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Cost targets for domestic fuel cell CHP

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Abstract

Fuel cells have the potential to reduce domestic energy bills by providing both heat and power at the point of use, generating high value electricity from a low cost fuel. However, the cost of installing the fuel cell must be sufficiently low to be recovered by the savings made over its lifetime. A computer simulation is used to estimate the savings and cost targets for fuel cell CHP systems.

Two pitfalls of this kind of simulation are addressed: the selection of representative performance figures for fuel cells, and the range of houses from which energy demand data was taken. A meta-study of the current state of the art is presented, and used with 102 house-years of demand to simulate the range of economic performance expected from four fuel cell technologies within the UK domestic CHP market.

Annual savings relative to a condensing boiler are estimated at €170–300 for a 1 kWe fuel cell, giving a target cost of €350–625 kW^{-1} for any fuel cell technology that can demonstrate a 2.5-year lifetime. Increasing lifetime and reducing fuel cell capacity are identified as routes to accelerated market entry.

The importance of energy demand is seen to outweigh both economic and technical performance assumptions, while manufacture cost and system lifetime are highlighted as the only significant differences between the technologies considered. SOFC are considered to have the greatest potential, but uncertainty in the assumptions used precludes any clear-cut judgement.

Keywords: Domestic CHP; Fuel cell performance; CHP modelling; Economic assessment; Cost target

1. Introduction

Many flaws have been identified with the current electricity generation mechanism employed in the developed world. The system of centralised power stations within a country wide electrical grid is inefficient, as 50–70% of the energy used is lost as heat to the environment. The inability to transport heat effectively has led to the widespread use of individual on-site heat generation, which in the UK is typically achieved by gas boilers offering up to 90% efficiency. Domestic combined heat and power (dCHP) is proposed as a logical step forwards, generating electricity at the point of use and thus utilising the by-product heat to dramatically improve efficiency.

Three technologies are strong candidates to be deployed on a domestic scale[1]: reciprocating engines, Stirling engines and fuel cells. Of the three, fuel cells provide the highest electrical efficiency and produce the lowest emissions, as no combustion of the fuel is required. In the domestic CHP market, fuel cells are typically still in the R&D stages, with several on-going field trials and projected release dates within the next few years.

The successful introduction of a new technology requires a marketable advantage over the traditional alternatives. The strongest incentive for individual home owners would be the financial savings offered by dCHP, whereas the ruling government may enact legislation enforcing its use based on reduced fuel consumption and emissions savings.

Until the magnitude of these savings can be demonstrated outright in field trials, it is useful to estimate the performance of these devices and model their operation. By calculating the amount of fuel that would be required by different technologies to heat and power UK homes, it is possible to estimate the financial savings that could be realised. These can be compared with estimates for the cost of purchasing the technologies, giving a complete understanding of the economic benefits from cradle to grave.

Such models have been presented by several authors, comparing fuel cells and other CHP systems in English, Canadian

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[1] ‘Domestic scale’ is a loose term, here taken to be around 0.5–5 kW of electric capacity.

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Table 1
Summary of previous techno-economic fuel cell studies

Study	SOFC, UK [1]	SOFC, Canada [2]	PEMFC, Japan [3]
Payback period (years)	5–7	5	20
Target cost for 1 kWe	€925–1150	€225	€4000
Annual saving	€250–325	€50	€250

and Japanese domestic scenarios [1–3]. Despite using similar modelling techniques, they gave somewhat varied results, with no consensus on whether fuel cell-based CHP would be beneficial or not. The general trends are that monetary savings of a CHP device are modest compared to the initial outlay, and that emissions savings depend strongly on the carbon content of purchased electricity. A brief summary of the key findings of the above papers is given in Table 1.

The model presented in this paper follows the typical design used in the papers referenced above, extending the scope in three areas:

- Considering a wider array of technologies, in more complicated combinations.
- Using specifically reviewed inputs for technical performance.
- Providing an analysis of the variation in results between different houses with installed dCHP.

2. Input parameters

Two categories of data are used by this type of model; the performance of each CHP system, and the pattern of energy demand it was simulated to meet (the demand profile). By developing a broad and reliable set of inputs into a domestic energy model, the quality of the results it gives should be improved.

The performance values used in previous works are typically from a specific model of fuel cell/CHP engine, or a general estimate for that technology. To gain a better understanding of their performance, the first aim was therefore to provide a range of values to represent the current state of the art for a number of CHP technologies.

There is a strong case for arguing that the most important and influential model input is the data on energy consumption. The way in which a CHP system is used – the utilisation[2] and on/off cycles – has an obvious impact on the benefit it provides, just as the way it responds to that usage would; due to its efficiency and response time. The link between the assumptions for the technical performance of a system and the end results are easily understood, e.g. higher efficiency leads to lower fuel usage, and longer lifetime gives a lower annual cost of replacement.

However, the relationship between the demand profile and the benefit of a CHP unit is usually only qualitatively known. Two general trends have been observed: that larger houses give improved results due to a better match with the heat to power ratio of the CHP unit; that more coincident demand (heat and electricity demanded occurring together) will give greater savings, as the purchase and export of electricity are minimised [1]. The uncertain effects of these assumptions reinforce their importance, as extrapolating results from one demand profile to another is virtually impossible.

Table 2
Operating parameters for AFC systems

η_{stack}	42.5–49.5%	
η_{system}	27.0–32.0%	
Operating	0.65–0.80 V × 0.10–0.25 A cm^{-2}	
Point	60–180 mW cm^{-2}	
Lifetime	4–10 kh	(0.5–1.1 years)
Degradation	10–30 μV h^{-1}	(10–35% $year^{-1}$)
Cost	€225 + €100–450 kW^{-1}	

In previous work, it is typical for a small number of profiles (e.g. three houses) [4,5] to be used due to the availability of data and computational time required by the model. As each pattern of energy demand leads to different results for the performance of a CHP system, using a small selection will give a skewed set of results, whose position relative to the 'global mean' of all UK demand profiles is not known. There is no solid consensus on how to categorise profiles, or how to choose a uniformly distributed selection. Thus, the second aim was to find the largest set of profiles, and rely on the spread of results between them to provide an indicator of the spread of performance that could be expected if CHP were to be adopted country wide.

2.1. Fuel cell performance

Fuel cell technologies have been considered in this study if they are well established, with commercial demonstrations and research activity aimed at the domestic market. Of the six maturing technologies, direct methanol fuel cells have not been considered as they cannot accept reformed natural gas as a fuel, and molten carbonate fuel cells are unsuitable due to the safety implications of siting a large pressure vessel in a domestic environment. The remaining technologies are discussed in the subsequent four sections.

