FUEL CELLS FOR DOMESTIC HEAT AND POWER:

ARE THEY WORTH IT?

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"For all the killers and the hundred dollar billas,
for real [figures] who ain't got no feelings."

– Albert Johnson

Acknowledgments

To Raj Saini, I will miss the cynical contempt we shared for all this fuel cell nonsense.

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Abstract

Fuel cells could substantially decarbonise domestic energy production, but at what cost? It is known that these micro-CHP systems are expensive but actual price data has been elusive. Economic realities constrain individuals' decisions to purchase and national policies on climate change, so this lack of understanding has delayed commercialisation and government support. Models were therefore developed to simulate the economic and environmental benefits from operating fuel cell micro-CHP systems in UK homes, and to project current purchase prices into the near future.

These models were supplied with economic and performance data from an extensive meta-review of academic and commercial demonstrations; showing for example that fuel cell efficiencies are a third lower when operated in people's homes rather than in the laboratory. These data inputs were combined with energy consumption data from 259 houses to give a broad definition of operating conditions in the UK. The techno-economic fuel cell simulation model was validated against results from literature and Japanese field trials, and then used to estimate the changes in home energy consumption from operating the four leading fuel cell technologies in the UK.

Fuel cells are shown to offer negligible financial benefits in the UK at present. Energy bills would increase in 30-60% of homes, due in part to the low value of exported electricity. Savings are higher in houses with larger energy bills, but significant variation between similar properties confirms that simple trends cannot be used to identify ideal houses for fuel cell micro-CHP. The feed-in tariff proposed by the UK government would radically improve economic outcomes; as 10p paid per kWh of electricity generation would reward fuel cell owners with £600-750 annually.

It is estimated that today's fuel cells produce 360-450g of CO_2 per kWh of electricity generated due to reforming natural gas into hydrogen on-site. Their carbon intensity is therefore 30-45% lower than the UK grid, enabling average annual emissions reductions of 1-2.2 tonnes per home. These reductions depend strongly on the displaced electricity generation method, and could therefore range from around zero when displacing high efficiency gas turbines up to 5.5 tonnes if displacing coal.

From learning-by-doing, the price of Japanese 1kW PEMFC systems is shown to have fallen by 19.1-21.4% for each doubling of production volume. Prices are therefore projected to fall from £15,000 today to £6,000 within 10±5 years, determined primarily by the speed and scale of deployment world-wide. A commercially viable price of around £3,000 is however expected to be two decades away, and widely held targets of under £1,000 per kW are argued to be unobtainable with current technologies due to the requirement for extensive balance of plant and auxiliary systems.

Combining all these findings, the payback period of PEMFC systems would be 25-45 years with the proposed 10p/kWh feed-in tariff. This could fall to within current system lifetimes after 5-10 years of cost reductions; however, without this level of government support the savings from operation will be unable to give payback without major improvements in technology performance or more favourable energy prices. The carbon cost of current PEMFC systems is estimated at £750-950 per tonne of CO_2 mitigated. This figure is highly sensitive to the carbon intensity of displaced generation, and would reduce to £175/T if generation from coal plants is avoided.

Fuel cells are therefore not among the 'low hanging fruit' of carbon abatement technologies, although the carbon costs will halve over the next ten years in line with system price reductions. Investment in this technology must therefore be considered a long term strategy for low-carbon energy production.

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Chapter 1:

INTRODUCTION

1.1. Motivation

The era of plentiful, cheap and consequence-free energy from fossil fuels is drawing to a close. Climate change, instability in energy supply chains and the desire for national self-sufficiency are all interrelated global concerns at the top of political agendas worldwide. Meanwhile, competition for diminishing resources is driving energy prices further beyond the reach of billions of the world's poor. Around the world, the need to use energy more wisely is a concern that is slowly filtering into the public consciousness.

Climate agreements such as those made in Kyoto and Bali, and at the up-coming COP15 meeting in Copenhagen reflect humanity's realisation that the once abstract threat of climate change is manifesting into a global ecological and humanitarian crisis. Current research tentatively suggests that warming should be constrained to 2°C above pre-industrial times[1] to avoid the most catastrophic climatic 'tipping points'.[2, 3] However, even in a 2°C warmer world it is estimated that a quarter of all animal and plant species would be committed to extinction, and millions of people will be forced to migrate away from low-land flooding and prolonged droughts.[4, 5]

The same scientists who made these predictions also believe that 2°C of warming is the minimum that should be expected, as monumental reductions in current greenhouse gas emissions would be required.[6] It is thought that by 2020, developed countries such as the UK would need to reduce emissions to 25% below 1990 levels, with an 80% reduction by 2050 and negative emissions beyond 2075 (more CO_2 being absorbed by manmade actions than is emitted).[7, 8] The emerging consensus is that these are not just targets that can be aspired to and missed; they are the bare minimum that is required with zero added safety margin.

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Within two generations, the average Briton will need to reduce his carbon footprint from 10.8 tonnes of CO_2 per year to just 2.2 tonnes.[9] Heating and lighting the average UK home currently produces 5.5 tonnes of CO_2 (2.3 per person), and contributes around 15% of the total emissions from developed nations, as shown in Figure 1.1.[10-13]

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[1] As of 2005, global average surface temperature was already 0.75°C above pre-industrial temperatures.[1]

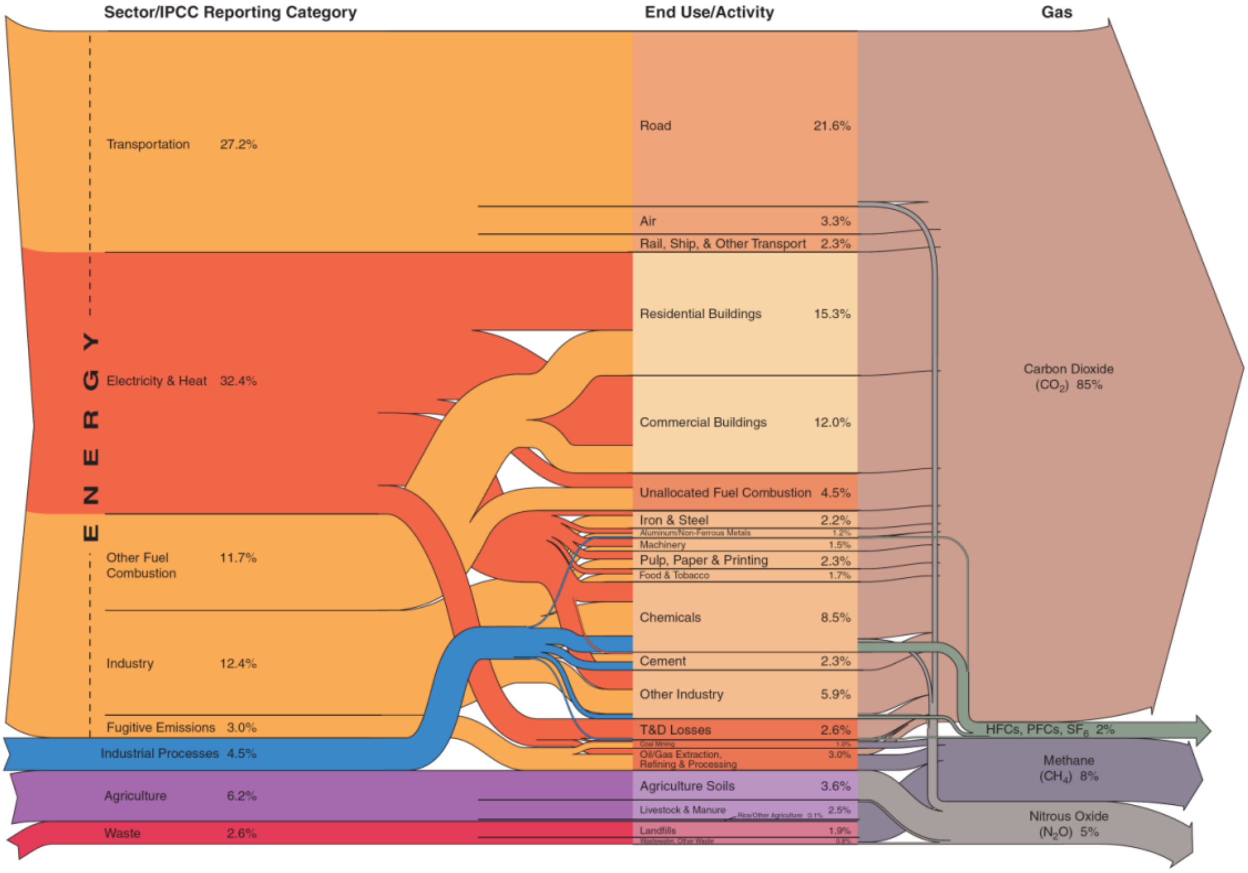

Figure 1.1: A Sankey diagram showing the contribution of different human activities to the annual greenhouse gas emissions of the USA in 2003. 86.7% of these emissions were due to energy generation, with 15.3% directly related to the domestic sector. Total emissions were 7.0GT of CO_2-equivalent from the USA, and 49.0GT globally. Image and data taken from the World Resources Institute.[11]

Global coal consumption has risen 27% in the last five years, fuelling the unrelenting increase in energy demand from developing nations[2].[14] This growth is enabling billions of people to rise out of poverty, and so it would be ethically questionable to limit their access to more energy. Instead, the efficiency and carbon intensity of energy production are the crucial factors which must be combated to allow for a more conserving means of powering the lifestyle that people strive for.

To this end, the traditional method of generating and distributing electricity to individual homes can be criticised for its wasteful design. Centralised thermal power stations in a country-wide electrical grid lose 50 to 70% of their energy input as heat to the environment, while their size and location prevents the widespread use of this heat for industrial or domestic consumption. The inability to transport heat over long distances has lead to a completely different model for heating houses, which typically uses separate generating equipment located on-site in each property, producing heat as and when required. Gas boilers are commonplace in the UK, offering efficiencies of up to 90% by burning natural gas in a compact unit.

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[2] Most notably, China's consumption of coal rose 65% in this period (2003-2008).

A distributed system of electricity generation, with individual power production in people's homes would offer significant advantages over the current system, as the by-product heat from generation could be utilised on-site rather than wasted. This concept of Combined Heat and Power (CHP) is widely used in energy intensive industries to reduce fuel costs, and distributed micro-CHP (dCHP, mCHP or μCHP) is emerging as an alternative for generating power in domestic properties. Most of the technologies employed in industrial CHP are suitable to use in domestic properties, and some such as fuel cells are being developed specifically for this market.

Fuel cells are poised to become one of the most widely used technologies of this century, with the potential for billions of units to be used in stationary electricity supply as well as transport and portable power applications. In the former of these areas, it is the high electrical efficiency and relatively low heat output that separates fuel cells from other domestic CHP technologies and the traditional centralised power stations. These benefits give fuel cells the potential to offer the lowest fuel consumption, lowest energy costs, and greatest CO_2 reductions.

The successful introduction of any new technology requires it to have a marketable advantage over the existing alternatives. This is especially true for fuel cells and micro-CHP, as they are aimed at a well established and mature market, where a cheap and convenient incumbent technology exists (electricity at the flick of a switch). The strongest incentive for individuals to purchase a micro-CHP system would be to save money on their energy supply. If people are to invest in fuel cells, they must be cheap: upfront costs must be within the reach of the average consumer, and should be recovered quickly by the savings made on running costs. Fuel cells also offer benefits to society as a whole, such as reduced dependency on imported fuel and national CO_2 emissions reductions. National governments may decide to invest with subsidies or regulations to enforce uptake if fuel cells offer a cost effective route towards these goals, or if they provide additional benefits which other technologies cannot.

A wide range of technologies and actions can contribute towards low-cost CO_2 emissions reductions. 6.2GT (12.5% of global CO_2 emissions) could be avoided at a cost of under $20 per tonne of CO_2, by fuel switching, improving plant efficiency, and installing nuclear and various renewables[3].[7] For fuel cells to compete in the low carbon free-market, they cannot solely rely

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[3] These include hydro, wind, geothermal and bio-energy; but not solar power.

on technical superiority, but must also be economically competitive and require little in the way of governmental support.[4]

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Fuel cells are still an emerging technology, virtually undemonstrated in the UK as of 2009. There is little information available on how much a micro-CHP system actually costs, and what they are likely to cost in the near future. Similarly, until the technical performance of these systems has been more widely demonstrated in the field, there is no consensus on the magnitude of carbon savings that could be expected.

Before the first fuel cell CHP systems begin to be mass produced, their environmental and economic 'credentials' need to be rigorously verified in order to ensure that they can genuinely offer a better way to meet society's demand for energy, rather than merely substituting the current problems with new ones. If the carbon savings from switching to fuel cell micro-CHP are marginal (or even negative), their development and deployment will not contribute towards greenhouse gas emissions reductions, and will have diverted much needed resources from other solutions. Similarly, if prices fail to reach competitive levels then systems will remain in laboratories and warehouses, and will never realise their potential installed in people's homes.

These types of concern have been raised and addressed with other low-carbon technologies such as nuclear fission, wind turbines and solar PV.[16-18] No such holistic assessments of fuel cell micro-CHP have been made to date. Key information such as the payback periods that potential buyers could expect, or the cost to society of abating emissions (the carbon cost) simply cannot be estimated at present. The starting points for producing such estimates are currently lacking, as there is no consensus on what figures to use for current prices and emissions reductions per household, let alone for how these will progress in the future.

Financial investment is universally founded on confidence. Until this confidence exists in fuel cell micro-CHP, the levels of investment required to boost the industry will fail to materialise.

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[4] Each year the EU gives over €20bn in subsidies to fossil fuel activities, four times the funding that all types of renewables receive.[15] A radical shift from protecting the status-quo should not be relied upon.

1.2. Project Rationale

The overall aim of this work is to provide a holistic assessment of the technical, environmental and economic potential of fuel cells for domestic microgeneration in the UK, and to provide the building blocks required to compare them with other low-carbon technologies and strategies. The focus is on evaluating the costs and benefits to the owner, and the global environmental impacts; shedding light on the significant grey areas which remain with:

- How much products are likely to cost, and how this will change in the future;
- What they need to cost in order to provide a financial incentive to customers;
- How much CO_2 they should be able to save in the UK, and the cost of this mitigation.

The two following chapters introduce some background information on fuel cells and microgeneration, and review the body of literature on the key topics of cost estimation, environmental assessment and techno-economic modelling.

Chapter 4 introduces a tool that was developed for simulating the operation of fuel cell micro-CHP systems, and presents a meta-review of the data used in this model: the performance of systems in the real world, and the conditions they must operate under. Chapter 5 demonstrates this model with testing and validation against established field trials and experimental work on micro-CHP systems. The results from simulating four fuel cell technologies in UK homes are then presented in Chapter 6, and used to estimate the economic and environmental benefits of operating fuel cell micro-CHP in place of the best alternatives in the UK.

Chapter 7 provides an assessment of the upfront purchase cost of such systems. Past data is used to reveal how rapidly these have fallen, and used to give projections for how prices will continue to fall over time. Finally, Chapter 8 ties this work together, providing an analysis of the whole life-cycle costs of fuel cell micro-CHP systems. Financial payback periods and other economic indicators are calculated, and the cost of carbon mitigation is estimated. Chapter 9 finishes by summarising the contribution, discussing the potential implications and areas that warrant further investigation.

