Future scenarios for micro-CHP in the UK as residential building insulation improves

A.D. Hawkes
Centre for Energy Policy and Technology, Imperial College London
a.hawkes@imperial.ac.uk

M.A. Leach
Centre for Energy Policy and Technology, Imperial College London
m.leach@imperial.ac.uk

Keywords
future energy demand, micro-CHP, economics, greenhouse gas, clustered application

Abstract

The economics of micro combined heat and power (micro-CHP) are generally highly dependent on the magnitude of thermal energy demand in the residence being served. Dwellings with larger annual thermal consumption usually benefit most from an economic point of view, with a corresponding environmental benefit through significant reduction in greenhouse gas emissions. This creates a tension between desirable demand-side energy efficiency and introduction of efficient supply-side technology because improving demand-side efficiency through improved building insulation results in this efficient supply-side technology becoming less economically attractive. This paper examines the changes in economic parameters for micro-CHP that are likely to occur under scenarios for changing household thermal energy demand in the UK, and considers the corresponding changes in environmental performance. Options for interconnection of dwellings in order to increase and diversify thermal demand (per micro-CHP unit) are explored and discussed in this context.

Introduction

In the United Kingdom and the rest of Europe micro combined heat and power (micro-CHP) is seen as a potentially important contributor to future residential energy provision because it helps to meet a number of energy policy objectives (DTI 2006b; Watson et al. 2006). It has the potential to be economically attractive, usually reduces greenhouse gas emissions from energy supply, and may improve the security of energy supply1 at the individual dwelling level (Hawkes and Leach 2005). However the improvement in these three key energy policy indicators – economics, environment, and security – provided by micro-CHP is largely dependent on the magnitude of thermal energy demand in the dwelling where larger annual thermal demand generally corresponds with a more positive economic and environmental outcome (Hawkes et al. 2007). This creates a tension between demand side energy efficiency and supply side energy efficiency, where improvements in demand side efficiency may result in a supply side efficiency improvement becoming uneconomic.

This paper investigates this tension in terms of the economics and greenhouse gas emissions for an average UK residential dwelling. Thermal load in an average existing dwelling, an average refurbished dwelling, and an average newly constructed dwelling are modelled with three types of micro-CHP; an internal combustion engine, a solid oxide fuel cell (SOFC) based system, and a Stirling engine. The driving fuel for all technologies is natural gas. The economic and environmental result in each case is compared with that of a baseline case; where energy needs are met via grid electricity and burning natural gas in a condensing boiler. Aggregation of demand through considering several dwellings together is then investigated in the same manner.

---

1. Micro-CHP may aid network stability in a local area, or may in the future be operated in a "islanded" mode where basic energy supply in a dwelling remains operational despite problems on the grid. However, as most micro-CHP is fuelled by natural gas, the technology probably doesn't reduce national energy import dependence.

Background

POLICY CONTEXT

Recent energy policy debate in the UK, as highlighted by the Energy Review (DTI 2006a), has been focused on how to meet projected future energy demand as the existing nuclear power stations come to the end of their life, with particular focus on energy security, climate change, and competitiveness of the energy sector and subsequent influence on the whole economy.

- Energy security concerns relate to a perceived over-dependence on imported natural gas for power generation and desirable diversification of fuels used for supply.
- The importance of climate change is highlighted by the government's 60 % greenhouse gas emissions reduction aspiration by 2050, and the recent Stern Review (Stern 2006) which showed the importance of mitigation measures in the short term in order to avoid negative economic consequences of climate change in the future.
- Competitiveness of the energy sector is always a primary concern for the government, and the deregulated market in the UK is intended to foster competition and therefore reduce prices. In theory, changes in the energy system should be directed by the free market.

Although replacement of existing nuclear generating capacity appears to be a central issue in the UK energy debate, other measures such as energy efficiency and an increase in the amount of decentralised generation are also broadly supported.