Data were collected from 20 to 30 sources for each fuel cell technology to give a wide view of the state of the art. Owing to the volume of data considered, the individual results and details of their processing are published separately online [6]. The values for each category were combined, and the ranges of one standard deviation either side of the mean ($\mu \pm 1\sigma$) are presented in Tables 2–5.

Table 3
Operating parameters for PAFC systems

η_{stack}	40.5–54.5%	
η_{system}	26.0–35.0%	
Operating	0.65–0.70 V × 0.15–0.30 A cm^{-2}	
Point	100–200 mW cm^{-2}	
Lifetime	30–53 kh	(3.5–6.0 years)
Degradation	2–4 μV h^{-1}	(2–6% $year^{-1}$)
Cost	€3000–4000 kW^{-1} retail price	

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[2] Defined as the amount of power output by the fuel cell over a given time, relative to the output if it was constantly running at full capacity.

Table 4
Operating parameters for PEMFC systems

η_{stack}	36.5–50.0%	
η_{system}	23.0–31.5%	
Operating	0.60–0.75 V × 0.40–0.90 A cm^{-2}	
Point	270–560 mW cm^{-2}	
Lifetime	7–19 kh	(0.8–2.2 years)
Degradation	2–10 μV h^{-1} permanent[a]	(2–11% year^{-1})
Cost	€300–900 kW^{-1}	

[a] A number of stacks also showed 50–250 μV h^{-1} of temporary decay, which could be recovered by switching the stack off [6].

Four parameters were considered as inputs into the model, namely: efficiency, lifetime, degradation and cost. The typical operating voltage was also found to convert degradation from the common units of mV kh^{-1} into terms of efficiency. The level of research and commercial activity, and any specific problems encountered by each technology were also noted for the sake of completeness. The information was processed according to the following rules, to give some standardisation between sources:

- The overall CHP system was defined as the complete package required to convert natural gas into ac electricity at the point of use.
- All efficiencies are given relative to the higher heating value (HHV), as natural gas is priced by HHV energy content, and it is convenient to condense the flue gases with a dCHP system.
- Stack efficiency was estimated for an ambient pressure H_2 system, excluding inversion and parasitic losses. System efficiency was estimated for a reformed natural gas system, net of these losses.
- All costs were converted to 2007 Euros based on a global average inflation of 2.5% per annum (0% for Japan), and exchange rates of ¥160 = \$1.30 = £0.69 = €1.
- System cost estimates were based on present day materials and technology, with high-volume series or continuous production. Where possible, embedded R&D costs and profit margins were excluded.

2.1.1. AFC—alkaline fuel cells

AFC were the first fuel cell technology to be demonstrated in a practical application, successfully powering over a hundred NASA space missions since the 1960s [7]. R&D applications branched out into terrestrial vehicles during the 1970s, but they never reached commercial potential. A handful of companies remain interested in AFC, focusing on niche electric vehicles (e.g. golf carts and fork lift trucks) and premium stationary generation for residential or marine applications.

AFC have failed to reach commercialisation so far due to problems with lifetime and degradation. CO_2 contamination is perceived as the major issue, due to the resulting need for expensive air scrubbers or a supply of pure oxygen [8]. These widely held beliefs are challenged by several authors, particularly Gülzow in his work on non-noble electrodes [9]. However, the demonstrable lifetime of AFC systems remains around 1 year, regardless of the CO_2 content of the reactants [10]. It is argued that durability never received extensive research and could be improved substantially, but with few active groups in the field progress is likely to be slow.

A commonly quoted benefit of AFC systems is the inherently greater reaction kinetics, leading to higher cell voltages and system efficiency [11]. However, as seen in Table 2, when performance is extrapolated from that of a hydrogen fuelled, dc stack (η_{stack}) to a natural gas ac system (η_{system}), this efficiency advantage is eroded. The cost projections for AFC present a more optimistic picture, with the basic materials and construction techniques expected to result in lower manufacturing costs than for other fuel cell types [8].

Table 5
Operating parameters for SOFC systems

η_{stack}	42.0–64.5%	
η_{system}	27.0–41.5%	
Operating	0.65–0.75 V × 0.30–0.70 A cm^{-2}	
Point	220–460 mW cm^{-2}	
Lifetime	15–47 kh	(1.7–5.4 years)
Degradation	0–8 μV h^{-1} without thermal cycling	(0–10% year^{-1})
Cost	€300–600 kW^{-1}	

2.1.2. PAFC—phosphoric acid fuel cells

PAFC were the first type of fuel cell to be commercialised, and represented 40% of the installed CHP units by 2004 [12]. UTC power (formerly ONSI) has dominated the industry with its PureCell system (formerly PC25), which provides the majority of the published information collated in Table 3. Installed PAFC systems have almost exclusively been for large stationary generation (100–200 kW), but a number of research stacks have also been produced in the range of 1–10 kW [13,14].

Due to the intense research by ONSI in the 1970s and 1980s the durability and lifetime of PAFC systems were raised to meet the demands of industrial cogeneration. Lifetimes of 5 years with >95% availability have been demonstrated in a variety of demanding conditions [15]. However, PAFC have never been considered economically viable, and have required heavy subsidies from the U.S. Department of Defence. The cheap alternative of diesel generators is neither suitable nor available on the domestic scale, creating a more favourable economic market for PAFC (or any fuel cell) to enter.

Research activity is limited, but commercial interest is recently regaining strength, with Fuji and UTC developing new systems. The development of PAFC is considered to be two or three decades ahead of that of other fuel cell types, which can either be seen as a benefit – as they are a tried and tested, mature design – or a drawback, as they will be far along the technology S-curve, with little scope for improvement.

2.1.3. PEMFC—polymer electrolyte membrane fuel cells

PEMFC (alternatively PEM, PEFC or SPFC) have been surrounded by much commercial hype, and were responsible for much of the dramatic rise in interest in fuel cells over the last decade. Therefore, the majority of research and commercial activity worldwide is now focussed on PEMFC technology [16], giving the greatest potential to realise the improvements required to gain widespread usage.

