provide solutions in the near to medium term, and should be considered from an early stage.

In amongst the variety of microgeneration technologies and efficiency measures, micro-CHP was assessed in terms of ability to provide economically-rational $CO_2$ reductions. Under specific assumptions regarding the final installed cost of micro-CHP products, and the results relating to performance revealed in this thesis, it appears that micro-CHP could be a very competitive option. Even modest levels of financial support (upfront and/or performance-based) could yield an attractive case for investment. The primary reasons for this result are the fact that investors will consider the cost difference between micro-CHP and the competing reference system (i.e. in this case a condensing boiler), and a perceived (relatively) low capital cost of micro-CHP with respect to other "home heating" microgeneration technologies.

A framework for providing upfront capital investment support and performance-based support were considered. Front-loaded capital support may be desirable, depending on final capital costs of micro-CHP systems. A method by which capital support could be provided was suggested, based on results presented in earlier chapters of this thesis. Three basic actions that could improve the average performance of supported installations are 1) minimum standards regulation to ensure high efficiency and other appropriate technical characteristics of micro-CHP systems allowed into the market, 2) classification of systems according the heat-to-power ratio and thermal output capacity, and 3) provision of support based on a match between technical characteristics and the thermal demand in the target dwelling. These actions could be supported by information/education actions to improve the likelihood that specific installations will perform well, including incorporation of relevant issues into the government's Standard Assessment Procedure for buildings. Useful links with the existing process for providing residential dwellings with Energy Performance Certificates were also identified, where data from the process could be used to verify the potential for good performance.

Performance-based reward was also investigated. It was shown the currently proposed methodology for support of micro-CHP (i.e. feed-in tariffs) can provide perverse incentives. This is because they can motivate owner/occupiers to increase thermal demand of their dwelling in order to be able to generate electricity (i.e. relax thermal constraints on operation and thus profit from high-value feed-in tariffs). A new support incentive was proposed that can avoid this issue; a $CO_2$ reduction reward based on metered consumption and production. This instrument would calculate a "baseline" $CO_2$ footprint for energy provision in the dwelling from metered amounts and the seasonal heat-to-power ratio of the micro-CHP unit, and would reward reduction of that $CO_2$ footprint through application of the micro-CHP unit. It was shown that this avoids the potential perverse incentive of feed-in tariffs, but sometimes at a higher cost (to the public) per tonne of $CO_2$ saved. In terms of effective performance-based incentives, it was concluded that the public cost of $CO_2$ reduction could be very high (up to £200/tonne $CO_2$ reduction), and indeed final inferences regarding the most effective instruments should be reserved until a better understanding of the true fair value of exported electricity is gained. In the meantime provision of export reward is reasonable, but performance should be monitored to prevent perverse outcomes.

Given the high potential public cost of $CO_2$ reduction, provision of both upfront capital investment support and performance-based support to the levels investigated in this chapter seems excessive. However, both modes of support may be required to effectively trigger uptake and incentivise appropriate operation. One possibility to address this issue is the potential to front-load performance-based support, where the investor would receive a certain portion of the value of their future electricity generation or $CO_2$ reduction at the time of purchase of the system (i.e. a portion of output is "deemed"). The remaining portion could then be awarded for low $CO_2$ operation of the device. This approach retains the potentially crucial upfront component of the incentive, whilst also providing the necessary performance-based signals. Regardless of the structure of the instrument, there remains a necessity to monitor the situation as time progresses because the incentives created depend on tariffs, technology characteristics, and grid electricity $CO_2$ rates (see section 7.1.4 for a discussion of the impact of grid $CO_2$ rate on achievable emissions reductions). Change in any of these factors could provide opportunities or problems with the effectiveness of chosen policy instruments.

Overall there is a need for much more joined-in energy policy for the residential sector. Currently there is a disconnect between instruments, which often only consider part of the picture. For example the building regulations treat carbon reduction is a substantially different way to supplier targets, and neither is explicitly linked to long term $CO_2$ reduction targets. With the advent of microgeneration (including micro-CHP) there is a need for simpler instruments that engage stakeholders across electricity and heat vectors, rather than focusing on one or the other. Instruments should be formulated with consumer engagement in mind, and fair access to the benefits of measures should be available to the corresponding owner/operator. Finally, if long term $CO_2$ targets are to be met, it is apparent that "packages of measures" will be required in each dwelling. Therefore, research is required into selection and integration of these measures. Alongside this, whilst technology-specific support is still justified (for reasons other than immediate economically-rational $CO_2$ reduction), appropriate long term policy is required that can act across issues for the residential sector (rather than focusing on specific technologies) and is explicitly linked to long term $CO_2$ emissions reduction targets.