Within the large variety of technologies that can be considered to be decentralised generation; for example, wind turbines, roof-mounted photovoltaics, combined heat and power plants, etc, micropower has been specifically highlighted as an option with good potential for significant penetration into the market. Micropower is defined as any energy supply technology with up to approximately 10 kW_e output capacity. Micropower technologies are generally appropriate for installation at a residential dwelling, and include micro wind turbines, solar-pv, solar-thermal heating systems, heat pumps, and micro-CHP, amongst others. The UK government recently announced an extra £ 50 million (approx € 75 million) support for such technologies in its Microgeneration Strategy (DTI 2006b) through the Low Carbon Buildings Programme (formerly the Clear Skies Programme), primarily focused on grant support to aid entry into the market of existing technologies.

The government also supports energy efficiency at the residential level through the Energy Efficiency Commitment (EEC) which is a regulatory measure that requires energy suppliers to reduce energy demand of their residential customers. The target energy consumption reduction is 130 TWh for the 2005 – 2008 commitment period, which is more than double the target of the 2002 – 2005 commitment period. Suppliers typically assist their customers to achieve energy savings by installing measures such as loft and cavity wall insulation, efficient boilers, appliances and lighting (Energy Saving Trust undated). The EEC is particularly focused on assisting those dwellings that are deemed to suffer from fuel poverty, helping to reduce energy demand and thus energy cost through reducing consumption for those least able to afford energy efficiency measures.

Overall the UK government is therefore supporting both energy efficiency and micro-CHP in the residential sector.

MICRO COMBINED HEAT AND POWER TECHNOLOGY

Micro-CHP is defined as a device that generates electricity and heat simultaneously, with a maximum electrical output capacity between roughly 1 kW_e and 10 kW_e. The heat generated is recovered and utilised rather than discarded as is the case in many large "centralised" power stations. A variety of micro-CHP technologies are commercially available or the subject of research and development. Commercially available technologies include gas internal combustion engines (Baxi undated) and Stirling engines (Powergen undated). Fuel cell micro-CHP is under development by a number of companies, primarily in Japan, and the United States, and a limited number of ventures in Europe.

Each type of micro-CHP has different technical characteristics. Of primary importance to this study is the efficiency and heat-to-power ratio of each technology. *Table 1* displays some estimated figures for these parameters for the leading technologies.

As residential dwellings usually do not have the capability to shed excess heat (and shedding excess heat has negative environmental implications, as it implies a reduced overall efficiency), micro-CHP is constrained to produce only enough heat to warm the dwelling and provide domestic hot water services. Thermal energy storage can be used to decouple the timing of heat supply and demand, but the overall energy balance between demand and supply remains constrained.

TRENDS IN RESIDENTIAL ENERGY CONSUMPTION

According to the Energy Saving Trust, the average dwelling in the UK could save 2 tonnes of greenhouse gas emissions if they installed energy efficiency measures (Energy Saving Trust 2006), The most cost effective emissions saving can be

Table 1. Technical parameters of four key micro-CHP technologies

Technology	Approximate Peak Electrical Efficiency	Approximate Overall Efficiency (Heat + Power)	Approximate Heat-to-Power Ratio
Stirling Engine	12%	90%	7:1
Gas Internal Combustion Engine	25%	90%	3:1
PEM Fuel Cell	30%	80%	2:1
SOFC Fuel Cell	40%	80%	1:1

achieved by installation of improved loft and cavity wall insulation. Therefore, with policy measures such as the Energy Efficiency Commitment, and life-cycle replacement of older housing stock with new, it is expected that significant energy efficiency improvements will be possible over the coming decades. UK historical energy consumption statistics corroborate this: the overall energy consumption for residential space heating in the UK only risen slightly since 1970 despite increasing population and rising internal temperatures. This is due to the installation of insulation in older housing, improved heating technology efficiency, and the construction of new housing with improved insulation (DTI undated). Since 1970 energy final energy consumption for space heating has risen only 24 percent, whilst electricity final consumption has risen 157 percent. In the residential sector, carbon dioxide emissions are attributable approximately 40 % to electricity usage 60 % to space and water heating.