Table 6
Technical and economic parameters used

Boiler efficiency	86 ± 2% HHV
Total CHP efficiency	80 ± 5% HHV
Price of natural gas	3.25 ± 0.15c $(\mathrm{kWh})^{-1}$
Price of electricity	12.25 ± 1.25c $(\mathrm{kWh})^{-1}$
Electric export value	50% of purchase price
Real discount rate	3% per annum
Ancillary components	Integrated backup boiler for heat demand; 20 kWh thermal storage; two-way grid connection (unlimited electrical sale)

The widely publicised high-volume estimates of as little as €15 kW^{-1} "are not valid for stationary systems" [17] as they typically represent future projections for vehicle engine replacements. Estimates for stationary systems are more conservative due to the different design criteria, particularly the need for more ancillary equipment, and a less aggressive power density.

Many of the advantages of PEMFC are particularly suited to transport applications, e.g. the high power density, mechanical robustness and low operating temperature. However, application in the dCHP market generates similar interest among manufacturers,[3] as none of the above features is considered a disadvantage for stationary use,[4] and overall performance appears to be similar to other low temperature fuel cells—as seen in Table 4.

2.1.4. *SOFC—solid oxide fuel cells*

SOFC differ from the other three technologies in that they are typically operated above 700 °C, bringing about a unique set of benefits and challenges. There are also a number of SOFC designs used by manufacturers, with differences in geometry, temperature and reforming affecting all aspects of the cell performance.

Siemens-Westinghouse and Rolls Royce began work on large, high temperature systems in the 1970s, with particular interest in integration with a gas turbine to form a high efficiency, MW-scale power plant. More recently, companies have begun considering SOFC on the domestic scale, with heavy development from partnerships between Japanese gas companies and fuel cell manufacturers. Interest in SOFC is now of the same magnitude as in PEMFC in the dCHP field [16].

SOFC systems are widely regarded as having particularly high electrical and total system efficiency, due to the relative ease of operating on natural gas, and simple extraction of heat from the higher temperature coolant. Consequently, their heat to power ratio is the lowest of all CHP technologies, typically between 0.5 and 1. While this provides the greatest economic benefit per unit of fuel consumed, it is a poor match to houses in UK; typically estimated as between 2.5:1 and 3.5:1 [18].

The durability of SOFC systems is highly dependant on the type of design and the operating conditions. Laboratory tests at steady-state conditions have demonstrated lifetimes of up to 8 years [19], but just 50 on/off cycles could cause irreparable damage due to thermal stresses [20]. To attain the lifetimes given in Table 5 with the highly intermittent demand from dCHP, an SOFC system would require a small or tubular design that was resistant to cycling, or a modified operating pattern that prevented unnecessary shutdown.

2.2. *Other parameters used*

The other parameters used in the model were chosen to reflect the current technology within the UK market, and are presented in Table 6.

The central value of 86% for boiler efficiency is the requirement for SEDBUK 'A rated' boilers, and is a conservative estimate for the maximum efficiency that can be achieved by top performing boilers in a real-world situation. The overall fuel cell efficiency (electrical + thermal) was taken to be 75–85%, which was the average seen for the four technologies. Different values were not chosen for each as this appears to be determined by the level of integration with the heat recovery system, rather than the method used to generate the heat and electricity.

Fuel prices were based on the standard direct debit package from seven major UK suppliers as of July 2007. The price paid for exported electricity was chosen to reflect the relative price paid by Powergen during field trials of the WhisperGen Stirling engine [21], and is approximately the wholesale price that suppliers pay for electricity. The discount rate was chosen to reflect the cost of domestic borrowing, with inflation excluded—as energy prices were simply assumed to rise in line with inflation.

Thermal storage was included in all scenarios, as this was estimated with the CHP model to give 95 ± 5% less purchase of grid electricity, and 40 ± 21% greater savings.[5] The thermal store had a 20 kWh capacity to represent a typical 300 l tank with a water temperature of 70 °C. Energy loss from the tank was simplified as a constant rate of 30 W (266 kWh year^{-1}). The backup boiler was sized according to each property, to accommodate the thermal demand placed on it.

Batteries were considered for the local storage of electricity, as an alternative means to avoid expensive purchase from the grid. However, the capital cost was found to be 8–15c $(\mathrm{kWh})^{-1}$ based on the current retail price and lifetime of 6 deep-cycle lead acid batteries. This was higher than the 6c $(\mathrm{kWh})^{-1}$ discrepancy between the import and export price with a 50% buyback price, and so batteries were considered to be uneconomical in the given scenario.

2.3. *Energy consumption data*

This study used the largest set of energy consumption data that was available, allowing for an investigation of the variation

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[3] Ebara–Ballard is leading the most extensive fuel cell field trial, with 1250 PEMFC units in Japan.

[4] Heat extraction is thought to be more difficult by some due to the low operating temperature, but the thermal efficiency of PEMFC is not found to be inferior to other technologies.

[5] Baxi estimate that their BETA 1.5 Plus would achieve a 53% cost saving with a 600 l hot water tank and only 24% without [22].

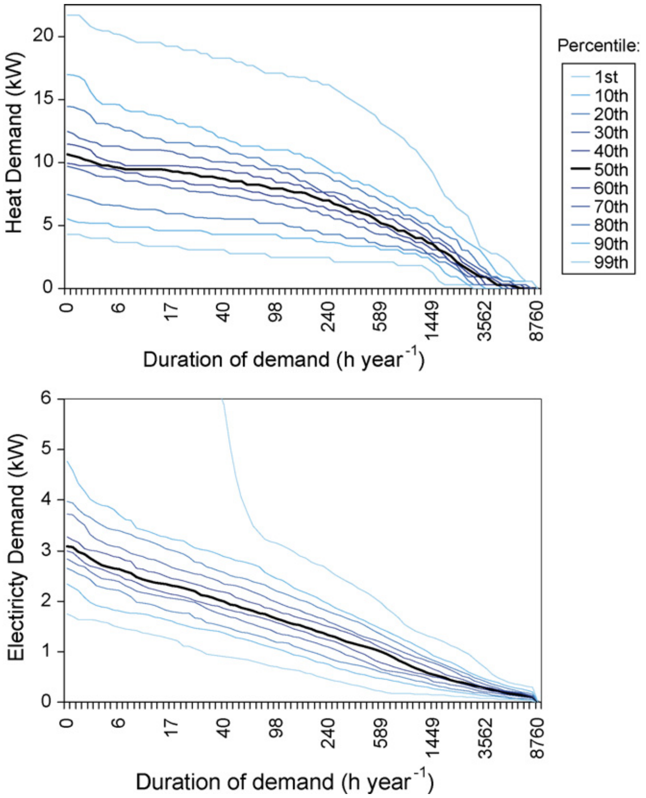

Fig. 1. Demand duration curves with a logarithmic time scale, showing heat and electricity demand from the 102 profiles used.

in CHP performance between houses. Data from 130 houses were originally collected by BRE from the Milton Keynes Energy Park during 1988–1991, and were supplied by The Bartlett, University College London. The houses were specially built using the latest technologies and construction techniques at the time, giving SAP ratings of 90–100—similar to the standard of houses built today in the UK.