# Chapter 10: **Conclusions and Further Research**

## 10.1 Conclusions

The residential sector produces more than a quarter of national greenhouse gas emissions in the United Kingdom, making it a focus of activity relating to mitigation of climate change. A number of recent developments in technology and energy policy aim to reduce the impact of the sector by motivating uptake of energy efficiency measures and encouraging installation of microgeneration. One microgeneration technology that could become important in this arena is micro combined heat and power (micro-CHP); an emerging class of technologies designed to replace existing residential boiler systems and provide heat and some electricity to single dwellings. Micro-CHP could speak to all of the three pillars of general energy policy; economic competitiveness, energy security, and environmental issues. It also has a very large potential market, with some projections predicting several million installations in coming decades. Therefore it is of interest to identify the potential of micro-CHP to meet policy aims at low public and private cost, to direct technology development with the aim of producing systems with desirable characteristics, and to consider how policy may appropriately support the technologies.

This thesis has developed a new modelling framework designed to facilitate examination of the techno-economic and environmental credentials of micro-CHP. The robustness of this modelling approach has been examined, followed by its application to study key economic drivers of the technologies and their ability to aid in meeting a defined set of primary energy policy goals. A characterisation of the capacity credit of micro-CHP was also developed to help understand the impact of a large scale introduction on the electricity system. The modelling framework was then employed again to investigate nine specific technical characteristics of micro-CHP systems in terms of their bearing on economic and environmental outcomes, with the intention of providing focus for research and development related to new systems. Finally, current and proposed energy policy related to the residential sector has been considered with reference to the results presented, followed by development and discussion of the justification for and structure of potential new policy instruments to support micro-CHP in coming years.

Four micro-CHP prime mover technologies have been investigated. These were chosen on the basis that they are the subject of the majority of commercial interest to date. Two are engine-based systems; Stirling engines and Internal Combustion Engines (ICE), and two are

fuel cell based systems; Polymer Electrolyte Membrane Fuel Cells (PEMFC) and Solid Oxide Fuel Cells (SOFC). The majority of the investigations considered 1kW$_e$ systems. The only primary fuel investigated was natural gas, which is widely available via a piped network in the United Kingdom and therefore does not require substantial infrastructure investment. Application of micro-CHP systems in a range of existing and potential future dwellings was considered, based on the observed characteristics of residential demand mapped to the census categories for dwelling constructions type. The dwellings were assumed to be grid-connected, allowing import and export of electricity.

The following sub-sections first present and discuss the broad overarching conclusions relevant to a cross section energy related stakeholders that can be drawn from the thesis as a whole, followed by conclusions that are relevant to specific stakeholders.

### 10.1.1 Key Overarching Conclusions

Micro-CHP can provide cost-effective $CO_2$ emissions reductions in a range of circumstances. This is because the maximum allowable installed cost difference, at 12% discount rate, between a 1kW$_e$ micro-CHP system and the competing conventional alternative (i.e. a condensing boiler) can be up to £1,300 for a system that can reduce annual $CO_2$ emissions by 1,500kg per year. This marginal cost between micro-CHP and a boiler is arguably achievable if systems are mass-manufactured, and in essence implies zero net cost greenhouse gas emissions reduction for dwellings that adopt the technology. However, micro-CHP cannot provide cost-effective (or indeed any) $CO_2$ emissions reductions in all circumstances. Based on the analyses in this thesis, the primary driving forces of performance are discussed below.

The value of micro-CHP systems with the respect to the competing boiler systems (i.e. the primary economic metric applied in this thesis) is driven by a combination of electricity production and presence of onsite electricity demand, and limited by excessive thermal production and/or lack of thermal demand. For appropriately sized units, heat-to-power ratio is the key technical metric that speaks to these issues because it captures the propensity of a unit to deliver electricity despite low thermal demands. At times of low thermal demand a micro-CHP prime mover with a low heat-to-power ratio will be able to continue operating (and displacing expensive electricity import) where a higher heat-to-power ratio technology will be required to modulate of switch off.