Figure 1.2 indexes the main body of thesis by theme, highlighting the interdisciplinary linkages within the research:

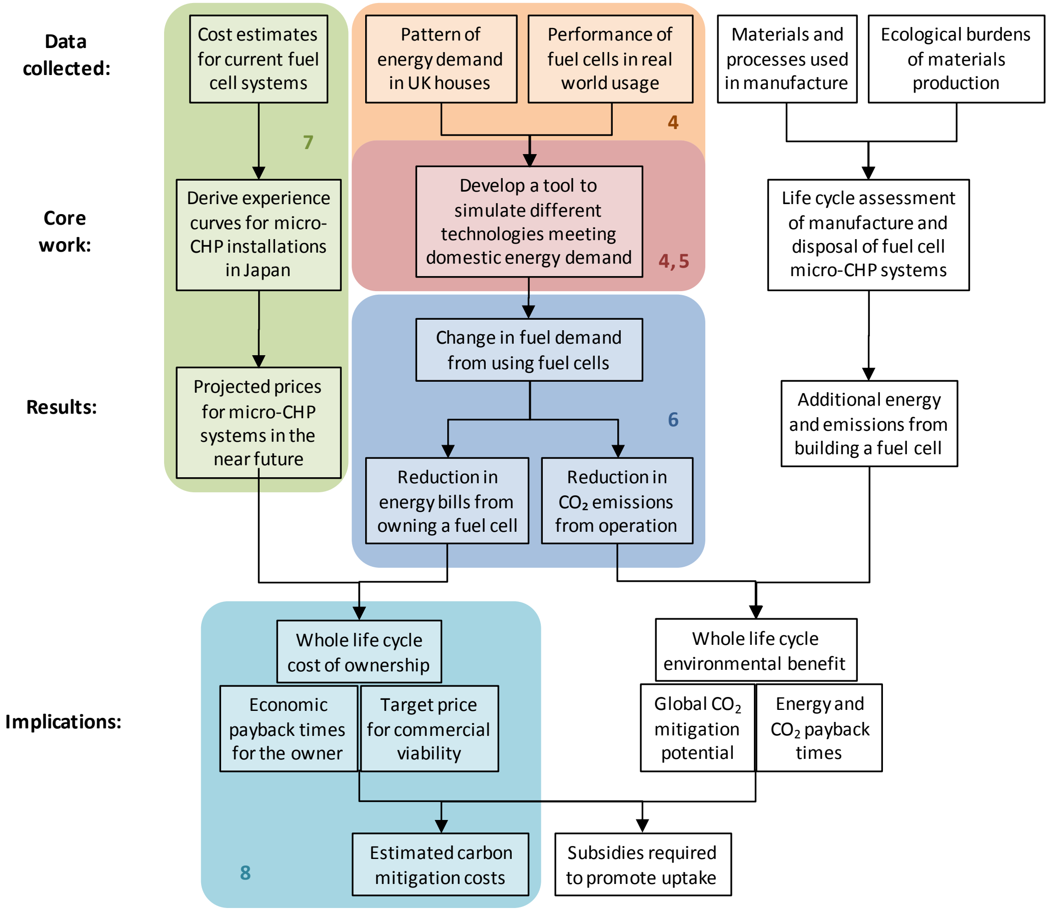

Figure 1.2: An overview of the work presented in this thesis, organised into colour coded topics. Chapter numbers are indicated for each topic, and ongoing work is shown with no background shading.

Chapter 2:

BACKGROUND

2.1. An Introduction to Microgeneration

The concept of microgeneration can most simply be defined as generating energy for the domestic sector at the point it is used – in people's homes. This enables greater utilisation of the fuel used or a switch to lower-carbon and renewable sources. Either of these improvements can lower the cost, fuel consumption and CO_2 emissions from meeting energy demands.[19]

There are several technologies that are suitable for domestic microgeneration, fulfilling the basic requirements of being small enough to fit comfortably in a single-family house and providing suitable energy outputs up to 3kW of electric power and 30kW thermal.[20] Boilers (or furnaces) which are commonplace in the UK are technically a form of microgeneration, converting natural gas or oil into heat in over 20 million homes.[13] The other technologies can be broadly split into three categories: ***combined heat and power (CHP)*** technologies which include fuel cells; small scale ***renewables*** such as solar panels and wind turbines; and ***low carbon heating*** from biomass or heat pumps. The strengths and weaknesses of each of these groups are outlined in Table 2.1.

Millions of houses worldwide employ some form of microgeneration; 30,000,000 solar thermal panels are used in China alone, and similar numbers of heat pumps are operating throughout Europe, Japan and the USA.[21-23] The UK lags behind the leading countries, with adoption rates an order of magnitude lower than in other nations.[5] There are only around 100,000 microgeneration installations in the UK (0.4% of all houses), more than 90,000 of which are solar thermal panels.[25]

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[5] For example, during 2008 approximately 1m^2 of domestic solar thermal collector was installed in the UK per 1,000 people, compared to 26m^2 in Germany and 42m^2 in Austria.[24]

Technology	Advantages	Drawbacks
Condensing Boilers and Furnaces:	+ low cost + widely demonstrated and proven across Europe	- dependence on electricity grid - high running cost & high emissions *(relative to other microgeneration)*
Combined Heat and Power: Fuel cells, Internal combustion and Stirling Engines	+ displaces high carbon electricity + relatively large CO_2 reductions are possible	- increased reliance on natural gas - technologies are emerging and currently too expensive
Low Carbon Heating:	*Over 80% of domestic energy demand is for heat, so decarbonising its production offers the greatest rewards, although dependence on centrally generated electricity would continue.*	
Biomass: heat from wood in the form of logs or pellets of compressed sawmill waste.	+ with sustainable forestry, net CO_2 emissions are almost zero + relatively common throughout the UK, with a well developed industry	- expensive to purchase, and higher running costs than a boiler - limited resource for growing wood fuel in the UK
Heat Pumps: electric heating which extracts ambient heat from the air or ground with high efficiency	+ separates heating from fuel combustion, allowing renewably sourced heat production + can be low cost relative to other microgeneration	- would increase demand for electricity, so more infrastructure would be required - grid decarbonisation is needed to offer greater CO_2 savings
Renewables:	*Power from the wind and sun offers zero running costs and zero carbon emissions, however energy output per property is relatively low, meaning the absolute savings are limited.*	
Solar Photovoltaic and Micro-Wind: electricity produced directly from the sun or wind with rooftop mounted systems	+ output displaces high carbon electricity generation + solar PV offers exceptionally long lifetimes and high reliability	- high upfront costs makes economic payback unlikely in the UK
Solar Thermal: direct water heating from rooftop mounted solar panels	+ the most common renewable technology, with established industries in the UK and worldwide + can be very simple and low cost (outside of the UK)	- continued dependence on centrally generated electricity - requires auxiliary heating due to poor match with seasonal demand - most only provide hot water demand, rather than space heating

Table 2.1: Advantages and disadvantages of the main microgeneration technologies available. Adapted from [19]

Governments across the world have recognised the benefits of microgeneration, and are prepared to offer strong incentives to promote its uptake. Capital subsidies are available to cover up to 50% of purchase costs – amounting to thousands of Euros per installation. Feed-in tariffs are also popular for electricity producing microgeneration, with more than 60 countries offering rates of €0.20-0.40 per kWh of electricity exported – up to 4x the cost of purchasing electricity.[26]

In the UK, the Low Carbon Buildings Programme began in 2005, offering support for the better established microgeneration technologies. Upfront subsidies of between £400 and £2,500 are available to cover up to 50% of installed cost.[27] Despite offering similar incentives to national programmes in other countries, the overall funding levels, lack of publicity and project mismanagement have resulted in widespread criticism and a failure to achieve significant uptake.[28] The UK was also the worst ranked country in the IEA's CHP scorecard series, being described as lacking an integrated strategy for micro-CHP that would accelerate growth.[29]

2.2. Domestic Micro-CHP

Micro-CHP systems can be thought of as small-scale power stations generating energy in the home. They are a special class of microgeneration which can simultaneously meet the demands for heat and electricity. This presents three significant advantages over the traditional reliance on central power stations:

- Electricity has 3.0-3.5 times the economic value of natural gas, so converting low cost gas into high value electricity allows households to reduce their energy bills.
- By capturing 'waste' heat, generating efficiency can rise from 30-50% in central power stations to 70-85%.
- Centrally decarbonising electricity generation is a particular problem for the UK, as there is sustained public opposition to both renewable and nuclear power schemes. Micro-CHP is unobtrusive, and offers the benefits directly to the consumer rather than large energy suppliers.

CHP is widely used in energy intensive industries such as paper mills and oil refineries, because large companies have the resources and long-term foresight to invest in technologies that reduce operating costs. The University of Birmingham hosts its own 6MW turbine, generating around half of the campus electricity demand while heating the surrounding buildings. The miniaturisation of engine and turbine based CHP technologies from industrial to domestic scale has proven a stiff technical challenge, but devices with as small as 1kW electrical output are beginning to enter the market. The same problem was never faced by fuel cells due to their modular design, allowing devices to be produced from the mW to the MW scale.[6]

Three technologies are currently available for domestic micro-CHP:[19, 30]

- **Internal Combustion (IC) engines** are similar to vehicle engines modified to run on natural gas. They offer mid-range performance of 20-25% electrical efficiency, but 1kW domestic models can only operate at a fixed output rather than following the demand of the house.
- **Stirling engines** use external (rather than internal) combustion, but are otherwise relatively similar to IC engines. Performance and reliability could theoretically be higher than IC engines, but the domestic systems currently available have such low efficiency

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[6] At the extremes, Toshiba have produced a 100mW methanol fuel cell measuring 11cm^3, and an 11MW power plant that was demonstrated in 1991.

(4-10% electrical) that they would likely increase CO_2 emissions in the UK if replacing a condensing boiler.[31]

- **Fuel cells** are for the most part less mature than these engine technologies, and are therefore more expensive and less durable. They offer significantly higher electrical efficiencies (30-45%) and good transient performance, which promises the potential to deliver the greatest benefits for domestic energy supply.

All three micro-CHP technologies command a small market share relative to other microgeneration. Domestic scale IC Engines are only available in Japan, where over 66,000 systems have been sold in the last five years, compared with millions of heat pumps and solar panels.[29] The UK is at the forefront of Stirling engine demonstrations, with both manufacturers and energy utilities hosting extended field trials.[31] It is thought that only a thousand units have been sold so far, however full commercialisation is expected imminently and Stirling engines are predicted by some to become the most widely used microgeneration technology in the UK.[32, 33]

Fuel cells are often seen as lagging behind these other technologies, “forever 5 years away from commercialisation”.[34-36] However, within the last year Japanese manufacturers have begun to roll the first units off automated production lines, marking the long-awaited transition towards mass production. With over 3,000 domestic micro-CHP units already operating in Japan and annual sales expected to more than double this, the commercialisation of fuel cells has already begun.

2.3. An Introduction to Fuel Cells

Fuel cells are electrochemical devices that convert the chemical energy of a fuel directly into electricity (and heat) without involving the process of combustion. A simplistic view of a fuel cell is a cross between a battery (chemical to electrical generator) and a heat engine (chemical to heat to generator via oxidation).[20]

As with batteries, individual fuel cells consisting of an anode, electrolyte and cathode are electrically connected to form a ‘stack’. Conductive interconnectors (or bipolar plates) are used to distribute fuel and oxidant to the individual cells, and to electrically connect them together. Coolant fluid can also be distributed through channels in the interconnects, or through additional plates inserted between cells.

As a rough guide, individual cells for micro-CHP systems measure 100cm^2 and a few millimetres thick, and produce 20-100 amps at 0.7V. Between 20 and 100 of these cells are connected in series, raising the voltage of the stack to 10-50V, giving around 1kW of direct-current (DC) power.

Hydrogen is the preferred fuel in terms of electrochemical performance and durability. Electrons are stripped from the incoming hydrogen at the cell anode, forming ions which pass through a conductive electrolyte to combine with oxygen at the cathode. The stripped electrons form an electric current through the circuit formed by the cells and interconnects, as shown in Figure 2.1. The exact reactions that occur depend on the type of fuel cell (as several technologies exist), but the overall balance is the reverse of electrolysis: $H_2 + ½O_2 \longrightarrow H_2O$.

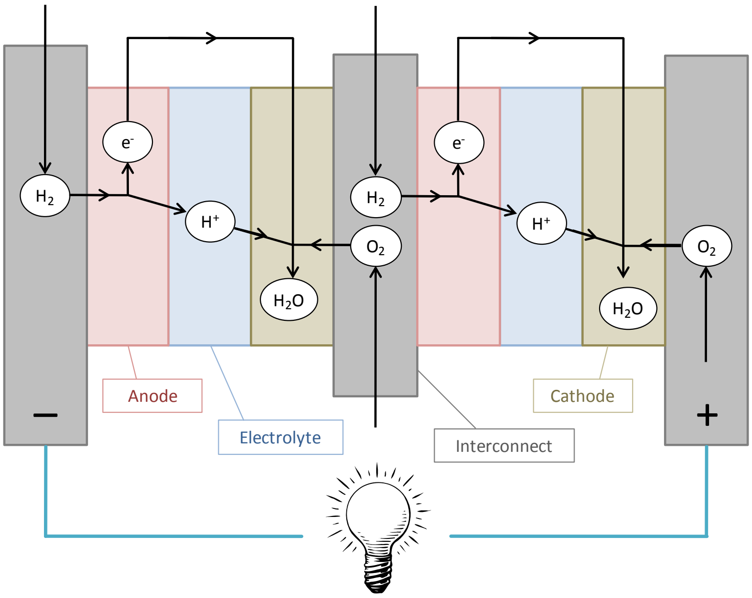

Figure 2.1: Diagram of the archetypal fuel cell – two polymer electrolyte cells are shown, connected by an interconnect.

A detailed knowledge of the principles and theories of fuel cell operation is not required to understand the majority of this report, although some familiarity with them would be beneficial. References [37] and [38] give a brief overview of fuel cell theory, while [39] and [40] provide a rich and detailed discussion.[7]

2.3.1. Overview of Stack Technologies

There are more than a dozen distinct fuel cell technologies under academic and commercial development, however only a select few are suitable for domestic micro-CHP. The fuel cell stack must have (at least the potential for) low cost production and long operating lifetime in sub-

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[7] To save searching through the references, URLs for these sources are: http://tinyurl.com/ltsu5y, http://tinyurl.com/n7pq4t and http://tinyurl.com/ndghpk

optimal conditions, particularly with regards to impurities in the hydrogen fuel. There are also considerations about safety and practicality which prevent a pressure vessel from being suitable; and cost-effectiveness which makes high operating efficiency paramount. Ideally, the underlying fuel cell technology should be well established, with commercial demonstrations and research activity aimed at the domestic market. Based on these criteria, only four technologies were considered in this work:

- **PEMFC:** Polymer Electrolyte Membrane Fuel Cells;[8]
- **SOFC:** Solid Oxide Fuel Cells;
- **PAFC:** Phosphoric Acid Fuel Cells;
- **AFC:** Alkaline Fuel Cells.

Domestic CHP systems based on PEMFC and SOFC stacks have received intense research and commercial development over the last decade. There are at least a dozen major companies actively pursuing this market, and products have been deployed in large scale field trials throughout Japan, South Korea and Germany.[9]

In contrast to this, PAFC and AFC are forgotten bystanders; they were developed 10-20 years earlier, but failed to retain substantial commercial interest due to difficulties in overcoming high manufacturing cost and low lifetime respectively. No significant products have been developed for the domestic CHP market, however they possess many of the desired characteristics; having been demonstrated at the 1kW scale operating on natural gas as CHP units.[41, 42] These technologies were included to broaden the scope of this study, giving a comparison of the status quo (PEMFC and SOFC) to their nearest and most suitable alternatives. A more thorough overview of the history and applications of each technology is given in references [20] and [43], which are provided in Appendix C.

While these technologies share the same operating principles outlined in the previous section, there are some fundamental differences in the way they achieve their electrochemical reactions. Three of the characteristic differences are the diverse materials they are made from, their range of operating temperatures and the fuels they can tolerate. Table 2.2 summarises the typical construction of each fuel cell stack, along with their operating conditions and tolerances to fuel impurities.

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[8] PEMFC is also referred to in literature as PEM, PEFC, and SPFC (solid polymer).

[9] Major manufacturers focussed on micro-CHP include ENEOS, Panasonic, Toshiba, Baxi, Vaillant, Plug Power, GS Fuel Cell, FCP and Hyosung (PEMFC); and Kyocera, TOTO, Sulzer Hexis, CFCL, Ceres Power and Acumentrics (SOFC).