The 40 % House project (Boardman et al. 2005) investigated what changes would be required in the residential sector to cut greenhouse gas emissions by 60 % as per the UK government targets. When considering space heating, the project differentiated dwellings built pre and post-1996. Pre-1996 dwellings that in 1996 consumed on average 14,600 kWh/year thermal energy for space heating could be refurbished to a high level and would consume on average 9,000 kWh/year in 2050. Dwellings built after 1996 would only consume 2,000 kWh/year for space heating in 2050[2]. Domestic hot water would consume approximately 5,000 kWh per year, reducing to 3,400 kWh per year in 2050 if solar hot water systems were implemented. Clearly there is a marked difference between old and new-build housing, and considerable energy savings are possible in the older stock.

Electrical energy consumption is also expected to change over the coming decades. In general consumers are purchasing more appliances, but these are becoming more efficient. Minimum performance standards are a primary driver for energy efficiency, and labelling pushes the consumer towards more efficient products. The trend in electricity consumption is more difficult to determine than that for heating, but in general the trend towards a larger number of more efficient appliances suggests that on average electricity consumption per dwelling may remain approximately constant. The magnitude of demand peaks may increase as the power rating of some appliances increases (particularly kettles and other electrical water heaters).

Overall it can be estimated that the annual heat-to-power ratio of demand in residential housing stock in the UK will decrease from approximately 5:1 to as little as 2:1 for existing housing stock and 0.5:1 for new housing stock over the next 20 to 50 years. Although this in itself is not sufficient analysis to reach definitive conclusions regarding the future of micro-CHP, it suggests that the nature of the micro-CHP technology required to meet these demands will also change over that time period.

Analysis Method and Input Data

The aim of this analysis is to determine the impact on the economics and greenhouse gas emissions of micro-CHP technology as residential energy demand changes over the coming decades, and to investigate the influence of aggregation of demand as a measure to improve performance in terms of these two indicators. The energy demand of three dwellings is approximated in order to represent a typical pre-existing dwelling in its current state (Existing Dwelling), a typical pre-existing dwelling that has been refurbished to a high standard (Refurbished Dwelling), and a typical new dwelling (New Dwelling). Three micro-CHP technologies will be considered in each dwelling; a 1 kW_e Stirling engine, a 1 kW_e internal combustion engine, and a 1 kW_e solid oxide fuel cell. Each micro-CHP has supplementary thermal capacity as required in the form of a condensing boiler.[3] This paper is not concerned with optimising micro-CHP sizing or operating strategy. For such analyses, please refer to (Hawkes and Leach 2005; Hawkes et al. 2006; Hawkes et al. 2007).

The chosen metrics for comparison are the equivalent annual cost (EAC) of meeting the dwellings energy demand and the annual greenhouse gas (GHG) emissions that could be expected from energy provision in the dwelling.

The following procedure is undertaken:

1. Establish the baseline EAC and GHG emissions for each dwelling based on current energy prices and combined cycle gas turbine (CCGT) emissions rates[4]. The baseline scenario is where no micro-CHP unit is present, electricity needs are met via grid electricity and heating needs are met through burning natural gas in a condensing boiler.
2. Establish EAC and GHG emissions for each dwelling/technology combination.
3. Multiply the number of dwellings being served by the micro-CHP unit by 2 for the refurbished and new dwellings, and establish EAC and GHG emissions. The multiplication of the number of dwellings provides more heat and electricity demand for the micro-CHP to serve, and should improve the economic and environmental result.
4. Multiply the number of dwellings being served by the micro-CHP unit by 3 for the refurbished and new dwellings, and establish EAC and GHG emissions.

Input data used in the analysis are presented in *Table 2.*

Electricity demand profiles are assumed to be the same for each dwelling, and are UK-average profiles with annual consumption of approximately 4,300 kWh. Space heating and domestic hot water demand for the “existing dwelling” is approximately 15,000 kWh/year. The “refurbished dwelling” has 9,000 kWh/year heat consumption, and the new dwelling has 2,000 kWh/year consumption. Figure 1 displays the heat demand profile for a typical winter day for the three dwellings, highlighting the magnitude of difference between them. The

---

[2] 2,000 kWh per year is close to passive house standards, and the authors believe reduction in average energy consumtion to this level to be a challenging target. However, for the present study it is required only to show a trend, and therefore these figures are acceptable.