The driving forces of $CO_2$ reduction for micro-CHP are identical to those of value, with the exception that annual electricity demand of the dwelling is not important. This is because

the $CO_2$ credit obtained for displacing imported electricity is similar to that for exported electricity. Conversely, for the economic case, the value of displacing onsite electricity demand is substantially higher than the value of electricity exported to the grid.

Another overarching conclusion is that heat-to-power ratio and thermal output capacity of micro-CHP systems also bear upon their capacity credit. Low heat-to-power ratio systems provide much higher capacity credit than high heat-to-power ratio systems. This result has identical roots to the economic and environmental result; low heat-to-power ratio systems can continue operating when heat demand is low, whilst other systems must modulate or switch off. It was shown that under certain circumstances fuel cell based micro-CHP could have capacity credit greater than one, implying that it could displace more capacity of centralised generation than its own installed capacity. The capacity credit result implies that low heat-to-power ratio micro-CHP can be a positive influence in achieving economically-efficient electricity system expansion.

On the whole technologies with low heat-to-power ratios, low thermal capacity, contributing to serving larger annual electricity and thermal demands are best placed to access economic value. For $CO_2$ reductions, technologies with low heat-to-power ratio, low thermal capacity, serving a larger annual thermal demand are best placed to provide savings. The factors that lead to significant $CO_2$ savings will also lead to high capacity credit. Therefore appropriately sized fuel cell based micro-CHP technologies, which have the lowest heat-to-power ratios of the investigated systems benefit from all of these attributes and provide the best performance. The SOFC-based systems as characterised here provide the largest allowable installed cost difference (w.r.t. boiler), the greatest $CO_2$ emissions reduction, and have very high capacity credit. Mid-range heat-to-power ratio ICE-based systems exhibit reasonable performance across factors, whilst very high heat-to-power ratio Stirling engines (as modelled here) are challenged to provide economic competitiveness, emissions reductions or appreciable capacity credit in any circumstance. The primary caveat to these statements is that the final mass-manufactured installed costs of each technology are not yet observable. For example, the relative advantages of SOFCs may be less relevant if the final products are much more expensive than internal combustion engines. Investigation of potential final installed cost of systems is beyond the scope of this thesis.

### 10.1.2 Conclusions Relevant to Residential Energy System Modellers

The development of the modelling framework presented in Chapter 4 (with background in parts of Chapters 2 and 3) and the investigations into the robustness of modelling presented in Chapter 5 lead to conclusions regarding how to model an emerging technology in the residential single-dwelling situation. These conclusions relate to the type of modelling applied and appropriate characterisation of technology and energy demand. They are discussed in the following paragraphs.

The relative merits of system simulation versus optimisation modelling were discussed in Chapter 3 (section 3.1), with the conclusion that unit commitment optimisation is a useful element of a toolkit that can be applied to assess the techno-economics of micro-CHP, which is an emerging technology. This is because it provides a feedback loop between a technical characterisation and the operating strategy of the unit. This means that where presence of a particular technical constraint results in a new operating strategy providing a better outcome (w.r.t. a defined objective function), the model will immediately identify this. Simulation could arrive at the same result, but only by "brute force" methods where models are run (hundreds of) thousands of times to investigate sensitivities. The relative advantage of system simulation, which is its ability to better represent system dynamics, is offset by the potential to structure constraints in optimisation modelling to emulate these dynamics.

Further information useful to modellers can be drawn from the approach adopted for development of the modelling framework. These relate to characterisation of micro-CHP. The primary economic metric chosen for analysis – the installed cost difference between the micro-CHP system and the competing reference system – is chosen on the basis that micro-CHP is a home heating system which completely replaces the conventional alternative (i.e. the reference system). Therefore the potential investor is more likely to consider this cost difference rather than the total installed cost. Policy makers and other stakeholders will also consider micro-CHP in relation to the reference system. Therefore the definition of the reference system is very important when assessing the credentials of micro-CHP. The choice of the primary economic metric in this thesis circumvents the need to estimate the capital cost of the reference system, but its valuation and estimation of $CO_2$ reductions still requires a reference. For this thesis the reference system has been chosen to be the case where electricity demand is served by grid electricity, and thermal demand is served by a natural gas fuelled condensing boiler. Each of the investigated micro-CHP prime movers has different technical characteristics relating to the fundamental principles

that govern their operation. Systems have been characterised at a relatively high level herein in order to enable tractable analysis whilst maintaining technical credibility for system developers. Basic parameters that define each system were chosen to be a) capacity, b) efficiency at part and full load to account for differences between systems, c) maximum ramp up/down rates, d) start-up and shutdown costs and associated energy consumption, e) minimum operating set-point, f) minimum up-time and minimum down time, g) degradation for fuel cells. This set of parameters is sufficient to perform economic and policy related calculations in that they provide good representations of steady-state performance whilst also enabling emulation of the dynamics of operation.