		PEMFC [40, 44-46]	**SOFC** [46-48]	**PAFC** [40, 45-47, 49, 50]	**AFC** [46, 51-57]
	Electrodes	Pt, Ru, C, PTFE	Ni, LSM	Pt, C, PTFE	Pt or Ni, C, PTFE
	Electrolyte	Solid polymer (PFSA)	Ceramics: YSZ, LSM	Liquid H_2SO_4	Liquid KOH
	Interconnect	Graphite, steels	Chromium alloys, steels	Graphite	Graphite, metal or plastic
	Operating Temperature	30-100°C	500-1000°C	200-250°C Must remain >70°C	50-200°C
	Fuels	H_2	H_2, CO	H_2	H_2
Fuel tolerance	Sulphur (as S, H_2S)	< 0.1 ppm	< 1 ppm	< 50 ppm	?
	CO	< 10-100ppm[10]	*Fuel*	< 0.5-1%	< 0.2%
	CO_2	*Diluent*	*Diluent*	*Diluent*	< 100-400ppm or < 0.5-5%[11]
	CH_4	*Diluent*	*Fuel / Diluent*[12]	*Diluent*	*Diluent*
	NH_3	Poison	< 0.5%	< 4%	?

Table 2.2: General operating characteristics of each fuel cell technology.
Abbreviations: PTFE (polytetrafluoroethylene – better known as Teflon™), PFSA (perfluorosulfonic acid – for example Nafion™), YSZ (yttria-stabilised zirconia), LSM (lanthanum-strontium-managanate)

2.3.2. Fuel Cell Micro-CHP Systems

Attempting to operate a fuel cell stack by itself in the domestic environment would be almost impossible, akin to expecting hot water and usable electricity to be produced by the engine of a car. Several auxiliary systems are required to provide suitable operating conditions and useful means of extracting heat and power from the stack.

The fuel cell stack itself typically makes up less than quarter of a micro-CHP system both in terms of volume and cost. Figure 2.2 shows how much equipment must surround the fuel cell stack (which is at the centre of the diagram):

- A **fuel processor** to convert natural gas into an acceptably pure hydrogen stream;
- An **inverter** to convert the DC power output into grid-synchronised AC;
- **Heat exchangers** to remove heat from the stack and provide it to the house;
- A **hot water tank** to store this heat when it is not needed;
- Sensors, pumps, valves, and extensive pipe-work to deliver fuel, air and coolant to the stack, and remove waste gases, heat and electricity;
- A **system controller** (not pictured) to regulate fuel input, power output, and all of these sub-systems.

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[10] Standard Pt anode catalysts can only withstand CO concentrations up to 10 ppm, and PtRu alloys up to 30 ppm.[46] These limits can be extended by bleeding air into the anode and using alternative bi-layer catalysts.[58, 59]

[11] CO_2 tolerance is highly dependent on the cell design. Strongly bonded nickel and silver electrodes with a circulating electrolyte can be tolerant, while platinum and carbon with an immobilised electrolyte are highly sensitive.

[12] Internal reforming is possible with SOFC anodes, making desulphurised natural gas a viable fuel. The long lifetimes required for domestic CHP operation have not yet been demonstrated by these systems though.

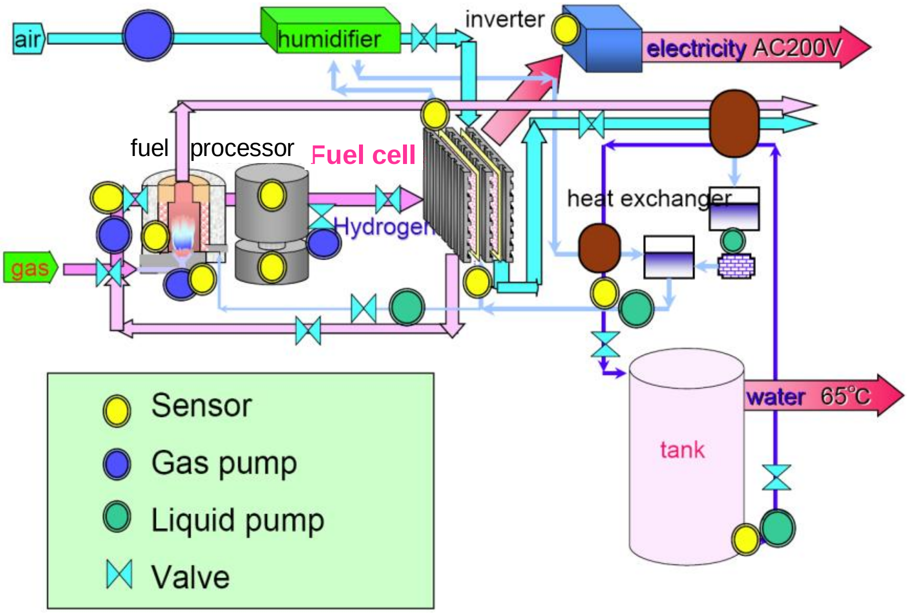

Figure 2.2: Schematic diagram of a stationary fuel cell CHP system, reproduced from [60].

The differences between stack technologies that were highlighted in the previous section have substantial impacts on the operation of a micro-CHP system. For example, low temperature fuel cells require precious metal catalysts to ensure adequate electrode reaction kinetics for high power output; but these raise the materials cost of the system and impose strict tolerances on fuel quality. Higher temperature systems on the other hand require a prolonged warm-up period when starting from ambient temperature, making it impractical to turn them on and off throughout the day when energy is required. Other differences between systems include the need for electrolyte humidification in PEMFC (shown in Figure 2.2), electrolyte circulation pumps and storage with AFC and PAFC; and a high temperature furnace in which to enclose an SOFC stack.

The following sections give an overview of the requirements and characteristics of these various sub-systems, and attempt to define the make-up of a generic fuel cell micro-CHP system.

2.3.2.1. Processing the Input Fuel

Choice of Fuel

Hydrogen is the ideal fuel for the stack, however it is not practical for direct use in homes. There is no way to deliver hydrogen from regional or centralised generation plants at present, and such plants only exist on the drawing board. Instead, hydrocarbons (particularly natural gas) are seen as the ideal fuel for micro-CHP systems, as these can be reformed into hydrogen at the point of use.[20] Natural gas is low cost, abundant (for the time being), and has extensive infrastructure throughout Western Europe.

All commercial fuel cell micro-CHP systems are fuelled by natural gas, LPG or kerosene. Academic authors have also described systems running off a variety of other hydrogen sources, for example gasified coal [61], diesel [62], biogas from waste [53, 63], biomass [64], and biologically produced hydrogen from sugary waste [65, 66].

In this study, natural gas was the only fuel considered due to its ubiquitous prevalence throughout the UK; approximately 21 million of the UK's 26 million homes are heated by mains delivered gas.[13] The impact of considering other fuels would be profound to both the economic and environmental benefits; however they are unlikely to take hold in the UK in the near future, and so were outside the scope of this study.

One of the criticisms of fossil fuelled micro-CHP is that it may be limited to a 20-30 year window of opportunity, after which the scarcity of natural gas and decarbonisation of centralised electricity would make it unattractive.[67] The potential to operate fuel cells on various types of biogas would however offer a solution to this problem whilst giving profound reductions in CO_2 emissions, assuming a sustainable and carbon-neutral production route could be found.[66, 68, 69]

Fuel Processing

Converting natural gas into an acceptably pure supply of hydrogen requires several processing stages, as outlined in Figure 2.3. The required stages for each type of fuel cell stack are integrated into a single, compact fuel processing unit such as those pictured in Figure 2.4. These units contain the first four stages (desulphuriser, steam reformer, shift reactor and preferential oxidation), plus thermal management systems and a steam generator to supply water vapour to the reformer and shifter.[70, 71] A high degree of thermal integration is required, as the optimal temperatures for each reaction range from ambient to several hundred degrees, and attaining high thermal efficiency is paramount to the overall efficiency of the fuel cell CHP system.[72]

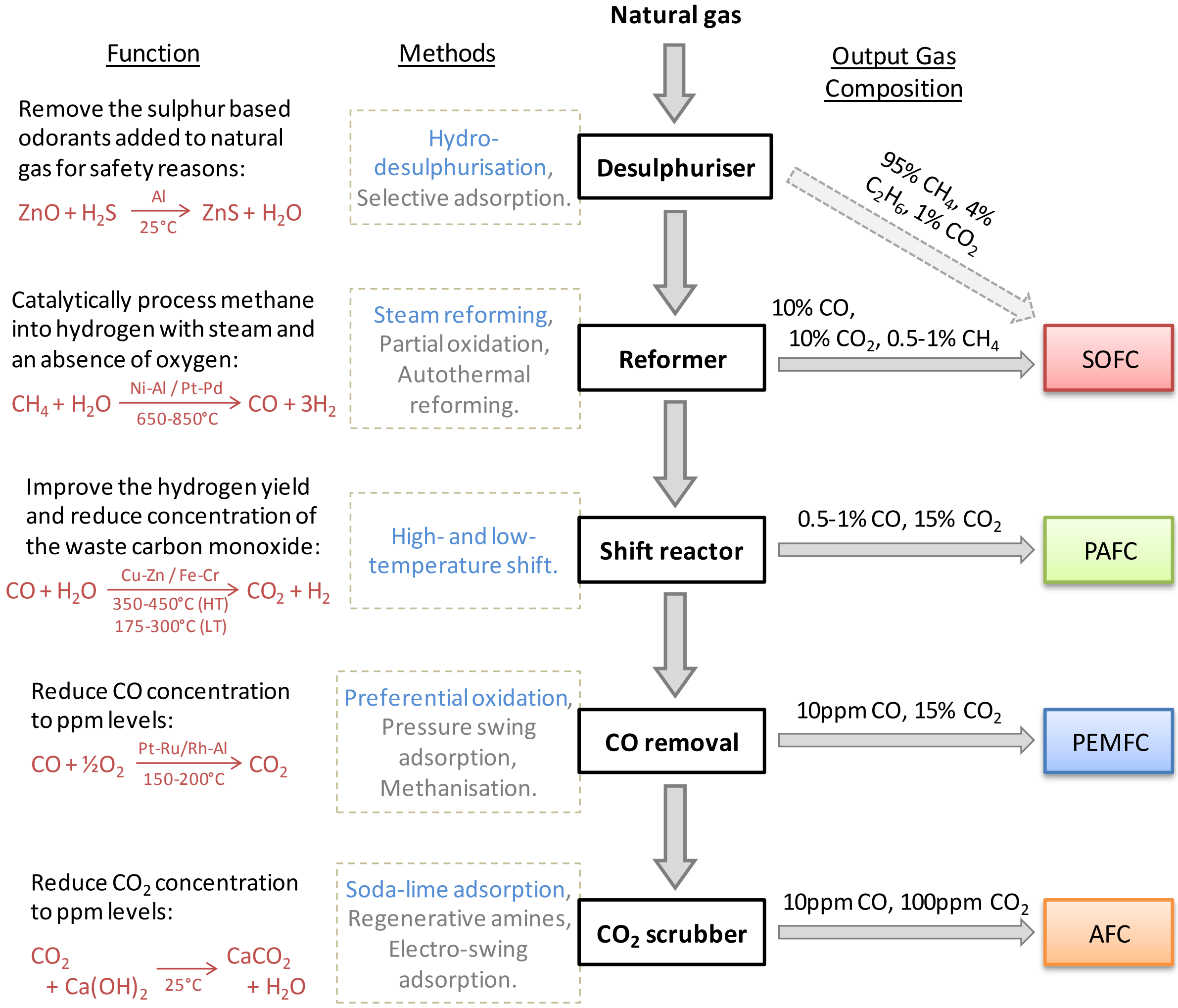

Figure 2.3: An overview of fuel processing for fuel cell micro-CHP systems. Each stage is highlighted in bold, and given with the most common methods that are used; for each stage, the primary method is highlighted in blue. A description of each stage is given at the far left, along with the ideal reactions for the primary method. Indicative ranges of gas composition after each stage are given to the right. Following the stages down from natural gas to each type of fuel cell on the right indicates which processing stages are required. Adapted from [46, 53, 72-76]

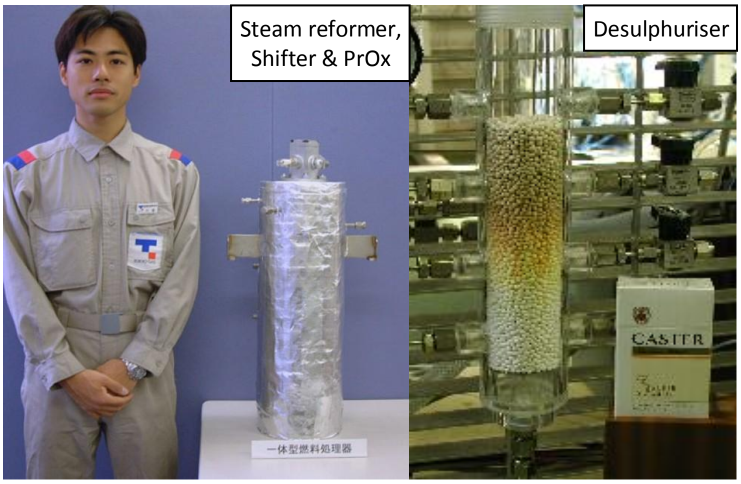

Figure 2.4: The fuel processing units used in ENEFARM fuel cell systems, produced by Osaka Gas (above) and Tokyo Gas (right). Images reproduced from [70, 71, 75].

The most striking difference between fuel processors from different manufacturers is the choice of reforming method; the majority choose steam reforming, although Plug Power (USA) and Hexis (Switzerland) use the other methods listed in Figure 2.3.[77] The main benefit of steam reforming is the high concentration of hydrogen in the output reformate – 70-80%, *cf.* 50-60% for autothermal and even less for partial oxidation; which consequently gives the highest operating efficiency.[72] The drawbacks are that the highly endothermic reaction (-250kJ/mol CH_4) and high operating temperature (up to 800°C) prevents the rapid start-up and transient performance that can be achieved with other methods.[71, 72]

2.3.2.2. Processing the Energy Outputs

Matching the Fuel Cell to the Home

There are some major complications in matching the energy provided by micro-CHP systems with the instantaneous demand from a house.[19] Unlike the electricity grid and traditional boiler, a fuel cell is not flexible enough to exactly match the highly variable and unpredictable energy demands. A typical house has low-level consumption for the majority of the day, punctuated by spikes of several kilowatts when high-power devices such as kettles and electric cookers are operated. Similarly, average monthly heat demands from UK properties are seen to range by a factor of 7.5 between summer and winter.[13]

Ideally, the fuel cell capacity would be chosen to meet the peak energy demands (as is done with condensing boilers), however there are competing pressures to minimise capital costs and keep the whole system to a practical size.[20] The compromise chosen by most manufacturers lies in the range of 0.75-1.5kW of electrical output, giving around 1-4kW of heat. Average demands in the UK are around 0.5kW electrical and 2kW thermal, but due to uneven distribution of demand a fuel cell of this size will be unable to provide all of the energy by itself.

Conversely, there will be times when energy is produced by the fuel cell that is not wanted; for example if electricity is demanded in summer when no heating is required. The production of electricity and heat is inseparably linked, and the relative amount produced (known as the heat to power ratio or HPR) lies between 0.8 and 1.6 for most fuel cell systems. The HPR of a house varies dramatically with time,[20] and while there are several methods available to dynamically change the HPR of the fuel cell, none of these have proven technically feasible in commercial models thus far.[78]

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[13] Section 4.3.2. gives a more in depth analysis of domestic energy demands in the UK.