The data set represent a large number of properties, with over 100 house-years of data from a range of 1 bedroom flats to 4 bedroom detached houses. The average demand from the properties was 12.2 ± 4.6 MWh year^{-1} of heat and 3.2 ± 1.3 MWh year^{-1} of electricity. The spread between properties is shown in more detail by the demand duration curves shown in Fig. 1.

The narrow specification of the properties does not give a good representation of the overall UK housing stock. They were all highly insulated, with lower than average heat demand, and so can be better thought of as an approximation of new build homes. The age of the data is also cause for concern, as it was collected in an era before the proliferation of laptops, mobile phones, low energy light bulbs and standby buttons.

A further problem is that the energy demand was measured at 60 min intervals, which has been shown to be insufficient for accurate CHP modelling. Hawkes and Leach showed in [4] that data with such a low temporal resolution will under-estimate the lifetime cost of meeting energy demand by 8%, and over-estimate the utilisation and emissions savings by 30–40%, over 1 day in three properties. Since electricity demand during an hour is uneven, the fuel cell will operate at part-load for most of the time, while being too small to meet the peaks in demand. These details are obscured with hourly resolution, hence the model predicted that some houses purchased no grid electricity when using a fuel cell and thermal storage (Section 2.2).

3. CHP simulation model

A model was created for this study with the aim of simulating the operation of CHP and other energy devices as they meet a pattern of heat and electrical demand. The program has been written in object oriented C++, and is intended to be flexible and extendable; allowing the user to create customised simulations, and providing a framework for adding new types of device, different operating logic and new formats of data output. Development is ongoing, and the program is intended to be released as open source upon maturity.

To perform a typical simulation, the inputs into the model are first specified: the combination of devices to use; the technical characteristics of each; the operating logic that governs how they meet the demand; the capital, operating and fuel costs; the patterns of demand they are required to meet; the information that should be output from the model. Provision is made for optimising and stochastically varying some of these inputs—e.g. optimising the capacity of each device to minimise total cost, or varying the technical and economic inputs for Monte Carlo analysis.

Once started, the model runs through each time period in the demand data set, deciding how to supply the current energy demand independently at each time-step. Each decision is based on simple arithmetic and logic, as opposed to predictive control,

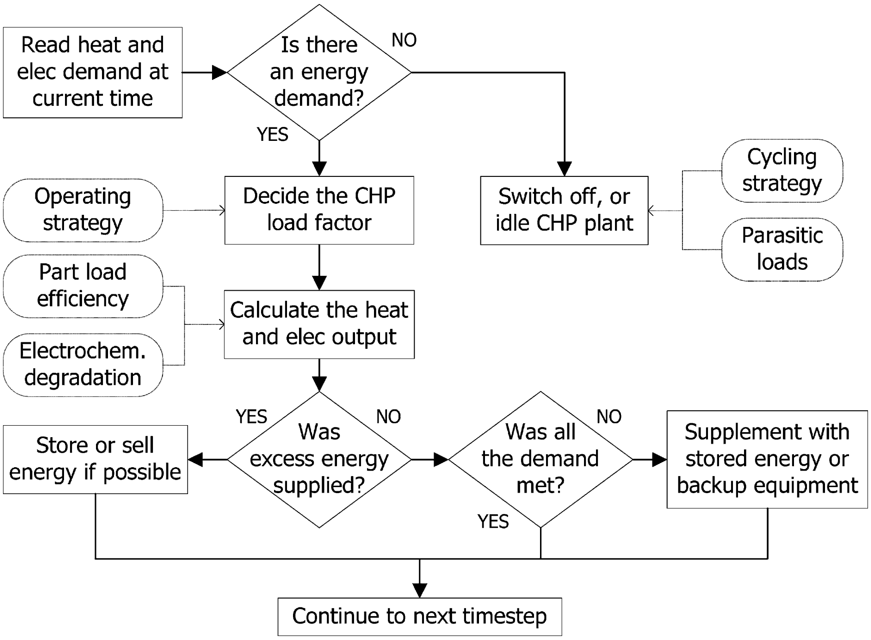

Fig. 2. Control logic for a typical CHP device at a single time-step. Data inputs, actions and decisions are represented by rounded boxes, square boxes and diamonds, respectively.

pattern recognition or global optimisation—to allow for a large number of scenarios to be processed quickly. At each time-step, the calculation consists of two main steps: determining the load factor of the CHP unit[6] and accommodating for any differences between supply and demand, as shown in Fig. 2. Every time this sequence is executed, the program calculates the amount of natural gas that was consumed, and the import/export of electricity from the house. Once these have been calculated for the entire year, the cost and CO_2 emissions from meeting the energy demand are calculated.

The energy supplied by the fuel cell was decided by its operating strategy, which for this study was chosen to be ‘maximum demand lead’. By minimising the amount of energy supplied by the backup boiler and electrical grid, this operating strategy has been shown to closely approximate the minimum possible operating costs with a fuel cell [23]. The load factor of the fuel cell was set to meet the greatest of the heat and electric demand at each time-step, as shown in the following equation:

$$L_{FC} = \max\left(\frac{D_{el}}{\eta_{el}}, \frac{D_{th}}{\eta_{th}}, 1\right) \tag{1}$$

L_{FC} is the load factor of the fuel cell, D_{el} and D_{th} are the demand for electricity and thermal energy, respectively, η_{el} and η_{th} are the electrical and thermal efficiency of the fuel cell at the given load factor. Multiplying the current maximum heat and electrical output of the fuel cell by this load factor gave the thermal and electrical power output during the time-step. The energy supplied by other devices was then set to meet any shortfall from the fuel cell, with electricity supplied by the grid and heat supplied by the hot water storage tank, or by the boiler if the tank was empty. When excess electricity was generated by the fuel cell – if ($D_{el}/\eta_{el} < D_{th}/\eta_{th}$) – it was exported to the grid. If the converse was true, the excess heat was stored in the tank, or if the tank was full the load factor of the fuel cell was reduced accordingly.