[3] Existing commercial micro-CHP units have this feature; an integrated condensing boiler to provide supplementary thermal capacity

[4] It is assumed that the micro-CHP will displace CCGT centralised generation, operating in the middle merit or baseload.

Table 2. Selected Input Data

Variable	Value
Stirling Engine Electrical Efficiency (where r is the instantaneous load factor of the generator – kWe output divided by kWe output capacity)	6 % + 6 % x r
IC Engine Electrical Efficiency	12.5 % + 12.5 % x r
SOFC Electrical Efficiency	30 % + 10 % x r
Stirling Engine Overall Efficiency	0.9
IC Engine Overall Efficiency	0.9
SOFC Overall Efficiency	0.8
Boiler Heat Efficiency	0.9
Natural Gas Cost (Euros/kWh) (DTI 2006c)	0.03329
Electricity Cost (Euros/kWh) (DTI 2006c)	0.1197
Electricity Buyback Rate (Euros/kWh)	0.0584
Stirling Engine Capital Cost (Euros)	3,500
IC Engine Capital Cost (Euros)	3,500
SOFC Capital Cost (Euros)	4,000
Boiler Capital Cost (Euros)	3,000
Discount Rate for Investment	12 %
CCGT Emissions Rate (kg CO_2/kWh)	0.43
Natural Gas Emissions Rate (kg CO_2/kWh)	0.19

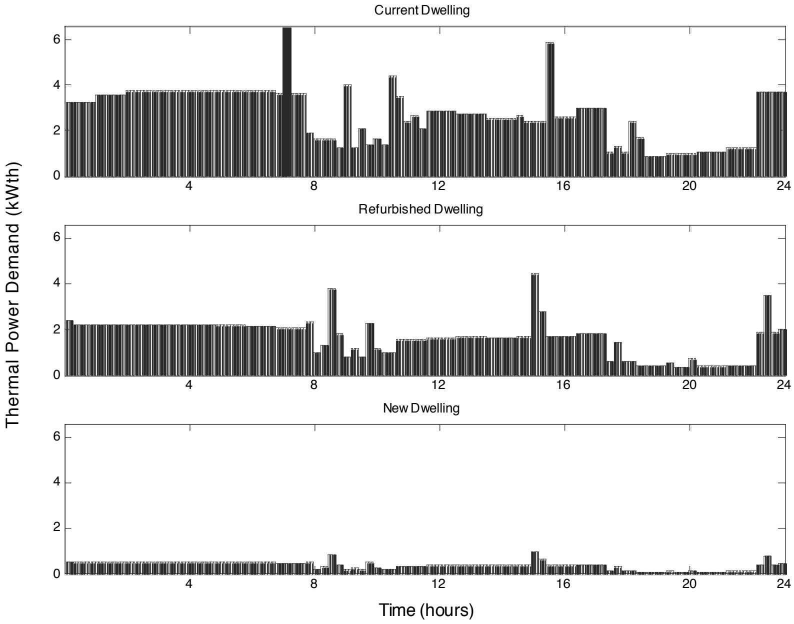

Figure 1. Heat demand profile on a typical winter day for the existing, refurbished, and new dwellings

reader should note that these profiles relate to constant underfloor heating, where internal temperature is maintained throughout the day and night, and summer/spring days were also modelled and included in the economic/emissions analysis. The modelling ensures electricity and heat demand are met at all times in the dwellings.