Together, these complications signal the need for additional energy generation and storage equipment. In order to delineate the supply and demand of energy, heat is stored locally (as distribution networks are rare in the UK), and electricity is exported to the national grid where possible. Together, these maximise the running time of the fuel cell without wasting the excess energy that is produced. Baxi estimates that by adding a hot water storage tank to their 1.5kW fuel cell system, savings on fuel bills can be doubled.[14]

Heat Extraction and Storage

Heat recovery from fuel cell stacks is markedly different depending on the stack technology. High temperature SOFC stacks are cooled by excess air flow over the cathode, which is then combusted with unconsumed fuel in an afterburner. This heat is used to pre-warm the gas inlets to the stack and maintain reformer temperature, and the excess is passed through a condensing heat exchanger to provide hot water for the home.[20] The other, lower temperature stacks are cooled by circulating a liquid through cooling plates interspersed through the stack, which is then passed through a liquid-liquid heat exchanger. The low operating temperature of PEMFC systems means that heat output is limited to 60-65°C, and a boiler is needed to produce hot water at higher temperatures if required.[80]

The hot water output is stored within a large, well insulated tank, which is gradually filled by the low capacity fuel cell throughout the day. These heat stores improve on conventional hot water cylinders by promoting thermal stratification with mixing valves and buffer zones. The majority of the water is stored as a warm buffer (~45°C) that is used as an intermediate heat exchanger between the generator and the central heating system. A smaller tank sits in the centre of the store, holding ~¼ of the water at a higher temperature for direct consumption.[19]

The heat stores supplied with fuel cell micro-CHP systems range from 75 to 750L, the upper end of which would traditionally be recommended to houses with 5 or more bathrooms.[79-84] The space required by such a tank poses a problem for installation in smaller houses, so they are currently installed in basements or outside. A 600L tank such as that shown in Figure 2.5 would hold around 28kWh of heat – just over half a day's requirement from an average house.[15]

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[14] Baxi estimate a 24% reduction in energy purchase costs by installing their fuel cell alone, rising to 53% if a 600L storage tank is also installed.[79]

[15] Based on an average inlet temperature of 10°C from the water mains, and weighted average storage temperature of 50°C.

Figure 2.5: The Baxi Beta 1.5 fuel cell system and a 600 litre Gledhill heat store that were installed into an outdoor enclosure at a demonstration house in the UK. The hot water tank measures approximately 1 by 1.75 metres, and weighs nearly three quarters of a tonne when full.

Electricity Conversion and Export

The fuel cell stack produces low-voltage DC current which must be converted into 50Hz, 240V AC for compatibility with UK domestic equipment. This is achieved with a standard transformer and inverter, such as those used in solar PV and wind microgeneration systems.

Most micro-CHP systems also integrate with the national electricity grid so that excess power can be exported at a profit to the household. As with heat storage, this allows a substantial improvement to the utilisation and economic benefit of operating a fuel cell. Storing the excess power output in batteries is an alternative that has been used in the past; however the increase in capital cost makes it uneconomical if export is available.[43]

In the UK, electricity export requires the installation of a smart meter (or a simpler export meter) to measure both the amount of imported and exported power, and additional equipment to provide frequency control, synchronisation and other power conditioning to meet the quality that is required by the grid.[19]

Additional Heat Generation

In cool climates such as the UK, houses are notoriously poor at retaining their heat and there is generally lower demand for electricity as air conditioning is not widespread.[85] The annual average HPR of UK houses is around 5.5:1, which is nearly double that of most fuel cell micro-CHP systems.[13, 20] It is unlikely that a significant portion of the UK housing stock will be retrofitted with the exceptional insulation needed for a tenfold reduction in space heating demand,[16] so an additional heat source is required to prevent the fuel cell owner from experiencing a loss in comfort. It would take the fuel cell alone several hours to replenish the typical sized hot water tank, so a boiler is also required when the household demands a lot of hot water.[80]

A condensing boiler is therefore integrated into commercial micro-CHP systems. Japanese PEMFC and SOFC systems are backed up by a 42kW gas burner, while the Baxi Beta and Gamma units (PEMFC) contain a 15kW condensing boiler.[79, 83, 87] Combining the two devices, rather than installing them separately offers lower installation costs (as one device rather than two must be connected to the property's gas supply), and offers the potential for integrated control of both devices. The overall system controller could theoretically operate the two devices in a complementary fashion to vary the system HPR, and increase thermal efficiency by burning anode off-gas more efficiently or supplying heat to the fuel processor.[17] This level of integration is not seen at present, and in some cases the auxiliary boiler can in fact hinder the performance of the fuel cell, with both devices fighting to produce hot water at times of high demand.[18]

2.3.2.3. Definition of a 'standard' Fuel Cell Micro-CHP System

Throughout the rest of this work, a 'fuel cell micro-CHP system' will imply the following equipment:

- A fuel cell stack with 0.7-1.5kW of electrical output, and thermal output determined by the system efficiencies;
- An integrated fuel processor, using the primary methods listed in Figure 2.3 that are required by each stack type;
- A transformer, an inverter, power conditioning equipment, and a smart meter for export of electricity;
- A hot water tank capable of storing between 10 and 30kWh of heat (~200-600L);
- An integrated condensing boiler with 15-35kW thermal output;
- Other components as required by the fuel cell technology (e.g. membrane humidification, electrolyte storage);
- Other balance of plant, such as manifolds for gas and air, pumps, valves, flow controllers, sensors, wiring, control systems, insulation, casing, human interface, etc.

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[16] By bringing UK houses up to the German 'Passive House' standard, space heating requirements could be reduced from around 11MWh to 1MWh per year. This would give an annual heat demand of 4-6MWh per year including hot water, which could be provided by a 1kW fuel cell alone.[13, 86]

[17] A simple non-condensing burner is typically used for these tasks, wasting the latent energy of water vapour.[20, 78]

[18] This was experienced during the UK field trial of a Baxi PEMFC system, and is described further in Appendix B.

2.4. Selected Fuel Cell Micro-CHP Products

During the four years of this project, fuel cell micro-CHP has moved from being a topic of academic and private R&D to a full-scale commercial venture, and after more than a decade the first commercial product – the ENE·FARM has been launched in Japan. The significance of this PEMFC micro-CHP system, and the wealth of information available on it mean that it is referred to throughout this work. Three other systems are also of particular importance: the Kyocera SOFC system which is also undergoing extended demonstrations in Japan, and two that were worked with directly as part of the project, a PEMFC system from Baxi and an SOFC stack from Fuel Cells Scotland.

2.4.1. Sanyo, Panasonic and Toshiba: ENE·FARM

The ENEFARM brand covers a group of micro-CHP systems launched in Japan. They are based on PEMFC stacks ranging from 0.7 to 1.0kW electrical output (0.9-1.4kW thermal) and are packaged with a fuel processor for either natural gas, LPG or kerosene, and a hot water tank (with integrated boiler) as shown in Figure 2.6.

Figure 2.6: Fuel cell systems and hot water tanks from the initial five ENE FARM manufacturers. Typical system dimensions are 0.9x0.9x0.3m for the fuel cell unit (105kg), and 1.9x0.75x0.45m for the water tank and burner (305kg when full).[81] Image reproduced from [88].

ENEFARM is the culmination of over a decade of collaborative research and demonstration by Japanese fuel cell manufacturers and energy distribution companies. Subsidiaries of major Japanese conglomerates developed fuel cell stacks, while oil and gas companies produced the fuel reformers pictured earlier in Figure 2.4. These companies agreed to collaborate on the development and commercialisation of the ENEFARM in the realisation that the problems that had to be overcome were too great for one company to achieve alone. System manufacturers decided on, and then published specifications for standardised balance of plant (BoP), and individual companies then openly competed to develop these components.[89] This collaborative strategy almost attained a four-fold decrease in BoP costs, whilst improving durability and readying the whole supply-chain for mass production.[90] In 2008, the ENEFARM brand was jointly launched by all the participating companies to maximise consumer awareness and collaborate further in promoting the technology.

From the five initial manufacturers listed in Figure 2.6, two have since withdrawn from the domestic fuel cell business due to the global recession in 2008/09. Toyota postponed their work to focus on their main automotive business,[91] whilst Ebara decided to dissolve their partnership with Ballard after a "review of their company".[92]

The three remaining systems are being sold through various energy supply companies in Japan, most prominently by Tokyo Gas, Osaka Gas and Nippon Oil. Sales of the different systems began between May and September 2009,[81, 92] with initial prices at ¥3.24-3.47 million, which can be reduced by a ¥1.4M government subsidy.[81, 93] Prices to consumers were therefore around £9,000-13,000 – €13,000-15,000 or $17,000-21,000 – depending on currency exchange rates. In a joint statement, six of the participating oil and gas utilities announced that they intend to sell 5,000 units at these prices during 2009.[94, 95]

Public demonstrations of these systems began in 2002 (then either unbranded or referred to as LIFUEL), with a government funded demonstration of 45 prototype systems over three years.[96] This was succeeded in 2005 by the Large Scale Residential Fuel Cell Demonstration Project, which was easily the largest of its kind in the world. More than three thousand systems had been installed by the end of 2008, increasing the world's stock of stationary fuel cells by nearly 30%.[19] During the four year demonstration project, the Japanese government provided subsidies totalling over €80 million, which formed only a small part of the €1.5bn total fuel cell and hydrogen research budget since 2001.[97, 98]

An extensive program of monitoring was undertaken by the project overseers the New Energy Foundation (NEF) who collected data from the energy utilities who operated the systems. Regular updates[20] are given on the utilisation, efficiency and reliability of systems in each home, as well as unprecedented data on the price paid for systems.[99, 100] This information is used

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[19] At the end of 2007, the cumulative number of small stationary installations (CHP and backup power) was thought to have reached 7,000.[31]

[20] The project website is http://happyfc.nef.or.jp/ (Japanese only)

heavily in the performance review of micro-CHP systems (Chapter 4), and as a reference point for current and future prices (Chapter 7).

2.4.2. Kyocera: Semi-tubular SOFC System

Japan is also at the forefront of SOFC research with companies such as Kyocera, TOTO and Nippon Oil developing and demonstrating 1kW-class micro-CHP systems. Externally these systems appear similar to the ENEFARM, with a small unit containing the stack, fuel processor and electronics, with a hot water tank and backup burner packaged separately. Their operation differs somewhat from the ENEFARM due to the SOFC stack, which means they operate continuously and cannot cycle on and off. These systems however stand out for their record-breaking electrical efficiency, which stands at 36% in the field, and around 50% (HHV) in the laboratory, when operating on natural gas.[101-103]

Figure 2.7: A Kyocera system installed in northern Japan, pictured operating at -17°C external temperature.

Small scale public field trials began in 2007 following the format of the PEMFC trials five years earlier, although with a greater emphasis on tackling basic issues such as durability.[104] During the first two years of this four year project, Kyocera have supplied 55 of the 65 systems being demonstrated.[90] As with the PEMFC demonstrations, data from the trials is submitted to the NEF and compiled into regular website updates[21] and annual reports;[101] which were used in the performance review, and in validating the fuel cell simulations (Chapters 4 & 5).

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[21] The project website is http://sofc.nef.or.jp/ (Japanese only)

2.4.3. Baxi-Innotech: Baxi BETA 1.5 Plus

The Baxi Beta is a 1.5kW PEMFC system that was developed in Germany from 2002 to 2008. It was superseded by the 1.0kW "Gamma" system in 2009, which replaces the original stack developed by European Fuel Cells with one from Ballard. Extended field trials within the German Callux programme will run from 2010-12, followed by commercial launch expected in 2013.[105]

Electrical output:	1.5kW
Thermal output:	3.0kW
Integrated boiler:	15kW (109% LHV)
Hot water store:	600L
Efficiency (full load):	32% electrical 85% total (LHV)
Dimensions:	1.85 x 1.0 x 0.73m (excl. tank)
Weight:	350kg (excl. tank)

Table 2.3: Specifications for the Baxi Beta 1.5 Plus, taken from [79, 105].

Figure 2.8: A photo of the Baxi Beta Plus 1.5 system installed at the hydrogen house – with front panel removed.

Field trials of the Beta began in 2006, with 45 systems installed throughout Europe by the end of 2008.[105] Three of these have been installed in the UK, including one in the fuel cells laboratory at the University of Birmingham, and another at a new-build house in the Black Country, dubbed the "Hydrogen House".[106] Operational data from the hydrogen house is presented in Chapter 5 and Appendix B. A more detailed investigation comparing the identical laboratory and real-world systems had been planned, but was not possible due to technical and contractual difficulties.

Chapter 3:

PREVIOUS WORK

3.1. Summary

Many of the individual aspects of this project have been studied before. Fuel cells for micro-CHP have been considered in several feasibility studies and broad assessments of microgeneration (e.g. [30, 107-109]). The general impression is that fuel cells have great potential to reduce costs and environmental impacts in this sector, but the technology is still emerging from its infancy. However, the immaturity of the technology hinders such studies, limiting both the accuracy and validity of their conclusions, and preventing a more thorough and integrated analysis from being undertaken.

Whereas data on other technologies can be found from actual sales and extensive field trials, estimates must be used for fuel cells as hard information is not readily available.[19] The most notable gaps in current understanding relate to the current and future price of fuel cell micro-CHP systems, and the efficiency and durability that can be achieved in real-world use. Poor understanding of this technology's cost and performance means that there is no way to judge the accuracy of the environmental or economic benefits that have been previously estimated. Confidence in current assessments is therefore lacking, as the general estimates and assumptions that have been used do not give a solid foundation to build upon.[107, 110]

Previous literature includes estimates of the potential and impacts that fuel cell micro-CHP may have in the domestic sector, however these aspects have only been considered in isolation.[86] There has been no unifying analysis which brings all of the elements together: the environmental impact is considered separately from the economic benefits, and the fuel cell's operation is considered separately from its manufacture. It is therefore difficult to compare fuel cells with other technologies as the more quantitative measures of performance – such as payback times and carbon costs – have not yet been calculated.

3.2. Modelling Fuel Cells

Large scale field trials are very lengthy and expensive to conduct. The ENEFARM demonstration has run for 7 years and required over €80 million in direct support from the Japanese government.[111] It should therefore be of little surprise that globally only six other fuel cell micro-CHP systems have been demonstrated at more than a dozen sites.[22] In the UK, only four

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[22] 210 PEMFC systems are being installed in South Korea as part of an ongoing project costing over €30M [112, 113]; Sulzer Hexis have demonstrated over 100 systems throughout Europe in private field trials since 1997 [114, 115]; So far, 65 SOFC systems from Kyocera and others have been installed into Japanese homes since 2007 [101];

domestic systems have been demonstrated in people's homes,[23] the most recent of which being the trial of a Baxi system at the hydrogen house.[121]

As data from the field is so limited, many authors have simulated how fuel cell systems would perform in a domestic environment, responding to the patterns of energy demand from a typical family. The usual goal of such modelling is to estimate the environmental benefits in terms of CO_2 emissions reductions and primary energy savings, or the reduction in operating costs from reduced purchase of electricity. This is referred to as 'techno-economic modelling', where "the technical characteristics of the system [are reflected] onto economic outcomes".[20]

Such studies consider the interactions between the fuel cell system, the building it is in and the environment; often generalising the fuel cell system as a single entity rather than dynamically modelling the stack, fuel processor and other sub-systems individually. Such 'high level' modelling relies explicitly on data inputs to govern how the fuel cell will perform in the dynamic environment of a house, rather than calculating its performance from a series of mass-, heat- and charge-transfer equations.

The models in use range in complexity from simple spreadsheet based calculations to extensive software suites developed by government bodies. The most basic models assume the fuel cell operates for a fixed number of hours per day or use only the rated performance specifications at full power.[109, 122, 123] These are useful for demonstrating the benefits of micro-CHP, but do not give an accurate assessment of the savings that could be achieved in real usage. Four types of improvement can be identified in the literature: [20]

- Using actual or simulated profiles of energy demand to determine the pattern and number of hours that the fuel cell operates, considering both full and part-load operation. *Examples: CODEGen [124, 125], Pawlik [126];*
- Modelling the heat transfers and interactions between the fuel cell, heating circuit, the house and the environment; to simulate how the profile of heat demand would be changed by installing the fuel cell. *Examples: ESP-r [127], TRANSYS [128]*

Baxi have installed 45 Beta 1.5 Plus systems in a private field trial centred around Germany [105]; The US Department of Defense installed around 100 PEMFC systems in military bases between 2001-05, approximately half of which were natural gas CHP units from Plug Power [116]; CFCL have installed at least 15 SOFC systems into commercial premises around the world since 2005 [117, 118].