The final conclusions with respect to energy system modelling relate to characterisation of residential energy demand. Firstly, and most importantly, residential demand (and output of the micro-CHP system) must be characterised with fine temporal resolution. The majority of existing studies in the literature use coarse hourly precision. As shown in section 5.1, hourly precision can overestimate the marginal value of the micro-CHP system by up to 70% and the annual $CO_2$ reduction by up to 30%. The source of this error lies in the fact that the coarse resolution entails substantial averaging of demand, combined with the fact that residential demand is particularly volatile. This means that the micro-CHP system can appear to be meeting a substantial portion of onsite demand when in reality a much of this demand is out of the capacity range of the prime mover. Demand (and system response) must be characterised at least at 10-minute resolution, although 5-minute is preferable and has been applied in the majority of this thesis. One further demand-related conclusion can be drawn from results; it is necessary to structure choice of "sample days" to properly characterise an annual demand profile for economic/environmental analysis. It was found that if says are sampled semi-randomly from a demand profile, a wide range of performance figures could be obtained for a single dwelling. This is because demand varies substantially from day-to-day in a dwelling. This problem is partially alleviated by imposing a structured sampling approach to select days based on;

a) adequate seasonal representation,
b) respect for aggregate annual energy demands of the dwelling (when days are weighted),
c) respect for the seasonal average coincidence of electrical and thermal demand in chosen sample days.

However, once these rules are applied to selection of sample days it becomes difficult to isolate days with the required qualities, although candidates can be identified by relaxing tolerances. It was shown that this approach results in selection of sample days that are adequate for estimating how micro-CHP would perform in the target dwelling.

### 10.1.3 Conclusions Relevant to Technology Developers

The primary conclusions of relevance to micro-CHP system technology developers relate to the technical characteristics of systems that are more likely to be commercially successful. This information can help them focus research and development activity with the aim of creating products with desirable characteristics. These conclusions are discussed below.

Chapter 8 investigated nine specific technical characteristics of micro-CHP systems, with several of these parameters straddling the boundary between prime mover, balance of plant, and thermal delivery systems employed. The nine parameters were;

1) overall efficiency (heat plus power),
2) part-load electrical and overall efficiencies,
3) thermal demand load factor,
4) maximum ramp rates,
5) system start-up cost (and associated energy consumption),
6) turndown ratio (minimum operating set-point),
7) minimum up-time, and
8) degradation for the case of PEMFC-based systems,
9) addition of thermal energy storage to the system.

Of these parameters, all were found to be important from both an economic and $CO_2$ performance points of view except for maximum ramp rates and minimum up-time, which both have virtually no measurable impact. Ramp rates were not important provided that a reasonably predictive control system was in place to switch systems on to provide space heating demands (e.g. simple control based on a heating timer and/or basic adaptive control). Minimum up-time was not important because systems typically operate for a significant length of time before shutting down, implying that only very long minimum up-time is likely to influence performance. Start-up cost and thermal-cycling based degradation were also relatively unimportant for fuel cell based systems because they are able to avoid start-up/shutdown cycling, as discussed below.

Of all of the other parameters (i.e. those that can significantly influence performance), it is possible to draw some general conclusions. These conclusions are closely linked with the discussion of the impact of thermal constraints (i.e. heat-to-power ratio, thermal capacity, and/or thermal demand) in relation to the key overarching conclusions. Broadly speaking, any change in a technical parameter that serves to alleviate thermal constraints acts to improve the performance of the prime mover. For example, increasing turndown ratio (whilst maintaining part-load efficiency) reduces the minimum thermal demand the prime mover can serve. Therefore it can operate more frequently and generate more electrical power. This improves its performance. Similarly, increasing thermal demand load factor (i.e. the average demand divided by the peak demand) tends to smooth out thermal demand, making a more consistent load profile to be met by the micro-CHP system. This change benefits low heat-to-power ratio fuel cell based systems because they can operate at rated power for a longer period of time. It does not bear so well on the engine based systems because it implies that there are less time periods with the higher thermal demand that would allow them to operate at rated power. Lastly, the addition of thermal energy storage was also shown to benefit low heat-to-power ratio systems more than high heat-to-power ratio systems. This is because a small amount of thermal flexibility benefits low heat-to-power ratio systems greatly as it allows them to generate relatively more electricity. The necessity for high heat-to-power ratio system to push a lot more energy through the storage, and thus suffer from greater turnaround efficiency losses, negates any advantages of reduced thermal constraints afforded by storage.