The resulting operation of the fuel cell with this control logic is shown in Fig. 3, which gives a sample of one week’s demand

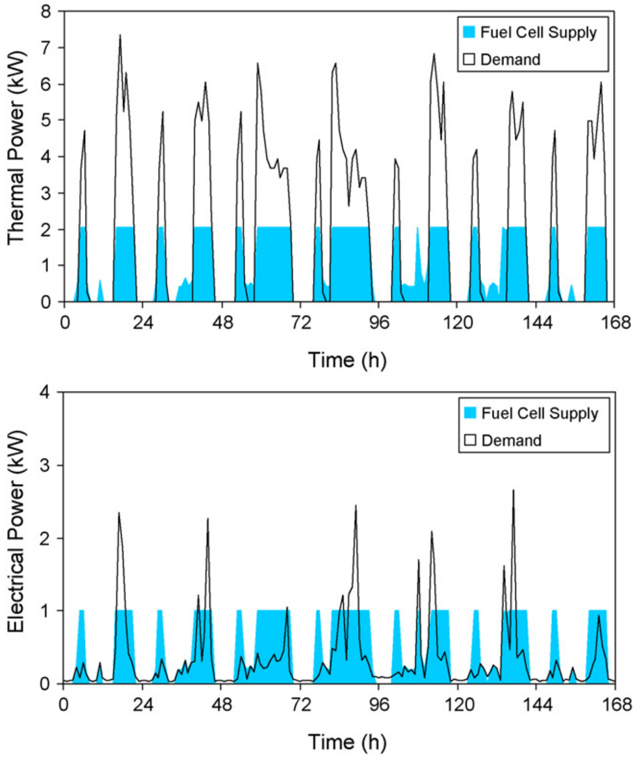

Fig. 3. Supply of energy from the fuel cell when meeting the demand from a typical house, using a maximum demand lead strategy.

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[6] Defined as the current power level relative to the maximum.

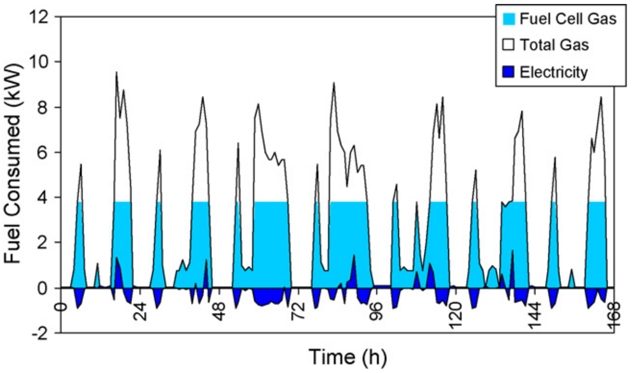

Fig. 4. Rate of fuel consumption by the entire energy system when meeting the demand from Fig. 3.

from a typical house. The demand for electricity and heat are shown as solid lines, with the outputs from the fuel cell as shaded areas. It can be seen that the fuel cell cannot meet all of the demand during periods of heating or peaks in electricity use, and conversely that there are periods when it generates either an excess of heat or electricity, due to the higher demand for the alternate product. The low heat to power ratio of the fuel cell means that less than half of the thermal demand can be met by the fuel cell, whilst there is often an excess of electricity generated, with little need for import. The total amount of fuel consumed in meeting this demand is given in Fig. 4. During periods of high demand, natural gas was consumed by both the fuel cell and boiler, as the tank was unable to meet the additional heat demand alone. Electricity was typically exported (negative demand) during these heating periods due to the high electrical output of the fuel cell.

Other constraints on device operation were incorporated into the model, including:

- A minimum required operating load.
- The time required until power output from cold start.
- A maximum allowable ramp rate between load factors.
- Power requirements for hot idling.
- The ability to turn on/off or not.

A minimum load factor of 20% was enforced for all fuel cells while they were operating, due to the significant loss in efficiency at low output from parasitic loads. SOFC was also required to run constantly to avoid thermal cycling, which is a potential cause of rapid degradation and failure of the fuel cell stack. Neither of these constraints was seen to have a significant effect on the annual fuel cell utilisation, or its economic performance—which changed by less than 2% when applying either constraint. The other constraints were not utilised in this study.

Devices were modelled as having a dynamic efficiency, which varied based on the current load factor, device age and time since the last maintenance or on/off cycle. This allowed for the simulation of varied part-load performance and electrochemical degradation, which are characteristic of fuel cells. Boiler efficiency was kept constant with load, while the electrical and total efficiencies of each fuel cell were modelled by the range of values found in Ref. [6]. Further dynamic effects, due to load commutation or recent operating history have not been included, as they have not been widely verified through experimental work.

3.1. Assessment methods

Two metrics were used to evaluate the performance of each fuel cell technology: the expected payback period and the target capital cost. These give an indicator of whether a technology will have an economic advantage over the traditional alternative, and thus whether customers would have an incentive to purchase it. Both of these values were derived by the CHP model from the money saved on energy bills.

The payback period is the time required for these savings to equal the cost of purchasing and installing the system. Typically, this needs to be less than 7 years to indicate an attractive purchase for UK consumers [21], but it must also be shorter than the lifetime of the fuel cell—as no further cost savings will be made after it has ceased working.

A problem with calculating the payback period is that it requires the knowledge of the capital cost of the technology. In the case of fuel cells, this is still the subject of much speculation [18], as is shown by the costs presented in Tables 2–5, which vary by factors of 2–4 for each technology.

To sidestep this uncertainty, the target cost of the system can be defined as the capital cost below which it would give a net economic benefit. This was calculated as the net present value (NPV) of the income stream from the fuel cell—the sum of the savings on quarterly energy bills over its lifetime. By choosing a discount rate to reflect the cost of domestic borrowing, the NPV equals the amount of money that could be borrowed to fund the purchase and installation.[7] If the fuel cell actually costs less than this target, it would save money over its lifetime and be a sensible investment.

To quantify the comparison between the target and estimated cost, the model calculated the probability that an overall profit could be made—i.e. that the total savings exceeded the cost of the fuel cell. The distribution of savings was integrated over the range of €0–2000, weighted by the probability that the system cost was below that point. There is no clear-cut yes/no answer as to whether a given fuel cell will be profitable, as this depends on the way it is operated. Instead, this probability accounts for the expected spread of cost and performance, and the range of energy demand that would be met.

3.2. Assessment methodology

Each of the fuel cell technologies was simulated in the 102 houses with 10,000 Monte Carlo trials, which stochastically varied the following parameters as normal distributions over the ranges given in Sections 2.1 and 2.2:

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[7] It is assumed that the home owner would purchase a fuel cell with a loan, in the hope that the future saving on energy bills would accumulate enough to pay back the debt.