Results and Discussion

The savings in equivalent annual cost, in euros per year, for the existing dwelling, refurbished dwelling and new dwelling are displayed in *Figure 2*. For the existing dwelling, both the IC engine and the SOFC-based micro-CHP provide positive economic outcomes, whiles the Stirling Engine is slightly negative. The refurbished dwelling also shows a positive case for investment for the IC engine and SOFC, although the magnitude of the saving has decreased when compared with the existing dwelling. None of the technologies offer a positive case for

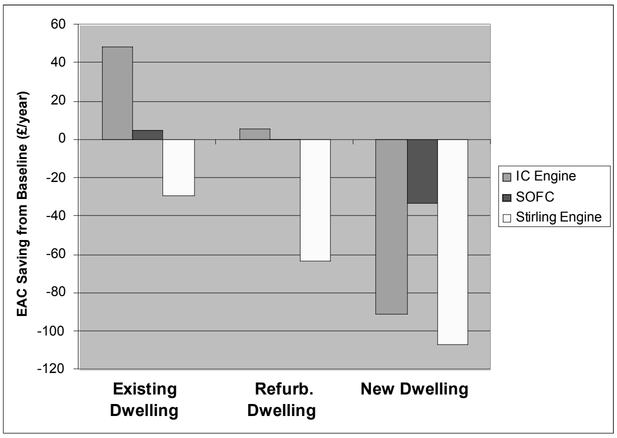

Figure 2. Equivalent Annual Cost (EAC) Saving from Baseline for IC Engine, SOFC, and Stirling Engine Technologies when Installed in Existing, Refurbished, and New Dwellings

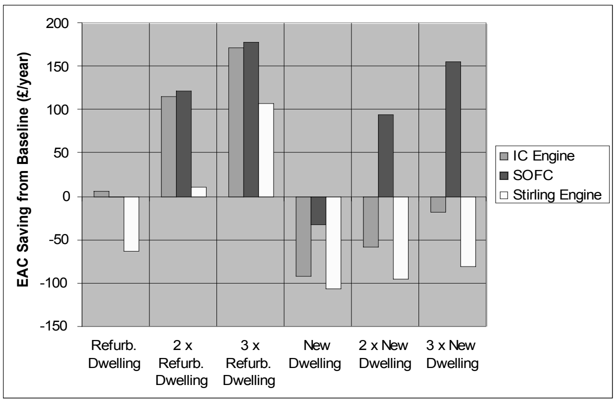

Figure 3. Equivalent Annual Cost (EAC) Saving for the Aggregated Dwellings Cases

Table 3. Greenhouse Gas Emissions Reduction (from Baseline) for each case

	Existing Dwelling	Refurb. Dwelling	2 x Refurb. Dwelling	3 x Refurb. Dwelling	New Dwelling	2 x New Dwelling	3 x New Dwelling
IC Engine	*14%*	*12%*	*10%*	*7%*	*3%*	*3%*	*2%*
SOFC	*13%*	*16%*	*9%*	*6%*	*16%*	*11%*	*8%*
Stirling Engine	*5%*	*4%*	*5%*	*6%*	*1%*	*1%*	*1%*

investment in the new dwelling. This result demonstrates the dependence of the economic result on the thermal demand in the dwelling, and indicates that in the future for average new dwellings it may be difficult for micro-CHP to compete with the conventional grid electricity and condensing boiler residential energy provision model.

Figure 3 displays the result where demand is aggregated. The chosen examples, which are by no means completely representative of the possibilities[5], indicate that as demand is aggregated the economic case for the technologies improves in that all technologies have a larger EAC saving above the baseline result as the number of dwellings being served increases. For the refurbished dwelling, all technologies are viable when the aggregation of dwellings exceeds one, although it is interesting to note that the SOFC-based micro-CHP becomes the preferred option when two or more dwellings are aggregated (as opposed to the single refurbished dwelling case, where the IC Engine is preferred). For the aggregation of new dwellings, only the SOFC-based technology becomes viable when two or three dwellings' loads are aggregated (it should, however, be noted that the others may become viable for larger aggregations.

The result for new dwellings in *Figure 3* is of particular note to this study. It demonstrates that as dwellings become particularly thermally efficient, micro-CHP technologies with low heat-to-power ratios become comparatively more attractive from an economic point of view. Whilst the IC Engine may be the preferred technology for an average existing dwelling based on *Figure 2*, lower heat-to-power ratio SOFC technology could overtake it as building insulation improves (*Figure 3*).