A similar yet distinct argument can be applied to the results in relation to start-up cost and thermal-cycling based degradation for the PEMFC system. This relates to the low heat-to-power ratio systems having the ability to avoid switching off. Where the cost of shutting down is high (due to either start-up costs or irreversible degradation), a low heat-to-power ratio system is more likely to be able to avoid shutdown. This is because that system can modulate to very low thermal output levels in order to avoid the thermal constraints that would require shutdown, whilst a high heat-to-power ratio system may be forced to switch off. Of course, this result is closely intertwined with the turndown ratio of the system and the presence of thermal energy storage (discussed above).

Overall the results relating to the investigation in Chapter 8 suggest that whilst informed technology design is clearly important, poor performance due to a number of technical characteristics can be circumvented through application of an intelligent control strategy.

For example, system developers should not concentrate on creating fuel cell products that can ramp up and down quickly, have a short minimum up-time, and low energy/cost start-up characteristics because these traits may not improve performance. Developers should instead ensure a reasonably predictive/adaptive control strategy such that shutdown is avoided, etc. Conversely, the research has shown the significant relative importance of part-load efficiency and turndown ratio, suggesting that R&D could be focused on creating prime movers and balance of plant that can turn down to very low output levels whilst maintaining electrical and overall efficiency. It has also been shown that thermal energy storage could have very strong synergies with low heat-to-power ratio micro-CHP, so developers should certainly consider its addition to the systems. These features, along with high full-load overall efficiency in a $1kW_e$ system combined with the requisite low heat-to-power ratio will result in a product with significant commercial value and good potential for reducing $CO_2$ emissions.

### 10.1.4 Conclusions Relevant to Policy Makers

Chapter 9 reviewed existing residential sector energy policy in the UK. Of the existing policy instruments, the Carbon Emissions Reduction Target (CERT) and the building regulations were found to be the most justifiable in terms of economically-rational and immediate $CO_2$ reductions. The Low Carbon Buildings Programme (LCBP) and particularly VAT relief for microgeneration were shown to be instruments that are not well directed in terms of economically rational $CO_2$ reduction. The LCBP is useful to raise the profile of microgeneration and provide information and signals to stakeholders, but will fall short of achieving any significant change regarding uptake or technology development. VAT relief for micro-CHP was found to be misdirected because it has the potential to support installation were no policy aims will be achieved (e.g. a high heat-to-power ratio micro-CHP technology in a dwelling with small energy demand). Overall current policy instruments were shown to be deficient in some regards, and more joined-up policy with explicit links to particular low carbon targets could be more effective overall if long term targets are to be achieved.

Despite these shortcomings, and for better or for worse, it was found that micro-CHP could be strongly supported by the suite of existing policy instruments. Under conservative scenarios for realisable emissions reductions and levels of support offered (under schemes such as CERT and LCBP) micro-CHP uptake could be significant because indicative payback times are short under assumptions regarding their final installed cost. Indeed micro-CHP was shown to be potentially competitive with efficiency measures such as loft insulation in

terms of payback period. It was also shown to be easily competitive with other home heating microgeneration solutions such as heat pumps. However, support of both thermal energy efficiency measures and micro-CHP in one dwelling was found to be likely to produce sub-optimal aggregate results. This is due to the relationship between micro-CHP $CO_2$ performance and thermal energy demand. The government would be better off supporting thermal energy efficiency in one dwelling and micro-CHP in another where capital resources are limited.

The structure of policy instruments that could support micro-CHP were then considered. Given the likely capital-intensive nature of micro-CHP investment upfront capital investment support could greatly aid uptake of micro-CHP. However, performance-based support could also be required to provide on-the-ground $CO_2$ savings as opposed to merely uptake of the technology which may then be poorly utilised.