- Technical assumptions: electric and total efficiency, boiler efficiency, degradation rate.
- Economic assumptions: cost of electricity and gas, system lifetime.

One set of parameters was varied while the others were held constant, so that the influence of each set of assumptions could be separated from the others, and from that of the different houses.

The simulated fuel cells had a fixed capacity of 1.0 kWe (kW electrical output), which was seen to give a utilisation of 51 ± 12%, which coincided with the rule of thumb that a CHP plant should be sized to give 50% utilisation [18]. Each fuel cell was compared to a base scenario of the best available alternative: heat from a condensing boiler, and electricity purchased from the national grid.

4. Results and discussion

Three areas of study were investigated using the CHP model: the relative influence of the demand profile and other model inputs; the sensitivity to the most influential of these inputs; a comparison between the four fuel cell technologies.

4.1. Spread of results

The target cost was calculated for a 1 kWe PEMFC, as this had the mid-range performance and lifetime of the three low temperature fuel cells. Fig. 5 shows histograms of the target cost when the three groups of inputs were varied.

The widest spread in the results was seen with the different demand profiles, whilst the variation in fuel cell performance gave the most consistent values. This was confirmed by the standard deviation in the cost target, which was ±28% for the demand profiles, ±11% for the technical assumptions and ±19% for the economic assumptions.

The uncertainty due to demand profile was examined further by considering the annual savings from running the PEMFC. Due to the direct correlation with the target cost, a ±28% standard deviation was also seen in the savings for each house. The overall magnitude of heat and electricity demand for each house was then scaled to the average of all the houses, to give a normalised set of demand profiles.

With no difference in the amount of energy demanded, the standard deviation was reduced to ±11%. This spread in savings was due only to the pattern of demand, particularly the amount of overlap between heat and power demand. It follows that the additional spread seen in the unscaled houses was due to the difference in the utilisation of the fuel cell. A larger house would have sufficient demand to make the fuel cell run at higher power levels throughout the year, saving more money as it avoids the purchase of more electricity.

4.2. Comparison of fuel cell technologies

The annual savings from each type of 1 kWe fuel cell are presented in Fig. 6, with the standard deviation across the different houses and Monte Carlo trials. The savings from each technology are very similar; with averages in the range of €225–250 year^{-1}. Only a 11% difference separates the technologies, compared to an average ±31% standard deviation within each.

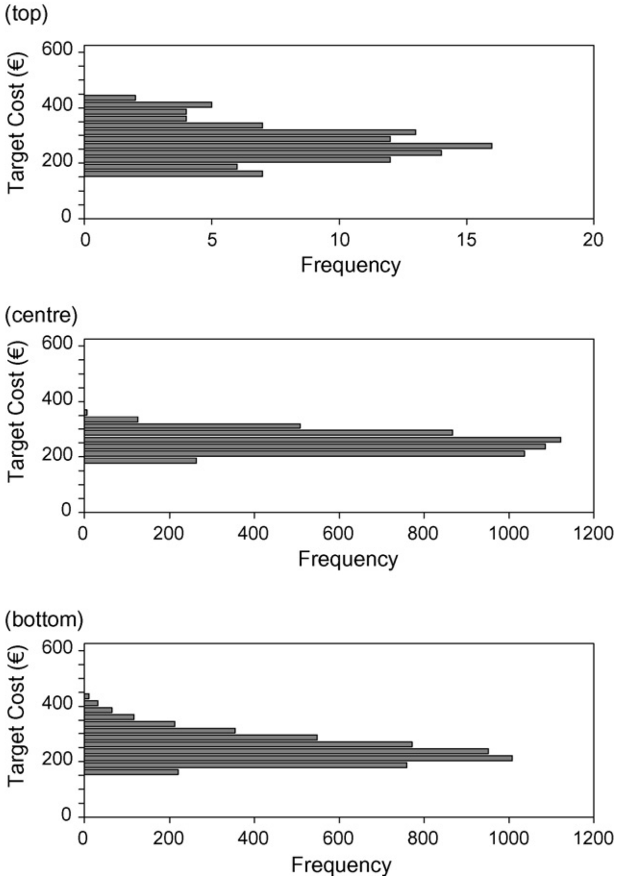

Fig. 5. Histograms of the target cost of a 1 kWe PEMFC system with varied demand profiles (top), fuel cell performance (centre) and economic variables (including system lifetime) (bottom).

Fig. 7 shows the total savings that would be made over the lifetime of each technology, which is taken as the estimated target cost. With so little separating the annual savings, the difference in system lifetimes was almost entirely responsible for the difference in the total savings.

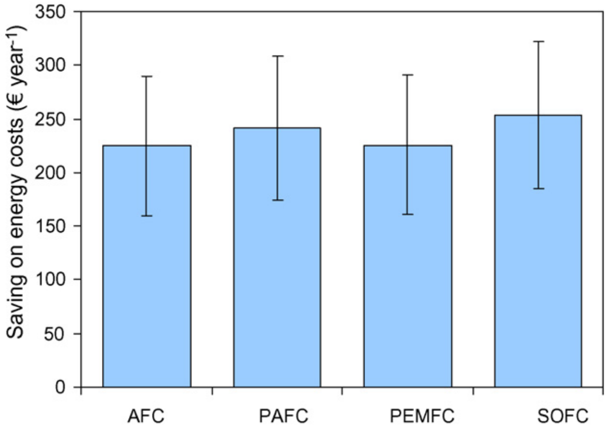

Fig. 6. Annual savings from each type of 1 kWe fuel cell.

Table 7
Economic comparison of 1 kWe fuel cells

	AFC	PAFC	PEMFC	SOFC
Estimated high-volume manufacturing cost	€325–675	?	€300–900	€300–600
Target sale price	€120–230	€660–1100	€220–420	€510–970
Estimated lifetime (years)	0.5–1.1	3.5–6.0	0.8–2.2	1.7–5.4
Payback period (years)	1.2–3.2	?	1.1–4.1	1.0–2.5
Probability of economic benefit (total savings > purchase cost)	0.01	?	0.17	0.88

The comparison between the estimated manufacturing costs from Section 2 and these target costs are summarised in Table 7. The payback period and 'probability of profit' were not calculated for PAFC, as no estimate for the cost of a domestic scale system was available.

Comparing the cost estimates with these targets gives an indication of the prospective market for each fuel cell technology. Under all circumstances, AFC are expected to cost more than is required to be competitive. For PEMFC and SOFC, there is an overlap between the estimated manufacturing cost and the target cost; the cheapest and longest lived systems of each technology could be economical if mass produced, especially if sited in larger houses which give the greatest savings.