Table 3 displays the greenhouse gas emissions reduction results for each of the dwellings and aggregations of dwellings discussed above. Once again the benefits of the low heat-to-power ratio SOFC are apparent for the new dwelling scenario. Whilst the IC Engine provides marginally superior emissions reduction for the existing dwelling and the refurbished dwellings[6], the SOFC-based micro-CHP continues to provide emissions reduction even in the new dwelling case. The other two technologies experience difficulty achieving emissions reduction in this case because they simply cannot operate as there is insufficient heat demand.

Overall these results indicate the advantages of micro-CHP being able to operate efficiently when there is little demand for heat, and thus the preference of lower heat-to-power ratio technologies in the UK average new dwelling case. Advantages are apparent for both the economic and environmental result. However, this does not imply that high heat-to-power ratio technologies such as Stirling Engines do not have a future in the UK market. This study focused on the UK-average residential demand case, but in the housing stock there is a wide variety of consumption profiles, and it is useful to have access to a wide range of technologies in order to improve the chances of having a match. Additionally, micro-CHP has many applications, the residential sector being only one.

---

[5] Aggregation possibilities are endless. One could consider aggregations of different dwellings types in any combination or number, and in different configurations. A few simple combinations have been chosen for this study.

[6] Percentage-wise, emissions reduction decreases as aggregation increases. This is because the micro-CHP size is limited to 1kWe, and does not indicate that further emissions reduction using micro-CHP are not possible.

One final point to note in this discussion is regarding the practicality of aggregation of residential demand. Interconnection of heating systems in dense housing such as flats or terraces should not pose a significant problem, although it will have a cost attached. Likewise it is easy to envisage electrical interconnection either through the existing grid, or via a private wire arrangement. A much more complicated aspect of demand aggregation is related to how it would fit with the principles of a deregulated market. Although many contractual models can be imagined, it is difficult to see who would own the device in an aggregated case, and how electricity and heat would be bought and sold between the parties in an equitable manner. There is also a strong temptation to adopt the view that if aggregation between a few properties is possible and makes economic sense, why not aggregate many more properties through a district heating system and install a few large CHP units rather than many micro-CHP units? Answering these questions is beyond the scope of this study, but they are clearly important for the future of micro-CHP, and could form an interesting basis for future research.

Conclusion

This study has examined the case for three forms of residential micro-CHP as building insulation improves in the United Kingdom. Over the coming decades it is expected that improvements in residential building insulation, driven by cost efficiency and regulations, will decrease the thermal load of UK dwellings significantly, reducing the (space) heating-to-power ratio of demand from 5:1 down to as little as 0.5:1. The decrease in thermal load for an average UK residential demand profile was modelled, considering the case of an existing dwelling, the case where an existing dwelling is refurbished, and the case where a new dwelling is constructed.

Load profiles of each dwelling were developed, and a model applied to estimate the equivalent annual cost of meeting those energy demands, including the annualised capital cost of any equipment required. The model also estimated annual greenhouse gas emissions from energy provision in the dwelling. Three micro-CHP technologies were considered with each dwelling; an internal combustion engine, a solid oxide fuel cell system, and Stirling engine micro combined heat and power. The baseline case was chosen to be when the dwelling meets its electricity needs by importing power from the grid, and meeting its heating needs through burning natural gas in a condensing boiler.

It was shown that although the internal combustion engine and solid oxide fuel cell (SOFC) system achieve a positive economic and environmental result for an average existing dwelling, in the future for the case of a single new dwelling, none of the technologies achieved a positive economic outcome. This highlights the importance of significant heat demand to ensure economic attractiveness of micro-CHP. When dwellings where aggregated in an attempt to provide sufficient demand to make the micro-CHP attractive, the refurbished dwelling became a positive investment when two or more dwellings where considered together for any of the three micro-CHP technologies. For aggregations of new dwellings, only the SOFC-based micro-CHP became economically attractive for aggregations of two or three dwellings, although the other technologies may present a positive case for investment at larger aggregations. This is because the low heat-to-power ratio of the SOFC system allows it to continue operating when there is little heat demand, whilst the other two higher heat-to-power ratio technologies must curtail their output when insufficient heat demand is present.