It was shown that upfront capital support could be awarded to potential owners based on potential for good performance, via vetting of installations against three parameters. These parameters are:

1. Ensuring high overall efficiency of micro-CHP systems via a process analogous to the existing boiler seasonal efficiency rating.
2. Mapping systems according the heat-to-power ratio and thermal capacity of the prime mover.
3. Providing support based on a match between heat-to-power ratio and thermal capacity with the predicted thermal energy demand to the target dwelling.

Application of these three metrics will result in support for installations that are more likely to provide $CO_2$ reductions and have high capacity credit. They also are likely to provide support were micro-CHP can be cost-effective, provided that the target dwelling's annual electricity demand is not small. Vetting of support based on these criteria was also found to be reasonably workable because the relevant data would be available through existing policy instruments, namely the government's Standard Assessment Procedure (SAP) for assessing dwellings against the building regulations, and dwelling Energy Performance Certificate (EPC) related assessment. Technical data regarding heat-to-power ratio and thermal capacity of systems would be available via a system accreditation step, similar to existing arrangements for boilers in the UK.

A set of performance-based policy instruments were then assessed. It was found that the feed-in tariffs incorporated in the recent Energy Act can provide a perverse incentive for micro-CHP. This is because they can incentivise gratuitous operation of the device in order to profit from high electricity buyback rates whilst discarding thermal energy produced. This mode of operation is associated with poor $CO_2$ related performance, and can even result in an increase in $CO_2$ emissions associated with energy provision in the dwelling. Three other possible performance-based incentives were then analysed, and it was concluded that an incentive based on $CO_2$ reduction motivates low $CO_2$ operation the most consistently. However, differentiation between this incentive and an incentive structured to provide (additional) reward for electricity exported to the grid is largely dependent on the value of fair reward for exported electricity. This value is in turn dependent on the wholesale value of exported electricity adjusted for typical "embedded benefits" associated with distributed generation, minus the costs of metering, balancing and settlement. Until this value is better understood it is not possible to differentiate effectively between the cost-effectiveness of instruments. In the meantime reward for electricity export could be offered for micro-CHP system operators, and the situation monitored to ensure avoidance of perverse outcomes.

It should be noted that linkage between upfront capital support and performance-based support would be required to adequately (but not overly) support the micro-CHP installation. In order to achieve this, performance-based support could be front-loaded via the value of a portion of "deemed" output being available at the time of purchase of the system, as was suggested in the UK government's recent Renewable Energy Consultation (BERR (2008d)). The remaining portion could then be awarded based on actual metered performance of the installation. Overall the situation should be monitored because changes in a variety of parameters can result in incentives motivating mediocre performance of systems.

The final and arguably most important point regarding policy support for micro-CHP relates to the fact that achievable $CO_2$ reduction is dependent on grid electricity embodied $CO_2$ rate. Chapter 7 (section 7.1.4) discussed this dependence, and concluded that high heat-to-power ratio micro-CHP cannot provide emissions reductions once the grid $CO_2$ rate falls below approximately 0.43kg/kWh. For the other micro-CHP technologies this tipping point occurs at grid $CO_2$ rates of roughly 0.3kg/kWh. This result indicates that gas-fuelled micro-CHP is likely to be a technology that is could provide $CO_2$ reductions in the near to medium

term, but less so in the long term. This is because if existing policies that aim to reduce grid $CO_2$ rates are successful, the "tipping point" rates noted above should be reached within the next few decades. Indeed the recent Committee on Climate Change (2008) report suggested in that grid- average $CO_2$ rates should be reduced to the critical 0.3 kg/kWh by as early as 2020, indicating a tough timeline for gas-fuelled micro-CHP commercialisation.

## 10.2 Critical Review and Recommended Further Research

The research presented in this thesis could be enhanced in a number of ways, and it has exposed a wide range of complementary avenues for future research. Some of the issues and opportunities revolve around the quality of information currently available regarding the technical characteristics of micro-CHP and residential energy demand, which require some attention if more robust modelling results are to be produced. For example, a data set that includes both electrical and thermal demand from a representative set of dwellings at adequate temporal resolution is required to better understand demand and how micro-CHP may interact with it. Furthermore, more empirical evidence is required regarding the performance of micro-CHP systems such that technology characteristics can be better mapped.

However, the critical review and recommendations for further research presented here focus less on the lack of empirical information and more on the goals and methods of the research. The following two sections discuss interesting possibilities for development of the modelling approach and deficiencies in the state of knowledge regarding effective residential sector energy policy.