The calculated payback periods are short compared to those in other studies presented in Table 1, due to the low estimated capital costs and low discount rate chosen. However, the estimated lifetimes of AFC and PEMFC are typically below their payback periods, indicating that these systems would not last long enough to deliver the required savings. The large range in each expected payback period is due to the combined uncertainty in estimated cost and annual savings.

To quantify the comparison between costs and targets for each fuel cell, the probability that the NPV of savings was greater than the estimated cost is also given in Table 7. The difference between the technologies becomes more apparent; in the majority of cases SOFC are expected to give an economic benefit, while AFC and PEMFC are expected to be an economic burden.

These probabilities were calculated from the distributions of estimated cost and target cost (total saving) for each fuel cell. Fig. 8 shows each of these distributions for a 1 kWe SOFC, and a 1 kWe PEMFC side by side.

For half of SOFC installations (with savings >€750), the total savings would exceed the entire range of estimated cost, and thus they would be guaranteed to make a profit. The remaining installations would only make a profit if the system cost was towards the lower end of its range. Conversely, no PEMFC – even one

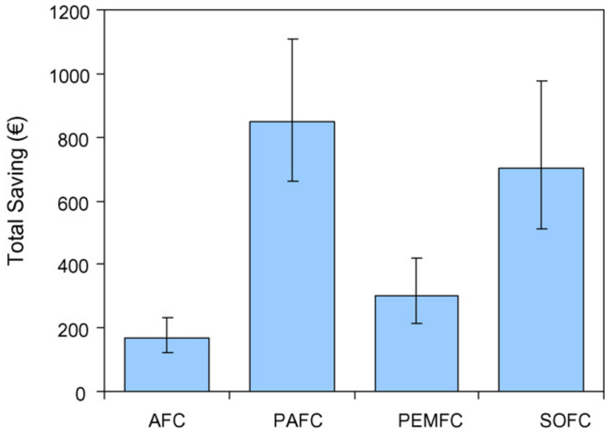

Fig. 7. NPV of savings over the lifetime of each type of 1 kWe fuel cell.

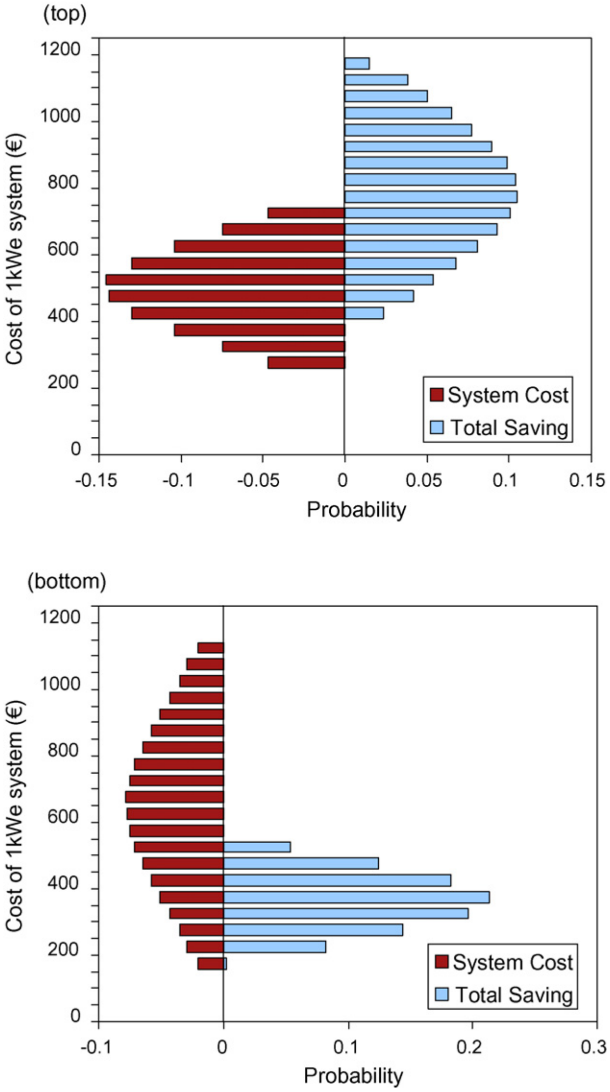

Fig. 8. Histograms showing the range of estimated system cost (lifetime expenditure) and total saving (lifetime income) for a 1 kWe SOFC (top), and a 1 kWe PEMFC (bottom).

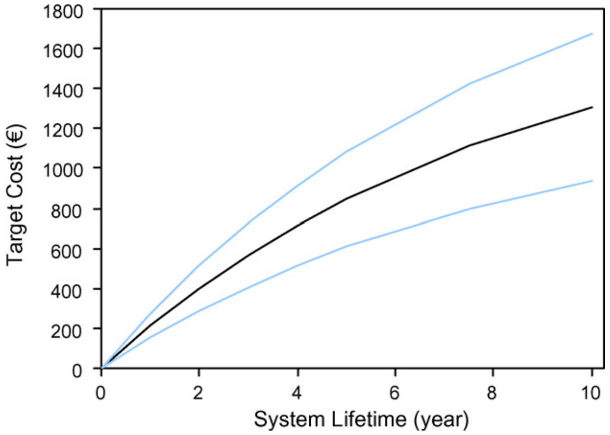

Fig. 9. Target cost for a 1 kWe PEMFC against lifetime, with the mean ± 1S.D. shown.

with above average performance installed in the most suitable house – would be guaranteed to make a profit, it must also have been purchased at the lower end of the expected construction cost.

4.3. Sensitivity of results

From the presented results, the two model inputs with the greatest impact on target cost were identified: the system lifetime and the total amount of energy demand from the house. The lifetime was responsible for the differences in target cost between the four technologies, whilst the utilisation of the fuel cell was responsible for most of the deviation within each technology.

The target cost was calculated for a 1 kWe PEMFC with a lifetime ranging from 0 to 10 years, as shown in Fig. 9. Due to the similarity in performance between the fuel cells, this target is representative of any of the four technologies.

The target cost scales almost linearly over the range of lifetimes of current systems (1–5 years), due to the low discount rate chosen. A target cost of €350–625 was found for a 1 kWe fuel cell with a lifetime of 2.5 years, rising to €625–1050 if the lifetime is increased to 5 years.