[23] These included a hydrogen fuelled AFC that was demonstrated in Sandwell [119]; a Plug Power system installed at a residence in the US Embassy in London [116]; and a previous trial of a Baxi Beta system in a house in Eyemouth [120].

- Increasing the detail of performance related inputs to consider fuel cell efficiency at part load, with degradation, and constraints on transients. *Examples: CODEGen, Annex 42 [129];*
- Optimising the operating pattern of the fuel cell rather than simulating it, to find and understand the maximum benefits that can be attained by changing design and operational parameters. Examples: *CODEGen;*

The majority of modelling studies rely on time-series data on the electrical and thermal power demanded from the house, which is either simulated or measured at fixed intervals. Such data can be acquired from a house over the course of a year with relatively inexpensive equipment.

3.2.1. Understanding of Modelling Processes

While most authors concentrate on the results arising from these models, some have studied the modelling process itself, and the influence that different parameters have on results. As the simulation process often involves logical or stochastic elements and the additional complexity of energy storage, variable efficiencies and constraints on operation, the influence of each input variable cannot be reduced to a purely algebraic relationship.

Attention has been paid to the impact of the energy demand profile of the house, and in particular the importance of high temporal resolution. In [130], Hawkes and Leach showed that using profiles with a typical resolution of 60 minutes would under-estimate the lifetime cost of the system and over-estimate utilisation and emissions savings by 30-40%, as electricity demand over the course of an hour is highly uneven. By modelling with the average demand from each hourly period, large spikes are smeared and the baseline power level is increased – both of which are beneficial for a low capacity fuel cell system.[131] Other work on energy profiles has shown that greater savings are achieved with more coincidence in demand (i.e. heat and electricity demand occurring together), as the purchase and export of electricity are minimised.[124]

The operating strategy of the fuel cell has also been studied, as altering what times power is produced is much simpler than improving system efficiency or convincing consumers to change their pattern of demand. Micro-CHP systems typically follow the heat demand of a property, however other options include following the electricity demand, the maximum of the two, operating at constant power, or being controlled remotely to serve as part of a virtual power station (following national, rather than local energy demand).[132-134] Using the CODEGen optimisation program, Hawkes showed that following the maximum of electricity and thermal demand with an SOFC micro-CHP system closely approaches the minimum operating costs that can be achieved in the current UK situation.[132] If exported electricity has no value, it becomes optimal to only follow electricity load, but as the value of exported electricity increases it becomes beneficial to run the fuel cell at higher power output even when energy is not required locally.

More generally, some broad qualitative trends have been observed relating to the performance and sizing of the fuel cell and energy demand from the house:

- Fuel cells with a higher efficiency (particularly electrical efficiency) will provide greater savings relative to traditional heating technologies [109, 124];
- Conversely, raising the efficiency (or lowering the cost, and carbon intensity) of the traditional system that the fuel cell replaces will diminish the benefits [86, 135];
- Decreasing the heat-to-power ratio of the micro-CHP provider also improves savings, as electricity is the more valuable product to produce and high heat production is likely to limit operation in summer months [31];
- Micro-CHP is better suited to houses with a large energy demand, as the system can operate longer hours without its output being constrained by lack of demand [20, 31];
- Integrating heat storage and allowing for electricity export also enable increased operating hours and thus greater savings [86, 136].

These findings are intuitive; however their magnitudes can only be assessed on a case-by-case basis in those studies which include a detailed sensitivity analysis. It is for this reason that the results of one study (for example actual field trials in Japan) cannot be extrapolated to another situation (e.g. the same systems operating in the UK) without performing a new simulation of the scenario.[85]

3.2.2. Results from Fuel Cell Micro-CHP Simulations

Several studies have used these simulation methods to estimate the reduction in energy bills, CO_2 emissions and primary energy consumption that could be expected from upgrading traditional heating systems to fuel cell micro-CHP. Some authors consider both the financial and environmental implications together, however many focus on only one or the other due to scarcity of data and the complexity of assessing both price tariffs and displaced emissions.[109]

In both types of assessment there is only limited agreement between studies. Most predict relatively large benefits such as 15-30% reductions in CO_2 emissions, however some authors suggest negligible or even negative impacts – with the fuel cell producing more CO_2 or costing more to run than the technologies it replaces. Assessment methods are broadly similar, so the observed variation is caused by the assumptions and data inputs used in each study.

While different assumptions for the fuel cell performance play a part, results are primarily determined by the economic and environmental setting in which it is placed. Micro-CHP in the UK must compete against high efficiency condensing boilers which are not prevalent in Japan for example. The cost and emissions from heating a standard Japanese home are therefore higher than in the UK, so the fuel cell does not require such high performance to equal or better the embedded traditional technology.

Economic outcomes are dominated by the assumed energy prices, both in absolute terms and with the relative price of gas to electricity. As the fuel cell converts one form of energy into the other, it is highly beneficial to have low gas prices and high electricity prices, known as a high spark gap. Similarly, receiving high revenue for exported electricity is vital to achieve significant savings – hence the popularity of feed-in tariffs for microgeneration. As can be seen in Table 3.1 gas price, spark gap and export value all vary considerably between studies, hence the significant variation in results. Few of these studies represent the current situation in the UK, so it is difficult to draw conclusions on the economic impact that fuel cell micro-CHP would have.

Similarly, environmental outcomes are strongly influenced by the efficiency and carbon intensity of the heating equipment and grid electricity that is displaced by the fuel cell. Heat from the fuel cell is credited with avoided production from burning gas with between 78% and 96% efficiency (HHV), giving a spread of 23% in the displaced emissions. Table 3.2 shows that the range of emissions factors is even greater for electricity, as specific types of plant can be considered (e.g. CCGT or coal), as well as the average mix of plants used in different countries. In coal and gas burning countries such as Germany, Japan and the UK, micro-CHP can offer a distinct advantage as it can displace ~600g of CO_2 for each kWh of electricity produced. In cleaner countries such as Belgium or Switzerland, less carbon is saved by displacing electricity than is produced by consuming natural gas – meaning it would be impossible for fuel cell micro-CHP to reduce emissions until zero-carbon biomass becomes viable.[86]

Tables 3.1 and 3.2 summarise the results of various modelling studies, giving the economic and environmental outcomes respectively. Notably, Table 3.2 cites the first results to have come from field trials of fuel cell micro-CHP systems, which suggest that PEMFC systems save 800-900kg of CO_2 per year, and SOFC save up to 1400kg. Section 5.4.2 is devoted to estimating the benefits that these systems would give in the UK, accounting for the different emissions factors and energy demand profiles in Japan and the UK, and the fact that fuel cells in Japan are not allowed to export electricity to the electricity grid.

Fuel cell technology	**Price of gas**	**Spark gap**	**Export value**	**Situation**	**Annual savings**	**Ref.**
1kW SOFC η_{el}: 38%, η_{tot}: 95% (LHV)	2.2	4.4	47%	Optimised dispatch in 3 UK houses (small, medium, large)	**€250-325**	[124]
4kW PEMFC η_{el}: 25%, η_{tot}: 80% (LHV)	3.3	4.7 / 2.5 (day / night)	14%	Following heat demand in a Belgian detached house	**-€130**	[135]
			100%		**€1010**	
2kW PEMFC η_{el}: 24%, η_{tot}: 84% (LHV)	4.8	3.5	54%	Following heat demand in a German detached house (top) and terraced house (bottom)	**23%**	[126]
					17.5%	
1kW SOFC η_{el}: 39%, η_{tot}: 90% (LHV)	3.5	2.1	0% 50%	Running at constant output in two large Canadian houses in Ottawa (top) and Vancouver (bottom)	**€51 (2%)** **€85 (3%)**	[137]
	3.3	1.4	0% 50%		**-€230 (-15%)** **-€204 (-14%)**	
1kW PEMFC η_{el}: 35% (HHV)	8.7	1.6	0%	Simulated in a large Japanese house.	**€150 (4.1%)**	[136]
Generic 1kW fuel cell η_{el}: 50%, η_{tot}: 90% (LHV)	2.5	4.1	29%	Simulated in a large UK house.	**€211**	[123]

Table 3.1: Results from previous economic studies. For each study the following are given: the price of gas in €c per kWh; the ratio of electricity to gas prices (the spark gap); and the value of exported electricity relative to import/purchase.

Fuel cell technology	Displaced technologies	Situation	Reduction in CO_2	Reduction in NRPE	Ref.
175 ENEFARM 0.7-1kW PEMFC systems η_{el}: 26.0%, η_{tot}: 63.1% (HHV)	Heat from a standard gas boiler (78% HHV, 236g per kWh of heat produced) Marginal electricity from the Japanese grid (36.9% HHV, 690g)	Average savings over 12 months, calculated from field trials in Japanese homes. Systems installed in 2005 (top), 2006 (middle) and 2007 (bottom).	28.0% 846kg	15.3% 2003kWh	[138]
777 ENEFARM 0.7-1kW PEMFC systems η_{el}: 26.4%, η_{tot}: 63.2% (HHV)			28.0% 792kg	15.8% 1920kWh	[139]
930 ENEFARM 0.7-1kW PEMFC systems η_{el}: 27.7%, η_{tot}: 64.8% (HHV)			30.8% 901kg	18.5% 2310kWh	[100]
27 Kyocera 0.7kW SOFC systems η_{el}: 34.1%, η_{tot}: 71.3% (HHV)		Average savings over 12 months (top) or 4 months (bottom) calculated from field trials in Japanese houses. Systems installed in 2007 (top) and 2008 (bottom).	34.2% 1135kg	15.3% 2220kWh	[101]
35 Kyocera 0.7kW SOFC systems η_{el}: 36.1%, η_{tot}: 74.0% (HHV)			37.2% 1404kg	18.7% 3027kWh	
1kW PEMFC system 26%, 85%	High efficiency gas boiler and average UK electricity grid mix (430g)	Simulated operating in a detached house (top number for each) and a terraced house (bottom for each)	1430kg 1040kg		[20]
1kW SOFC system 40%, 80%			1410kg 1320kg		
Generic 1kW fuel cell η_{el}: 50%, η_{tot}: 90% (LHV)	Heat from a 90% efficient condensing boiler (200g), average UK electricity mix (430g)	Simulated in a large English house.	16% 892kg		[123]
Baxi Beta 1.5 Plus (1.5kW PEMFC) η_{el}: 32%, η_{tot}: 85% (LHV)	Standard (low temperature) boiler and average German electricity grid mix.	Simulated operating for 5000-6000 hours per year in a low-energy home		56%	[105]
Hexis Galileo 1000N (1kW SOFC) η_{el}: 30%, η_{tot}: 90% (LHV)	Condensing gas boiler and average German electricity mix (614g).	Simulation in German households	16%		[115]
1kW SOFC η_{el}: 32%, η_{tot}: 85% (LHV)	Condensing gas boiler (97%) and average German electricity mix.	Simulated operating for 4786 hours per year (full load) in a German house	36%		[122]
4kW PEMFC following heat demand η_{el}: 25%, η_{tot}: 80% (LHV)	Condensing gas boiler (107%), and electricity from: The average Belgian mix (top, 37%, 272g); CCGT (middle, 50%, 404g); Fossil mix (bottom, 42%, 617g).	Simulated in a detached house in Belgium with 4 occupants.	-6%	29%	[135]
			12%	12%	
			37%	22%	
2kW PEMFC, following heat demand η_{el}: 24%, η_{tot}: 84% (LHV)	Gas heating (241g) and average German electricity mix (600g)	Simulated in a German detached (top) and terraced house (bottom) with 4 occupants	18% 2000kg		[126]
			17.5%		
SOFC of unknown capacity η_{el}: 45%, η_{tot}: 85% (LHV)	Heat from 91% efficient condensing boiler, average UK electricity mix (420g). Exported electricity was given no credit.	Simulated in an apartment (top), terraced (middle) and semi-detached house (bottom) in the UK	17kg		[109]
			-139kg		
			-108kg		
1kW SOFC η_{el}: 31%, η_{tot}: 96% (LHV)	Condensing gas boiler (108%), and electricity from the European average (top, 29.7%, 554g); or Swiss average (bottom, 150g)	Simulated in an average Swiss house.	13% -11%	21%	[86, 140]

Table 3.2: Results from previous emissions studies. Electrical and total efficiency of the fuel cell are given (η_{el} and η_{tot}), along with the efficiency and CO_2 emissions (in g/kWh) of the displaced technologies. The estimated annual reductions in CO_2 emissions and NRPE (non-renewable primary energy) from each study are given.

3.3. Cost Estimations

The current and future cost of fuel cell micro-CHP systems is of great importance, as the battle to convince consumers to purchase these systems will be heavily swayed by how much it is going to cost them. The price one could expect to pay for the systems currently under development, either now or in the future is however poorly understood, and so must be estimated.

At the start of this project there were few, if any, published prices for fuel cell CHP systems as each machine was individually built and not sold without a tight confidentiality agreement. With the exception of the newly released ENE-FARM systems, it is still challenging to find any manufacturers who can or will openly state how much their systems cost to produce today: the strategic value of knowing competitor's costs is continuing to keep firms quiet.[108] It is therefore difficult to give a single number for the price of a fuel cell micro-CHP system. As an indication, anywhere from €20,000 to €200,000 is required to acquire one,[24] with specific prices depending strongly on the manufacturer and order volume. Trying to estimate what these prices would be in other scenarios (e.g. when mass produced or in the future) therefore poses an even greater challenge.[110]

Two estimation methods are typically employed: bottom-up cost analysis and using learning curves. The former method involves estimating the materials and manufacturing costs for each component of the system, while the latter relies on historical data for prices and sales volumes to extrapolate how they will fall in the future.

3.3.1. Bottom-up Cost Estimates

Even if the present cost of manufacturing systems was widely known, it would not give an indication of how much they would cost to build en-masse once they were fully commercialised. The transition from low volume, highly specialised assembly to automated mass-production lines will bring about enormous reductions in labour intensity and plant utilisation, and thus in manufacturing costs. The cost of producing systems at high-volume is therefore estimated to give an idea of where this bottom-line could be expected to lie.

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[24] This is indicative of the range of costs quoted to the University of Birmingham's Fuel Cells Group for CHP systems between 2005 and 2009.

To do this, the fuel cell system is broken down into components, and then into individual materials and production stages. These are often parameterised; for example, the area of electrolyte required is expressed as a function of power density, so that a sensitivity analysis can be performed. The cost of each material, process and component is then estimated from interviewing relevant companies or with industrial cost estimation software, which contains a database of reviewed costs for standard manufacturing goods and processes.

Assumptions about the construction and performance of the system are critical to the results, and estimates for the future costs of specific items (e.g. polymer membranes) have to be speculative as there are no solid foundations on which to base future costs. Estimated costs can therefore vary widely between studies as different assumptions are used.[141]

This is most obvious when comparing studies of fuel cell stacks for automotive use and those for stationary purposes such as micro-CHP. The widely publicised high-volume estimates of as little as €15/kW "are not valid for stationary systems"[141] as their design criteria are too different.[25] Automotive stacks are usually 50-100kW, with a focus on high power density and low cost, rather than long lifetime on reformed fuels. As seen in Table 3.3, the estimated costs for mass produced stationary stacks and systems are somewhat higher, however they compare favourably with the estimated economic value of such a system to its owner – based on the savings presented in Table 3.1.[20, 43, 124, 137].