From a policy point of view, results from this study suggest that instruments designed to support micro-CHP should be tailored to the individual case, rather than broadly supporting any micro-CHP installation. Similarly to current UK measures related to CHP, where non-domestic installations are exempt from paying the UK climate change levy (DEFRA 2007) if their CHP is deemed to be "good quality", residential CHP installations should only be eligible for grant support if there is a match between the load being served and the technology serving it, therefore ensuring that economic and environmental policy objectives are met. Alternatively, although perhaps more controversially, personal or household carbon allowances could provide a financial incentive to dwelling occupiers to purchase micro-CHP that actually results in emissions reduction and cost savings rather than any micro-CHP unit backed by a blanket grant support programme. In terms of policy instruments that furnish interconnection (i.e. aggregation) of load, no clear conclusion can be obtained. Although it may be prudent to ensure building regulations result in constructions that allow cheap heating and electrical interconnection, it is beyond the scope of this study to assess the relative merits of large CHP and district heating networks versus interconnection of a few properties to support micro-CHP, or the contractual arrangements that would be required for such schemes. These issues could benefit from further research.

References

Baxi. (undated). "Baxi DACHS Mini CHP." Retrieved Jan 12th, 2007, from http://www.baxitech.co.uk/Baxi_Tech/BaxiTechWeb.nsf/overview.

B. Boardman, S. Darby, G. Killip, M. Hinnells, C. N. Jardine, J. Palmer and G. Sinden (2005). 40% House. Oxford, UK, Environmental Change Institute.

DEFRA. (2007). "Climate Change Levy." Retrieved January 19th, 2007, from http://www.cclevy.com/.

DTI (2006a). Energy Review: The Energy Challenge. London, UK, Department of Trade and Industry.

DTI (2006b). Microgeneration Strategy. London, UK, Department of Trade and Industry.

DTI (2006c). Quarterly Energy Prices: December 2006 London, UK, Department of Trade and Industry.

DTI (undated). Energy Consumption in the United Kingdom. London, UK, Department of Trade and Industry.

Energy Saving Trust (2006). Domestic Energy Primer - An Introduction to Energy Efficiency in Existing Homes. London, UK, Energy Saving Trust.

Energy Saving Trust. (undated). "Energy Efficiency Commitment." Retrieved Jan 12th, 2007, from http://www.est.org.uk/housingtrade/eec/.

A. Hawkes and M. Leach (2005). "Solid oxide fuel cell systems for residential micro-combined heat and power in the UK: Key economic drivers." Journal of Power Sources 149: 72-83.

A. D. Hawkes, P. Aguiar, B. Croxford, M. A. Leach, C. S. Adjiman and N. P. Brandon (2007). "Solid oxide fuel cell micro combined heat and power system operating strategy: Options for provision of residential space and water heating." Journal of Power Sources 164(1): 260-271.

A. D. Hawkes, P. Aguiar, C. A. Hernandez-Aramburo, M. A. Leach, N. P. Brandon, T. C. Green and C. S. Adjiman (2006). "Techno-economic modelling of a solid oxide fuel cell stack for micro combined heat and power." Journal of Power Sources 156(2): 321-333.

Powergen. (undated). "WhisperGen." Retrieved Jan 12th, 2007, from http://www.powergen.co.uk/Business/Technology/Technology-Whispergen.htm.

N. Stern (2006). Stern Review on the Economics of Climate Change. London, UK, HM Treasury and the Cabinet Office.

J. Watson, R. Sauter, B. Bahaj, P. A. James, L. Myers and R. Wing (2006). Unlocking the Power House: Policy and System Change for Domestic Micro-Generation in the UK. London, UK, University of Sussex.

Acknowledgements

Many thanks to the European Commission which funded this work through the FLAME-SOFC Research Project.