To investigate the influence of demand and utilisation, the electrical capacity of the fuel cell was varied between 0.2 and 3 kW—giving utilisations that ranged from 90 ± 10% to 28 ± 7%. The target cost per kilowatt of electrical capacity is shown in Fig. 10.

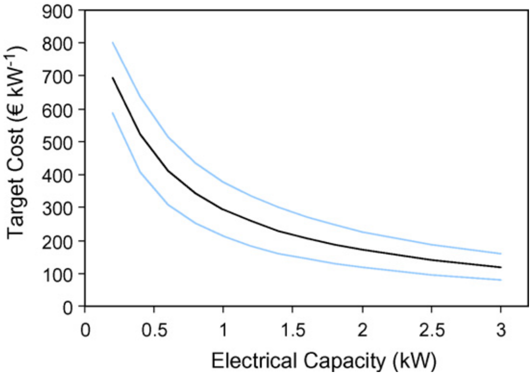

Fig. 10. Target cost for a PEMFC system against installed capacity, with mean ± 1S.D. shown.

It is seen that reducing the capacity of the fuel cell increases the target cost per kilowatt, due to the increased CHP utilisation; the economic benefit per kilowatt increases as the fuel cell operates for longer during the year. Above 0.5 kWe, doubling the installed capacity only allows for a 10–30% increase in the total cost. The target cost for a 1.5 kWe PEMFC was estimated as €150–270 kW^{-1}, almost doubling to €240–430 kW^{-1} for a 0.75 kWe unit.

5. Conclusions

There is considerable uncertainty in the cost targets for fuel cell CHP [24], with €300–700 kW^{-1} being a typical range quoted [25]. Using the presented CHP model, the target capital costs for both PEMFC and SOFC were estimated to be at the extremities of this range: with mean targets of €320 and €740 kW^{-1}, respectively. The estimated target for AFC was significantly below the quoted range, and for PAFC the estimate was significantly above.

If fuel cells were mass produced today, only SOFC would be expected to stand a significant chance of competing with traditional UK technology. However, this judgement is based on estimates for production costs and system lifetime, both of which were subject to significant uncertainty.

More meaningful conclusions can be drawn when targets for cost and lifetime are specified together—eliminating the uncertainty in the assumptions used. Due to the similarity in performance between the fuel cell technologies, these targets can broadly apply to all of those considered.

A target of €350–625 is found to be viable for any 1 kWe fuel cell with a lifetime of 2.5 years. If the target lifetime can be increased, the cost becomes significantly more favourable. Also, if the chosen fuel cell capacity is reduced, the reduction in this target is small, giving an easier target price to attain.

When modelling dCHP technologies, more importance should be placed on the choice of demand profiles. Using the demand from just one house would be expected to give savings and target costs that deviate by up to 28% from the mean values presented. Using data from just a few days, as opposed to a whole year, would distort these results further. These distortions are similar in magnitude to the error introduced by using low resolution data as calculated in [4], suggesting that the quantity of data used is equally as important as the quality.

Conversely, the variation in electrical and total efficiency found between current fuel cell systems had little significance. The variation in energy demand, estimated lifetime, and estimated capital cost all individually had a greater influence on the resulting target cost. This is partly due to the relative certainty in the efficiency of current systems, which was to within ±4% for each technology—compared to the capital costs which ranged by a factor of 2 or 3.

With continued research effort, it is feasible that any of the four fuel cell technologies could meet this combined lifetime and cost target, and become economically viable in the UK domestic CHP market.

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References

[1] A. Hawkes, M. Leach, J. Power Sources 149 (2005) 72–83.
[2] K. Alanne, et al., J. Power Sources 158 (1) (2006) 403–416.
[3] H. Ren, W. Gao, Y. Ruan, Appl. Therm. Eng. 28 (2008) 514–523.
[4] A. Hawkes, M. Leach, Energy 30 (10) (2005) 1759–1779.
[5] J. Cockroft, N. Kelly, Energy Convers. Manage. 47 (15–16) (2006) 2349–2360.
[6] I. Staffell, Review of fuel cell performance. 2007 [cited Sep 2007]. Available from: http://www.fuelcells.bham.ac.uk/staffell.htm.
[7] K.A. Burke, First International Energy Conversion Engineering Conference, Portsmouth, Virginia, USA, 2003. Available from: http://gltrs.grc.nasa.gov/reports/2003/TM-2003-212730.pdf.
[8] G.F. McLean, et al., Int. J. Hydrogen Energy 27 (5) (2001) 507–526.
[9] E. Gülzow, M. Schulze, J. Power Sources 127 (2004) 243–251.
[10] E. DeGeeter, et al., J. Power Sources 80 (1999) 207–212.
[11] P. Gouérec, et al., J. Power Sources 129 (2004) 193–204.
[12] N. Sammes, R. Bove, K. Stahl, Curr. Opin. Solid State Mater. Sci. 8 (2004) 372–378.
[13] M. Ghouse, H. Abaoud, A. Al-Boeiz, Appl. Energy 65 (2000) 303–314.
[14] J.C. Yang, et al., J. Power Sources 106 (2002) 68–75.
[15] A.J. Appleby, J. Power Sources 58 (2) (1996) 153–176.
[16] Pricewaterhouse Coopers. Fuel cell industry survey. 2007 [cited Sep 2007]. Available from: http://www.pwc.com/extweb/pwcpublications.nsf/DocID/25582836BD5E736A852570CA00178BC7.
[17] D.B. James, F.D. Lomax, C.E. Thomas, Manufacturing cost of stationary polymer electrolyte membrane (PEM) fuel cell systems. 1999, Directed Technologies Inc.
[18] J. Halliday, et al., Fuel cells: providing heat and power in the urban environment. 2005, Tyndall Centre Technical Report No. 32.
[19] M.C. Williams, J.P. Strakey, S.C. Singhal, J. Power Sources 131 (2004) 79–85.
[20] W. Bujalski, C.M. Dikwal, K. Kendall, J. Power Sources 171 (1) (2007) 96–100.
[21] M. Pehnt, et al., Micro Cogeneration: Towards Decentralized Energy Systems, Springer, Berlin, 2006.
[22] Baxi Innotech, Beta 1.5 Plus Product Brochure. 2007.
[23] A.D. Hawkes, M.A. Leach, Energy 32 (5) (2007) 711–723.
[24] G. Gummert, W. Suttor, Stätionare Brennstoffzellen. Technik und Markt, C.F. Müller Verlag, 2006.
[25] K. Kendall, S.C. Singhal, Solid Oxide Fuel Cells, Elsevier Science, 2003.