When the ENEFARM system was launched in Japan it helped to answer one of the major questions relating to a sound economic assessment: how would the cost estimates given in Table 3.3 relate to the actual price offered to consumers? A chasm exists between these estimated costs and current prices which are over €20,000. Increasing production volumes and continued research into cheaper and more effective designs will help, but it cannot be expected that such reductions will be made in a short time-scale. A different type of analysis is required to estimate how rapidly costs will fall to these estimated levels, and what prices can be expected to be in the near future.

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[25] Most estimates in literature lie between €15 and €100/kW for production volumes above 100,000 vehicles per year (e.g. [142, 143]).

	Stack cost	BoP cost (for 1kW)	Details	Ref.
PEMFC	€180-5500 / kW	€230	Domestic system costs were extrapolated from a 50kW pressurised stack produced at 500,000 units per year, with a separate assessment for BoP components. (2000)	[144]
	€630 + 260 / kW	~€3,000	3 to 50kW systems were considered at 10,000 per year volume. Estimates were made with industrial cost estimation software and information from the US Department of Energy.[26] (1999)	[141]
	€600 / kW	€190 + €175 / kW	Materials cost for the stack and balance of plant, estimated using empirical formulae relating to capacity.[27] (2005)	[146]
SOFC	€550-600 / kW		Manufacturing costs for 3-10kW systems from six American manufacturers, estimated at production volumes around 50,000 per year as part of the SECA Phase I project. (2007)	[147-149]
	€150-450 / kW		Estimated cost of 5kW residential units, conducted with sensitivity analysis.[28] (2004)	[150]
	€350 / kW	€625	Estimated materials cost for a 1.3kW system based on the Fuel Cells Scotland stack. (2006)	[151]
AFC	€600 / kW		The actual bill for materials required to produce an Elenco V1.1 module, approximately €220 of which was platinum.[29] (2003)	[152]
	€220 / kW		Claimed materials cost for the Astris Powerstack M-250. (2006)	[153]
	€400-500 / kW		Based on a review of reports from DLR, LBST, ZSW, Hoechst & The Royal Institute of Technology in Stockholm. (1992-1994)	[56]
	€130-560 / kW	€225 + €2-26 / MWh	Estimates for high-volume manufacture of a domestic AFC system, including the cost of soda lime consumption for a CO_2 scrubber. (2001)	[144]
	€200 / kW		Projected cost of a Zevco module, which was sold for €1600/kW at the time. (1998)	[144]

Table 3.3: A summary of previous bottom-up and materials cost studies for stationary fuel cell stacks and systems. All values are given in 2007 Euros.

3.3.2. Learning and Experience Curves

Several authors have estimated the rate at which fuel cell prices will fall by the use of learning curves. The theory of 'learning by doing' proposes that the cost of manufacturing a product decreases with rising production as companies gain the experience required to optimise their process, reduce labour intensity and develop specialised production machinery. This theory gained recognition in the 1960s, and has been widely used to explain the cost reductions seen across numerous technologies and time periods – from the Model T Ford to photovoltaic panels.

The cost reduction achieved each time cumulative output doubles – known as the learning rate – has been 9-27% for most energy related technologies, as shown in three histograms in Figure 3.1. There is "overwhelming empirical support for such a price-experience relationship from all

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[26] The original report suggested $717 for a 1kW stack, which was modified to be more consistent with the domestic CHP systems in use today. Further details are given in [145] which is provided in Appendix A.

[27] The original report suggested $500 for the stack and $700 for the balance of plant. Assumptions for the BoP were modified as in [145].

[28] The original report suggested a central estimate of $90/kW, which was modified as in [145].

[29] The original cost was updated to use more recent platinum prices of €32/g.

fields of industrial activities, including the production of equipment that transforms or uses energy".[154]

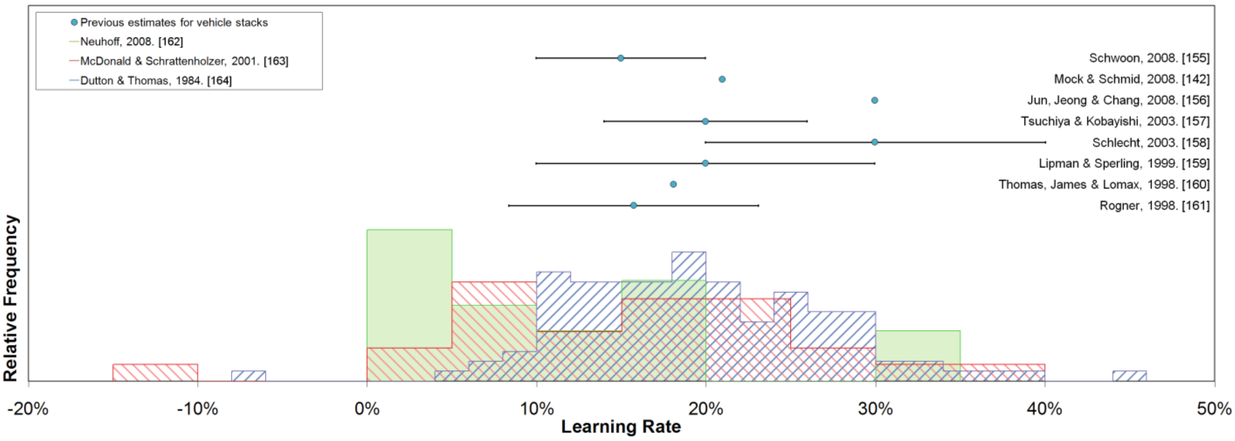

Figure 3.1: A comparison of the learning rates for PEMFC fuel cells presented in previous works,[142, 155-161] along with histograms of the observed values for other energy technologies, taken from [162-164].

Two recent reviews of fuel cell cost estimation highlight the extreme difficulty that has been faced in developing such a model for this technology.[110, 155] They conclude that there have simply been too few installations to provide an estimate of the present-day cost, and information about them is kept private by manufacturers, making it "difficult, or even impossible" to calculate a learning rate. It is therefore not surprising that no previous studies have used historic data to develop a learning curve model, and authors have instead estimated the rate at which they will fall in the future.[110]

The learning curve parameters used in previous papers therefore vary significantly due to the different assumptions made. As with the bottom-up cost estimations, fuel cells for vehicle engine replacements have been the main topic of study (e.g. [142, 155-161]). The lower cost per kW of vehicle stacks, and high assumptions for the initial production rate (up to 50,000 vehicles per year) contribute to the low present-day costs presented in these studies, which can be two orders of magnitude lower than those for current domestic systems.

Figure 3.1 summarises the learning rates used in past fuel cell cost estimations, which fall towards the higher end of the range observed for other technologies – averaging 14-28%. Neij argues that modular technologies such as fuel cells have experienced higher learning rates than monolithic products such as turbines, but concedes that rates as high as 30% are rarely observed.[110] Conversely, Schwoon opted for more conventional learning rates of 10-20%, arguing that several components of a fuel cell system (pumps, motors, inverters) are already well developed within other products, and would not benefit strongly from the early phase of the fuel cells' own learning curve.[155]

3.4. Life Cycle Assessments

Two broad aspects of the environmental impact of fuel cell micro-CHP have been studied: the benefits that can be obtained from their usage (as given in Table 3.2); and the costs of producing these systems, in terms of materials and energy requirements and the emission of pollutants.

The latter of these is considered with Life Cycle Assessment (LCA), which is now most widely associated with estimating the 'carbon footprint' of various consumer products.[165] With LCA technique, the total environmental burden of manufacturing a fuel cell can be estimated from cradle to grave, as summarised in the following stages:

- The individual stages required to produce a fuel cell system are identified, either by observing and interviewing manufacturers or from reviewing literature on cell design and construction;
- Each stage is broken down into sequentially smaller processes as shown in Figure 3.2, giving a hierarchy that extends from extracting raw materials from the earth up to the final delivery of the system;
- An inventory is produced for each of these processes, giving the material and energy inputs and waste or by-product outputs. Data is acquired from peer-reviewed inventory databases, or further research for the less common processes;
- The hierarchy of processes and their inventories are entered into an LCA software package, which ties every raw material and emission to an environmental impact and can therefore calculate the total impact of producing the fuel cell.

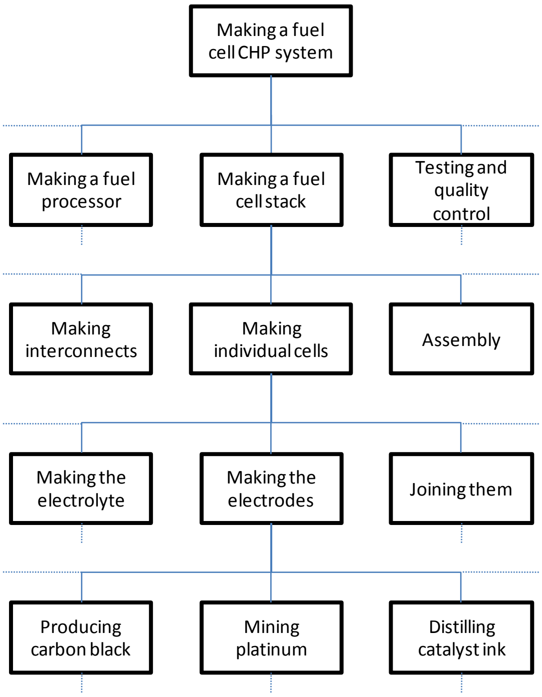

Figure 3.2: A portion of the inventory for producing a fuel cell CHP system, following the stack assembly down as far as sourcing platinum for electrodes. Each box could be expanded in a similar way as the central column, producing a large and complicated hierarchy.

As with economic studies, the majority of published work on the environmental impact of fuel cells has considered vehicle propulsion systems: of 113 fuel cell LCA studies identified by HySociety, only 7% were for stationary CHP systems.[166] Of those that are relevant, many reports are obscured due to commercial secrecy, presenting only normalised results or omitting important assumptions.[167] Table 3.4 summarises the scope and results of previous LCAs published in this field, highlighting data or stages of the study that were omitted or considered questionable.

The power of LCA technique lies in its ability to consider the entire life cycle (manufacture, usage, disposal) of a product in great depth, however relatively few fuel cell LCAs consider more than the manufacturing stage. The two studies in Table 3.4 that go on to consider usage only provide a simple treatment of the fuel cell's operation, despite arguing that this is clearly the most important stage of the life cycle.[108, 168] In contrast to the detailed modelling presented in Section 3.2, these studies assume that the fuel cell runs at full power and constant efficiency for a fixed number of hours (the stack lifetime).

Also in contrast to the modelling studies, these LCAs consider the emissions from the fuel cell in isolation, rather than the reductions achieved in comparison to a traditional system. Rooijen concludes that the impact of operating the fuel cell far outweighs that of manufacturing it, as the sheer amount of natural gas consumed over 10 years vastly outweighs the energy embodied in the fuel cell's construction.[168] While this informs manufacturers that improving efficiency will offer the greatest environmental benefits, it does not provide any comment on whether fuel cells are better or worse than the alternatives they could replace.

The LCAs listed in Table 3.4 estimate that anywhere between 10 and 3000MJ of primary energy is required to produce a 1kW stack. Part of this range can be explained by the varied manufacturing stages for each stack technology, and the different designs chosen by manufacturers. In particular, SOFC are thought to be energy-intensive to manufacture as the ceramic cells must be sintered at high temperatures.[169] PEMFC and other platinum-based cells however require closed loop recycling to recover the catalysts and membrane materials which contribute significantly to the environmental impact.[170]

Two other reasons can be drawn from these studies: the amount of energy consumed in assembling the stack varies by a factor of 1000; and data on the production of exotic fuel cell materials is not widely available. Three of the studies do not consider energy inputs in the production stages, and two only use personal estimates. Those that consider either the energy consumption or exotic materials in detail conclude that they contribute a significant part of the environmental impact from manufacture. The need for a more transparent and complete life cycle assessment of these technologies is apparent.

	Product	**Materials Input**	**Energy Inputs**	**Usage**	**Recycling**	**Results**
PEMFC	Ballard-Alstrom 250kW CHP system. 2000. [167]	Inventory presumably taken from literature. Aggregate amounts given. BoP data were personal estimates. Background data was questionable.[30]	Personal estimates. 5.6MJ per kW of stack. 6.0MJ per kW of BoP.	–	–	Given in full, however they were suspected to be erroneous. Impact of manufacture dominated by production of the catalysts.
	Ballard 275kW CHP system. 2001. [172]	Inventory collected at Ballard. No information given.	–	–	Considered for platinum (90% rate)	Given in full. 293kg CO_2 emitted producing 1kW stack, reducing to 86kg with 90% platinum recycling.
	PlugPower 10kW stack. 2006. [171]	Inventory collected at Plug Power. Aggregate amounts given.	–	–	–	Only given for individual materials rather than the whole stack. Commented on lack of information regarding exotic materials such as Nafion™ and graphite.
	Idatech 1kW stack. 2005. [108]	Aggregate amounts given. Erroneous catalyst data used.[31]	–	Simple model of a 100kW SOFC supplying 500 houses.	–	Results were for a mix of micro- and large scale CHP, PEMFC and SOFC. Concluded that "fuel cells do not compare favourably with other CHP technologies" due to erroneous input data.
SOFC	Sulzer Hexis 1kW CHP system. 2000. [167, 174]	Inventory presumably taken from literature. Aggregate amounts given. BoP data were personal estimates.	Personal estimates. 35MJ per kW of stack (3 sintering stages), 112MJ per kW of BoP.[32]	–	–	Given in full. Impact of manufacture dominated by chromium for interconnects, and steel for BoP. 383kg CO_2 emitted producing 1kW system.
	Siemens 24kW stack. 2001. [169, 170, 175]	Inventory data collected from Siemens, given with a full breakdown. Most exotic materials (ceramics and perovskites) were researched, although limited information was presented.	Detailed research into energy required for sintering. 2950MJ electricity per kW of stack. (2 sintering stages)[33]	–	–	A limited set of normalised results given. Impact of manufacture dominated by chromium for interconnects, and electricity for sintering.
PAFC	PureCell 200kW CHP system. 2006. [168]	Inventory data collected from UTC Power, given with a full breakdown. Background data on exotic materials (PTFE, Nafion™, graphite) had to be substituted as no data was available.	Estimated from total consumption of the manufacturing facility. 1191MJ electricity and 1640MJ heat per kW of stack assembled.	Assumed system ran at full power for 85,000 hours. No credit was given for heat or power produced.	High recycling rates for all materials, with 98% of Pt recycled by the manufacturer.	Given in full. Impact of manufacture dominated by platinum and electricity/heat for the stack, plus copper and stainless steel for the BoP. 990kg CO_2 emitted producing 1kW system (51% from the BoP, 11% from energy consumed)

Table 3.4: Summary of previous life cycle assessments of fuel cells for stationary CHP. Items highlighted in gold were considered problematic.

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[30] The energy required to source platinum, ruthenium and carbon paper was suspected to be several orders of magnitude too high. For example, producing 1g of platinum required 202 GJ, compared to 50MJ calculated in SimaPro and [171]. This resulted in 23.8 tonnes of CO_2 and 4.0 tonnes of SO_x being emitted in the production of materials for 1kW of stack.

[31] The materials inventory had been misconstrued from the original source (which had obscured catalyst contents), and so it was assumed that 100g of both platinum and palladium were needed per kW of stack, compared to typical values of around 1g/kW (e.g. [171, 173]).

[32] 60% of this process energy was assumed for producing the gas boiler and auxiliary burner to accompany the fuel cell.

[33] The breakdown of electricity consumption was 65MJ for mixing, rolling and assembly, 2400MJ for 2 sintering and drying stages, and 485MJ for coating and cutting the interconnects.

Chapter 4:

SIMULATING FUEL CELL MICRO-CHP SYSTEMS

4.1. Summary

The aim of this study was to estimate the potential and impacts of installing fuel cell micro-CHP into UK homes today. Previous simulations have relied on isolated studies or manufacturer's quotes for technology performance rather than sourcing data from broad evaluations in the field. Similarly, due to computational constraints most studies only study the energy demand profiles from a small sample of houses. As every home is unique, this gives only a snapshot of the wide range of results that could be expected.