### 10.2.1 Potential Directions for Modelling

As has been noted in the conclusions, there is a trade-off between the benefits of optimisation modelling for emerging technology, and the better characterisation of system dynamics afforded by high quality simulation modelling. The presented model does not benefit greatly from incorporations of lessons to be learned from such simulation. Future research could aim to close this gap by bringing the key dynamic elements of building and/or system simulation into an optimisation framework. This may require iterative optimisation, but computational expense may be justified if more accurate results can be obtained. The first step towards bridging the differences between modelling approaches could be to formulate thermal constraints in terms of building internal temperature (rather than thermal energy demand as has been done in this thesis), and improve characterisation

of thermal energy storage. This would make thermal demand an endogenous variable in the model, rather than its current exogenous representation.

A further improvement that could be applied to the modelling framework is more robust treatment of uncertainty in input variables. This thesis dealt with uncertainty via an array of sensitivity analyses, which is appropriate when information regarding ranges of uncertainties is limited. Future research could develop a more detailed understanding of uncertainties, and then use these within a stochastic optimisation framework to assess the risk associated with performance (as they relate to economic drivers, ability to meet policy aims, and the relative importance of various technical characteristics). A Monte Carlo approach based on mixed integer linear programming could achieve this aim, and other least-squares optimisation approaches may also be applicable.

The state of knowledge regarding appropriate marginal emissions factors has been identified as another area that could benefit from further research. This, by its nature, would need to be tackled by energy modellers because empirical studies of the impacts of energy efficiency or microgeneration measures on centralised generation is problematic. Research could seek to understand which centralised generators respond to system load changes to gain an understanding of the instantaneous or near-term impact of demand changes. One could then search for causal rules to appreciate the driving forces of these responses. Subsequently, because *future* projections of marginal emissions as required, research could attempt to establish a) longer term impacts of demand-side change on dispatch behaviour of centralised generators, and b) the impact of demand-side measures in delaying (or making redundant) new plant build. In this case, the correct marginal emissions factor depends on what type of plant would have been built had the measures not been installed. A starting point in investigating this issue could focus on the capacity credit of measures, which is an indication of its propensity to displace capacity.

Indeed the treatment of capacity credit presented in section 7.3 could be revisited to improve certainty and expand scope. As noted, a higher-quality set of input data could be applied from more recent investigations such as the Carbon Trust Micro-CHP Accelerator. Consideration of larger capacity micro-CHP systems, which are likely to have much lower capacity credit, could also augment understanding of demand and supply side interactions. Moreover, the capacity credit analysis could be extended to a wider range of microgeneration and energy efficiency measures, which would feed useful information into future directions for policy-related research, as discussed below.

### 10.2.2 Themes for Policy-Related Research

It has been noted that UK energy policy for the residential sector is disjointed and lacks direct linkage to long term aggregate $CO_2$ reduction targets. Therefore there is a need for assessment of the range of energy policy options available and development of new regulatory approaches that will deliver climate change related targets like the government's suggested 80% greenhouse gas reduction by 2050.

Recent policy developments in the UK, such as the Code for Sustainable Homes and the Carbon Emissions Reduction Target suggest that substantial change will occur in the residential sector in coming years. Indeed the scale of action required has been demonstrated in the 40% House project (Boardman et al. (2005)), which showed that many demand-side measures such as building fabric changes, efficient lighting and appliances, improved control systems, and behavioural changes are required. Importantly, in addition to these measures, one or more microgeneration technologies operating in dwellings were shown to be required. Furthermore, achieving "zero carbon" status with respect to the new Code for Sustainable Homes will require some of these technologies to be exporting electricity to the grid to offset emissions from dwelling heating and electricity use. To achieve the best performance from residential energy systems requires that they be designed to operate in a coordinated fashion, where supply and demand are integrated and aligned with respect to specified outcomes.

There is no existing research that systematically identifies appropriate "packages of measures and technologies" (and interactions between technologies), based on stakeholder motivations, that are relevant for low carbon futures. Without this integrating base of evidence and research to tackle uncertainties and help shape policy, it is likely that commercial developments will be fragmented and will fail to contribute effectively to overall policy objectives. Therefore there is a need for research to create a robust and systematic analysis framework to provide insight regarding the most effective pathways to deliver a low carbon residential sector at low private and societal cost. Framed by longer term emissions reduction targets, this research would identify technology options and combinations, stakeholder business cases and motivations, and appropriate supporting policy and regulation that is relevant for the next few decades.

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