These issues were addressed by developing a new simulation model with a novel emphasis on the breadth and quality of data inputs. A review of the real-world performance of fuel cell micro-CHP systems is presented, alongside an assessment of energy demand profiles measured from a total of 259 UK houses. This is followed by a description of a techno-economic model that was designed to allow these high volumes of data to be used in simulating fuel cell micro-CHP systems.

4.2. Theoretical Arguments

> *"In God we trust, all others bring data."*
>
> – W. Edwards Deming

From the advent of the first computing machines there has been an element of mystery and misunderstanding about the capabilities of numerical methods. The father of computing, Charles Babbage was famously asked by members of parliament *"Pray, Mr. Babbage, if you put into the machine wrong figures, will the right answers come out?"*. The same confusion of ideas he experienced in the 19th Century still persists with today's more complex and opaque computer simulations.

Many models used in the realms of energy and economics are described as "garbage in, garbage out", in that the quality of their results is directly dependant on the quality of the data inputs.[176] The results from such models cannot be taken at face value without an in-depth assessment of the assumptions that are relied on; if the data inputs seem implausible to the reader, nothing of interest can be gained from the conclusions.[176, 177] This criticism was levelled at the UK government, whose use of the MARKAL model in 2003 predicted that achieving 60% cuts in CO_2 emissions by 2050 would be surprisingly inexpensive[34].[176, 179]

There are two routes to avoiding this pitfall: increasing the transparency of the models used – so that readers can easily discern the capabilities and limitations; and placing a greater emphasis on the data inputs and assumptions used in such models. More importantly, the source and rationale of choosing the data inputs must be stated explicitly in order for the results to be taken in the correct context. The modelling of fuel cells has suffered in this respect, as hard evidence on which to base data inputs has only recently become available. Authors typically had to provide estimates for efficiency, lifetime and cost, and then use sensitivity analyses to explore the impacts that they have on results.

Emphasis on data inputs is prevalent throughout this work, and so detailed definitions have been produced for the performance of the fuel cell and the reference system it is compared to, the properties in which the fuel cell will operate, and the cost and carbon content of the energy sources that are used and displaced.

4.2.1. Characterising Fuel Cell Efficiency

The efficiency of fuel cell systems is often quoted from laboratory based systems, which do not account for the penalties imposed by fuel processing and other ancillary components, or from operating intermittently at variable power levels. There are a number of caveats which cannot be represented by a single value for efficiency, and which must be considered to give a representative and accurate simulation:

- There are several conventions for measuring efficiency: using different definitions of the fuel input, the power output, and the system itself;
- The efficiency of the fuel cell stack and system changes with time as the cells degrade, and with power output as the electrochemical operating point changes. Conventional wisdom on these changes is not matched by observations of real systems;
- Energy consumed by the fuel cell itself must be accounted for, both during steady state operation, and during start-up and shut-down cycles.

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[34] It is argued that overly optimistic assumptions about the cost of wind energy were fed into the MARKAL model (which determines the least-cost market penetration of low-carbon technologies), which naturally produced an unexpectedly low overall cost of achieving the government's targets. It is argued that this conclusion delayed the UK's response to climate change by 3 or 4 years.[178]

The following sections stress the importance and discuss the implications of these effects.

4.2.1.1. The Use of Lower and Higher Heating Values

The efficiency of a fuel cell is defined by the amount of useful energy it produces (heat and electricity) relative to the energy content of the fuel consumed. The enthalpy change of formation ($\Delta\bar{h}_f$) is generally used to define the chemical energy of the reactants and products, as it is with other fuel consuming technologies.[40] When considering the standard reactions within a fuel cell, two reference points can be used depending on the state of the water produced:

$$\begin{aligned} H_2 + \tfrac{1}{2}O_2 &\longrightarrow H_2O_{(\text{liquid})} \quad \Delta\bar{h}_f = -285.84\ \text{kJ/mol} \\ H_2 + \tfrac{1}{2}O_2 &\longrightarrow H_2O_{(\text{steam})} \quad \Delta\bar{h}_f = -241.83\ \text{kJ/mol} \end{aligned} \tag{4.1}$$

These enthalpies are referred to as the Higher Heating Value (HHV) and Lower Heating Value (LHV) respectively.[35] The HHV is the strict thermodynamic definition as the products are returned to the same temperature and pressure as the reactants, while LHV excludes the energy that was used to vaporise the water.[180] The latter definition was widespread in the 19th Century as combustion heat below 150°C was considered useless due to the highly corrosive vapour produced when burning sulphur-rich coal.[181]

The advent of condensing natural gas boilers meant that the latent heat of water vapour could be utilised in home energy production. This greatly improves the efficiency of combustion, so much so that condensing boilers are advertised as being up to 108% efficient. As the first law of thermodynamics remains to be disproved, LHV efficiency is unsuitable for describing stationary energy generation. This argument is delivered forcefully by Bossel (e.g. in [182, 183]), who argues that hydrogen fuelled systems (such as fuel cells) benefit greatly from choosing the LHV reference point. Measuring efficiency against the LHV rather than HHV fuel content gives values that are 18.3% higher for hydrogen fuelled systems – a greater discrepancy than for any other fuel (Table 4.1).

	LHV energy content (kJ/g)	**HHV energy content (kJ/g)**	**Ratio of HHV / LHV**
Natural Gas	50.02	55.53	1.110
Hydrogen	119.93	141.86	1.183

Table 4.1: Energy contents of hydrogen and methane.[184, 185]

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[35] HHV and LHV are also referred to as Gross and Net Calorific Value (GCV and NCV) respectively.

A problem with many studies of fuel cells is that LHV efficiencies are used without qualification. Aside from giving misleadingly high values for stack and system efficiency, this can cause problems with the analysis of financial and environmental benefits. Natural gas is priced according to HHV energy content (in p/kWh) in the UK [186], meaning that running costs will be underestimated by 11% if LHV efficiencies have been used for the fuel cell. Similarly, the CO_2 emissions from burning natural gas can be given against HHV or LHV,[36] so if the wrong combination has been used, absolute emissions will be underestimated.

It is therefore essential to be explicit over which convention is used, and to ensure that this is consistent throughout the analysis. HHV efficiencies are quoted in this work unless otherwise stated.

4.2.1.2. Degradation of the Fuel Cell Stack

It is well documented that the maximum power output and nominal voltage of a fuel cell decreases over its operating lifetime, due to reduced catalytic activity and increased cell resistance.[188] This effect has been well characterised and demonstrated in real-world field trials and long-term laboratory experiments (e.g. [189-191]). The rate of degradation per cell is typically in the range of 2-20mV per 1000 operating hours, relative to a nominal operating voltage of around 700mV, giving 0.3-3% voltage loss per 1000 hours.

The electrical efficiency of a fuel cell stack is directly related to the cell voltage. The theoretical maximum operating voltage can be determined from the calorific value of hydrogen to be 1.482V with reference to HHV.[40, 192] It therefore follows that as stack voltage degrades, the system efficiency also falls with time. This change in electrical efficiency has been widely reported in the fleet of industrial CHP systems deployed by UTC Fuel Cells: electrical efficiency of 40% (LHV) at the beginning of life decreases to 38% after infancy, ending up at 35% by the end of the guaranteed lifetime (40,000 hours).[45, 49, 193-195]

If the initial power output of a stack was to be maintained over its lifetime, efficiency would fall at a higher rate than voltage due to the changing operating conditions of the cells. A higher current density would required to achieve rated power as voltage degraded, thus decreasing the cell voltages further.[40] This can be quantified for the UTC fleet by collating data on their efficiency and voltage loss over time ([45, 49, 193-195] and [45, 195, 196] respectively), which

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[36] Burning natural gas emits 182g of CO_2 per kWh of fuel input (HHV), or 202 g/kWh (LHV).[187]

shows that efficiency falls around 1.5 times faster than voltage when power output was not rolled back.

The majority of manufacturers instead choose to preserve efficiency somewhat by fixing the maximum operating current (rather than power) over the system lifetime; maximum power output therefore falls gradually along with efficiency.[115, 189, 197] The combination of these effects will be non-negligible to the results of fuel cell modelling, as it should be expected that power output and efficiency will fall by at least 10% over the lifetime of the system (a commonly held target for manufacturers).[196-198]

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Decreasing electrical efficiency is not the only change that voltage degradation should cause, as thermal efficiency should also rise.[190] The chemical energy of the fuel cannot simply disappear when a lower voltage is produced; it is seen as additional ohmic heating from increased cell resistance, or as unreacted products in the anode waste stream (H_2 or CH_4) which can be combusted.

Ideally one could assume that the amount of additional heat produced by the stack at a given operating point would be equal to the loss in electrical power: $\Delta Q_{th} = -\Delta Q_{el}$. The amount of useful heat (and thus rise in thermal efficiency) will however not have the same magnitude as the fall in electrical efficiency, as thermal recovery systems are not 100% efficient. Thermal energy is lost as low temperature heat in the exhaust gas and as radiation from the various system components.[107] In order to relate the thermal and electrical efficiencies (η_{th} and η_{el}), the thermal utilisation ratio (ν_{th}) can be introduced:

$$\nu_{th} = \frac{heat\ extracted}{heat\ available} = \frac{\eta_{th}}{1 - \eta_{el}} \tag{4.2}$$

Considering a typical PEMFC system with $\eta_{el} = 30\%$ and $\eta_{th} = 45\%$; 1kWh of natural gas will be converted to 0.30kWh of electrical energy and 0.70kW of heat. Of this produced heat, 0.45kWh is harnessed by the thermal recovery system and transferred to hot water; giving a thermal utilisation ratio of $\nu_{th} = {}^{0.45}/_{(1-0.3)} = 0.643$. Table 4.2 gives a worked example of calculating the change in electrical and thermal efficiency over the lifetime of a fuel cell system.

One final caveat is included in the calculation in Table 4.2: the thermal efficiency of equipment will also degrade over its lifetime. It is unlikely that a condensing boiler installed today will still be operating at its initial efficiency in 2025 due to fouling of the heat exchangers, wear to the pumps, etc. No quantitative information could be found on performance loss in similar equipment such as industrial CHP units or gas boilers, so an arbitrary rate was chosen to save neglecting this effect. It was assumed that the rated efficiency of a gas boiler would fall by 10% over its lifetime (giving ~80% efficiency after 10-20 years), implying a relative drop of 0.5-1% in thermal efficiency per year.

System age:	**Cell voltage (mV)**	**Maximum electrical power (W)**	**Maximum thermal power (W)**	**HPR**	η_{el}	η_{th}	η_{tot}
Beginning of Life	666	1000	1500	1.500	30.0%	45.0%	75.0%
1 year	646	970	1595	1.565	29.1%	45.5%	74.6%
2 years	626	940	1696	1.633	28.2%	46.1%	74.3%
3 years	606	910	1805	1.706	27.3%	46.6%	73.9%

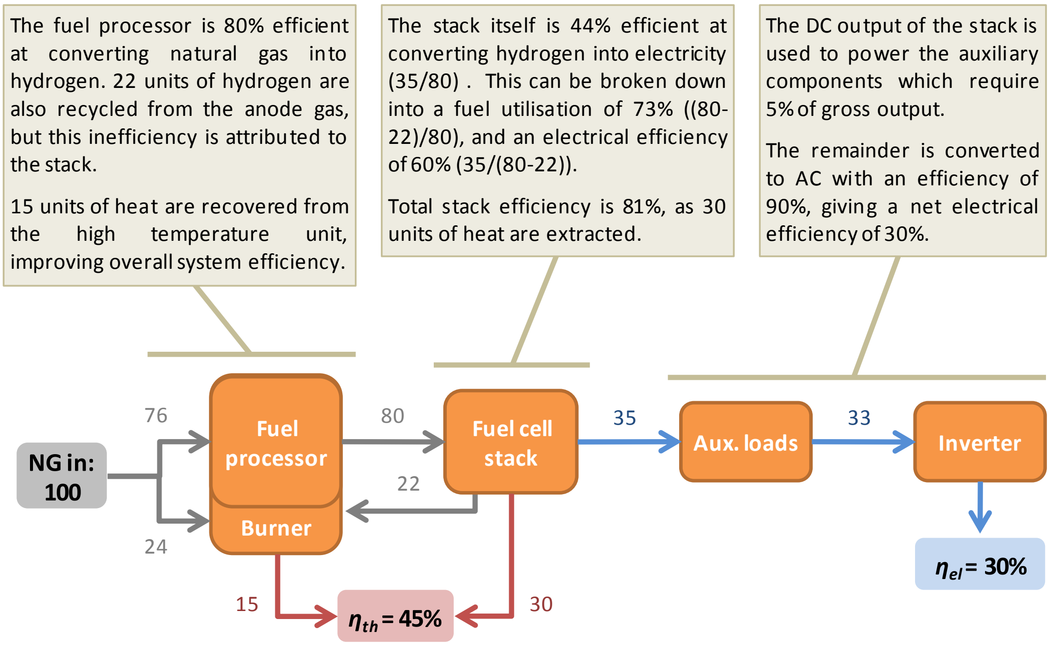
Table 4.2: Hypothetical changes in system efficiency over the lifetime of a fuel cell. The assumptions used were 4,000 operating hours per year; degradation of 5mV per thousand hours (0.75%); and a thermal utilisation ratio of 0.643.

According to these calculations, the total efficiency of a fuel cell micro-CHP system is not expected to change significantly over its lifetime, as the rise in thermal efficiency partly offsets the fall in electrical efficiency. The falling electrical power and rising thermal power outputs produce the more striking effect; which is that the heat to power ratio will gradually rise by around 1.1% per thousand hours.

4.2.1.3. Stack vs. System Efficiency

An aspect of generating efficiency that is often overlooked is the energy that is consumed in the process of producing power. For example, power stations in the UK consume 2% (gas), 5% (coal) and 9% (nuclear) of the electricity they generate,[199] and electricity consumption by condensing boilers and renewable microgeneration can prove to be significant.[19, 31]

This is also the case with micro-CHP systems as energy is required by the pumps, fans, inverter, system controller and fuel processor; all of which is neglected if only the stack is considered in isolation. An example of these additional losses is illustrated in Figure 4.1.


The fuel processor is 80% efficient at converting natural gas into hydrogen. 22 units of hydrogen are also recycled from the anode gas, but this inefficiency is attributed to the stack.

15 units of heat are recovered from the high temperature unit, improving overall system efficiency.

The stack itself is 44% efficient at converting hydrogen into electricity (35/80) . This can be broken down into a fuel utilisation of 73% ((80-22)/80), and an electrical efficiency of 60% (35/(80-22)).

Total stack efficiency is 81%, as 30 units of heat are extracted.

The DC output of the stack is used to power the auxiliary components which require 5% of gross output.

The remainder is converted to AC with an efficiency of 90%, giving a net electrical efficiency of 30%.

Figure 4.1: A typical breakdown of the overall efficiency of a micro-CHP system, adapted from [200].

The electrical efficiency of a whole system is typically one-fifth to one-third lower than the stack efficiency, which would obviously have an appreciable effect on its overall costs and benefits. A review of the efficiency of these ancillary components was therefore conducted, as their impact cannot be overlooked.

4.2.1.4. Part Load Efficiency

One of the widely reported benefits of fuel cells is their high efficiency at part load. This is an inherent characteristic of the fuel cell stack itself as individual cell voltages rise towards Open Circuit Voltage (~1V) when less current is drawn from them, giving the highest efficiency at low loads. This is seen as an important benefit for domestic power generation, as the demand from individual houses is highly intermittent with significant periods of low-level baseline demand.

As Colella observed in 2002 this is sadly not the case with whole CHP systems: in practice, efficiency falls rather than rises as output power decreases.[85] This is in part due to the impact of the ancillary power loads mentioned in the previous section, which are overlooked when the fuel cell stack is considered by itself. These losses do not scale linearly with power, and present relatively higher losses at low loads. As the power output of the fuel cell decreases, a point is reached when the system is no longer thermally self sufficient, and electric heaters would need to be activated in order to maintain the system temperature – giving a negative thermal efficiency.[20]

4.2.1.5. Dynamic and Seasonal Effects

Low temperature fuel cells are expected to operate intermittently in people's homes, starting up and shutting down on most days[37].[80, 201] The energy required to start and stop the fuel cell system over the course of a year can be significant, as electronic systems must run before and after operation to provide adequate stack conditions, and a long period of pre-heating is required to raise the generator's mass up to operating temperature. Although the fuel cell stack may be able to operate from ambient temperature (for PEMFC and AFC), the fuel processor must be heated to several hundred degrees before hydrogen can be produced. The impact of similar requirements have been observed in field trials of both Stirling engines and condensing boilers.[31]

The amount of energy required to start a fuel cell micro-CHP system has not been widely studied, and only one prior experimental investigation was found. During tests on a Vaillant "Euro 2" it was found that 9kWh of natural gas (HHV) was required to pre-heat the system from cold,[38] suggesting that around 2kWh of gas would be required for a 1kW domestic-scale system.[202] Using the same methodology with data from the Baxi Beta field trial, it was found that 1.3±0.4 kWh of gas was required to pre-heat this 1.5kW PEMFC system.[39] Both of these analyses suggest that significantly more energy is required to start fuel cells than other technologies: the Carbon Trust estimated that 0.5kWh of heat and 75Wh of electricity is required by a Stirling engine, and condensing boilers incur a penalty of 0.17kWh gas consumption for every start up.[31]

The gas consumed in pre-heating the fuel cell system is effectively wasted, as the heat embodied in the generator is not transferred to the house in useful ways.[203] Systems are typically located away from the main living areas of the house due to constraints on space or noise. Most systems are located in basements and garages, or outside in the case of ENEFARM, Kyocera and Plug Power – where any heat lost through radiation or conduction will be useless. If the fuel cell is located in an occupied area of the house, any heat dissipated to the surroundings will be of use during the heating season, but will be unwanted during the summer months when only hot water is required.

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[37] Many SOFCs are not able to cope with this due to the materials degradation caused by thermal cycling, and so current systems have to operate continuously.

[38] This fuel cell was a prototype 4.6kW natural gas fired PEMFC system. Some useful heat was produced during start-up, which was credited by avoided use of a condensing boiler, as explained in Appendix A.

[39] This analysis is given in Appendix B.

The annual seasonal efficiency of the fuel cell (as reported in field trials) will therefore be lower than when measured at steady-state, as the additional gas and electricity consumed during start-up and shutdown will be accounted for. In the Baxi trial, pre-heating the system accounted for 3% of the total consumption, and so is not a negligible effect. Two consequences are that system efficiencies will be slightly higher during winter months when longer periods of heating are required, and that fuel cells will be better suited to houses with higher demands for space heating which can guarantee fewer on-off cycles.[31]

Hawkes has factored this into more recent studies (e.g. [20, 204]), assuming that starting a PEMFC and SOFC system requires 17Wh of electricity plus 1.6 and 2.0kWh of heat respectively. More experimental analysis of these energy requirements, and their integration into future modelling studies is recommended.

4.2.2. Simulating Fuel Cell Operation

4.2.2.1. Importance of Domestic Energy Demand

The way in which the fuel cell is operated, rather than how well it *can* operate is what ultimately determines the impact it will have on domestic energy consumption. The amount of energy displaced from traditional and less efficient means will be greater if the fuel cell is given ideal operating conditions – long running times at high output. The pattern of energy consumption in UK homes will therefore have substantial influence over the benefits the fuel cell can provide as current systems follow the instantaneous or predicted energy demands.[40] The importance of the energy profile is compounded by the lack of a quantitative relationship between profiles and the impacts of installing micro-CHP, as explained in Section 3.2. It is therefore crucial that the simulation of the fuel cell's operation is representative, and accurately mirrors how it would be run in reality.

In previous work, it is typical for a small number of profiles to be used, due to the limited availability of data and computational time required to run the simulation. It is typical to use data from 1-3 houses either measured over a whole year, or just from a selection of days (e.g. winter, summer and shoulder).[109, 130, 132, 205] Such a limited number of profiles will give only a small subset of the results that could be expected. There is no reliable method to categorise profiles and choose a uniformly distributed selection of houses or days, and so there

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[40] As opposed to operating at constant power output, or as a virtual power station.

is no guarantee that this subset will be representative of the whole population, or that a skewed set of results has been avoided. It is therefore imperative to use the greatest possible number of energy profiles; placing an equal importance on the amount of data used as on its quality.

There is however very little data on energy profiles available in the UK, which poses a barrier to researching microgeneration. There is no particular reason for this lack of data, although it is time consuming and laborious to collect and process. It is common for fuel cell manufacturers to collect their own demand profiles for in-house research, however the commercial value of such data prevents it from being made available to the public.[206] The following data sets were found to be publicly available on request[41] in the UK:[207]

- Electricity demand collected from 217 homes as part of the DTI photovoltaic field trials,[208] which is available as a DVD set from the DBERR.[209]
- Electricity and thermal demand data collected by the BRE from 130 homes in the Milton Keynes Energy Park between 1988 and 1991.[210-212] The data set was made available by Alex Summerfield at The Bartlett, University College London.

Data could alternatively be sourced from other countries, however energy consumption habits are different throughout the world, and so demand profiles are not easily transferred from other countries' building stock.[85] Another option would be to simulate domestic energy profiles; the integrated building simulations introduced in Section 3.2 have been used by many authors [86, 108, 135], and other methods of simulating demand have been demonstrated.[213-216] These are typically based on time-usage surveys of household occupants, which are combined with consumption profiles for individual devices.

It is argued that these simulations add a further level of theoretical abstraction to the model and are no substitute for real data.[126] The time-use surveys they rely on are also limited in number and often outdated; and those methods which rely on building construction and design will not capture the enormous variation in demand that two outwardly similar houses could have.[42] Furthermore, there have been no comparisons between simulated and measured profiles (as even the methods of comparison are not well established), and the impact of using simulated rather than measured profiles on micro-CHP models has not been investigated. For

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[41] In addition to these, researchers at Herriot-Watt University have access to electricity and gas consumption data measured with 1 minute resolution in a set of 30 homes.[123, 205]

[42] A Danish study showed that two identical houses on the same street with the same number of occupants could have energy demands that varied by a factor of 10 or more; one household presumably operates on a thrift economy while the other is more hedonistic (or has teenagers).[217]

these reasons simulated energy profiles were avoided in favour of the limited amount of measured data available.

4.2.2.2. Choice of Operating Strategy

The system controller will govern how the fuel cell system operates in the home. As well as making low level decisions (fuel and air inlet rates, coolant pump speeds) it will decide when the unit should switch on and off, and what level of power output should be produced. Two classes of logic have been demonstrated in current micro-CHP products: those which follow the instantaneous energy demand (electrical, thermal, or both); and those which use predictive or learning algorithms. The latter of these attempt to compensate for the limited transient performance of the fuel cell (i.e. long start-up time) by analysing the demand of energy from the home and ensuring that the fuel cell is operational when energy is required. Hawkes however showed that by simply following the maximum of electricity and thermal demands from the house, a fuel cell with constrained ramping ability can approach the optimal minimum operating costs.[132]

While the predictive type of controller is beneficial for maximising the utilisation of the fuel cell, it will increase the overall complexity of the system, and thus increase capital costs and the number of components that are susceptible to failure. Similarly, modelling such a system controller would increase the complexity of the computer simulation, reducing transparency and increasing the time required to perform calculations. It was therefore decided that simple load-following operating strategies would be used, allowing high volumes of profile data to be processed and yet still producing results which approached the optimum for each system.

From the load-following strategies identified in Section 3.2, following the maximum of heat and electricity demand was seen as ideal, enabling the greatest running time for the fuel cell and thus maximising the benefits it provides. Following the electricity demand was used as an alternative in scenarios where the production of excess electricity was forbidden; i.e. when there was no ability to export to the national grid.[43] Following only the heat demand or the minimum of heat and electricity would be sub-optimal, as electricity output should be maximised due to its high value and displaced carbon intensity.

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[43] This was used to model ENEFARM systems operating in the current situation in Japan.

These simple load-following strategies were augmented with simple fuzzy logic which attempted to maximise the utilisation of the fuel cell and minimise the number of shut-downs required. These adaptations, and the way in which they were implemented in the fuel cell simulation are discussed later in Section 4.4.

4.2.3. Calculating the Marginal Impact of the Micro-CHP System

When calculating the marginal benefit of fuel cell micro-CHP systems, the choice and performance of the reference system is as important as that of the fuel cell itself. This is seen in the previous studies mentioned in Table 3.2, where entirely different results were obtained due to the choices of reference heating system and source of electricity. These choices therefore deserve equal attention to those relating to the fuel cell itself, but are often only generalised or briefly mentioned.

As the goal of this study was to consider the benefits of fuel cell micro-CHP in the UK, the reference system must be broadly applicable in this country. Two obvious choices for the heating system stand out: either standard gas boilers, or high-efficiency condensing models. Together, these are used in ~80% of UK households, with condensing boiler ownership reaching 15% by 2006.[13] Average central heating efficiency in the UK is estimated to be 76% (HHV), however this is rising as building regulations have mandated that all new boilers installed since 2005 must be of the condensing type.[13]

If a household is considering installing micro-CHP, it is likely that the house is new-build, or the existing heating system is old and about to be replaced. In either case, the only alternative would be a condensing gas boiler,[44] as lower efficiency systems have been outlawed. It is widely accepted that the best available heating system is used as the alternative, and so a typical condensing boiler was considered in this study.

The efficiency of condensing boilers is advertised at up to 109% (equivalent to 96% HHV), however these laboratory measured figures are not matched in real-world usage. Two UK field trials have shown the efficiency of 'A-rated' boilers to average 82-89% HHV, 4-5% lower than their performance in the laboratory.[19] These boilers were also found to use around 10Wh of electricity for every kWh of heat produced (-1% electrical efficiency), consuming 225 kWh per

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[44] Excluding microgeneration systems or heating systems based on other fuels; neither of which are as widely available or cost effective.

year on average. CO_2 emissions from the reference heating system were therefore taken to be 210-230g per kWh of heat produced.

The reference source of electricity was the national grid in the UK, but as mentioned in Section 3.2.2 it is difficult to define this collective source accurately. This does not impact on economic calculations, as electricity is priced according to static tariffs determined by utility companies, and does not depend on the actual source of power. The environmental impact of the fuel cell is however highly dependent on the specific power station that is displaced, as carbon emissions are directly linked to the individual power sources rather than the overall average.

This presents a substantial complication to calculating the actual CO_2 emissions abated, as there is no simple way to determine which power station will reduce its power output because the fuel cell is operating. There are many models of the electricity grid detailed in literature, for example [218, 219]. These give an estimate of which plants would provide marginal generation throughout the day, and thus what CO_2 emissions would actually be displaced. Integrating this type of modelling into the results of this study is suggested as further work, as it could not be completed within the time constraints of this project. The chosen cost and carbon emissions from electricity generation are defined in Chapter 6.

4.3. Presentation of Data

4.3.1. Fuel Cell Performance

Appendix A presents a meta-review of the current technological status of fuel cells for small stationary CHP. Approximately 150 academic and commercial sources were consulted and classified into data inputs for the fuel cell simulation model, giving an industry-wide assessment. The rationale for conducting this review was that data must be aggregated from as many sources as possible to assess how the plurality of future fuel cell systems would impact on the UK. Only considering the performance of a single product (or worse, using general estimates) would give simulation results that only related to that one product.

Seven categories of data were considered; of which the efficiency, lifetime and degradation rates are summarised in Table 4.3. The real-world performance of state-of-the-art systems was sought from data taken from field trials wherever possible; giving the performance actually experienced by users, rather than quoted by manufacturers. Both commercial and research systems were considered, so long as they could eventually be suitable for a micro-CHP product.

Due to the vast differences in research activity for each fuel cell technology, there was a wide range in the quality and availability of sources. Much of the PEMFC data came from the extensive field trials in Japan, which were heavily relied on due to their relevance to this study. More of the SOFC data was found in academic publications, as commercial demonstrations have only recently begun. Studies of PAFC and AFC systems were much less common, coming mostly from related products (industrial CHP systems) and publications that are over a decade old.

The reviewed data were modified where appropriate to give a standardised view of each technology and to avoid biased comparisons. For example: quoted efficiencies were all converted to HHV, and the losses from fuel processing, power inversion and parasitic loads were estimated for studies which did not include them. In compiling the averages and standard deviations presented in Table 4.3, a semi-quantitative weighting method was developed to favour data coming from more relevant sources. This was analogous to the data quality indicators (DQI) used in life cycle assessment, in that it promoted data from more recent and representative sources such as field trials, as opposed to highly controlled lab experiments or marketing material. This method is discussed fully in Appendix A, as are the individual results presented.

	PEMFC	**SOFC**	**PAFC**	**AFC**
Initial performance at full power:				
Net electrical efficiency	26.7 ± 3.5%	34.7 ± 4.5%	32.5 ± 3.3%	29.7 ± 2.6%
Total system efficiency	66.9 ± 6.6%	72.4 ± 4.4%	72.0 ± 4.0%[45]	66.6 ± 6.0%
Heat to power ratio	1.51 ± 0.23	1.09 ± 0.14	1.22 ± 0.15	1.24 ± 0.16
Thermal utilisation *(ν_{th})*	0.55 ± 0.07	0.58 ± 0.04	0.59 ± 0.07	0.52 ± 0.07
Part load efficiency:				
Variation in electrical and thermal efficiency with load factor *(L)*	$\eta_{el} = -0.220 + 5.277L - 9.127L^2 + 7.172L^3 + -2.103L^4$ $\eta_{th} = 0.900 - 0.070L + 0.170L^2$ *(valid for $0.2 \le L \le 1.0$)*			
Durability and degradation:				
Voltage degradation *(μV/h)*	8.0 ± 7.8	12 ± 16	2.6 ± 1.3	19.5 ± 9.4
(per 1000 hours of operation)	1.2 ± 1.1%	1.7 ± 2.3%[46]	0.4 ± 0.2%	2.9 ± 1.4%
Rate of electrical efficiency loss	*Same rate as voltage loss, with maximum power output also decreasing*			
Rate of thermal degradation	*Assumed to be 0.5-1.0% per year*			
Operating lifetime *(kh)*	19.7 ± 10.0	11.3 ± 7.1	58 ± 15	6.7 ± 1.9

Table 4.3: The performance inputs for each technology that were used in the fuel cell simulation model. For each entry, the mean and standard deviation of the consulted sources is given; and where values had been calculated (i.e. the HPR, ν_{th} and lifetime average efficiencies) these ranges were propagated to give a standard deviation in the calculated value. All efficiencies are given against HHV of natural gas.

4.3.1.1. Operational Lifetime

The functional lifetime is a crucial and contentious issue for the commercialisation and economic viability of fuel cell micro-CHP systems, and is one of the characteristics which varies most between designs. The de-facto target of 40,000 hours continuous operation has hung over the industry for nearly a decade, only being attained in the field by industrial PAFC systems from UTC and Fuji.[40, 220] Figure 4.2 shows that the demonstrable lifetime of PEMFC systems is gradually moving towards this target, but SOFC and AFC appear to have stagnated with stack tests not lasting for more than 10,000-20,000 hours for SOFC, or 5,000-10,000 hours for AFC.

Manufacturers of ENEFARM expect that their new generation of PEMFC systems is now able to meet the 40,000 hour target,[221] however as none of these units have been operating for more than a year in the field it is impossible to verify their claims yet. The longest reported lifetimes so far from the Japanese field trials have been around 20,000 hours.[189, 198, 222, 223]

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[45] The total efficiency of industrial PAFC systems is 70-78% HHV. The lower end of this range was taken for micro-CHP systems, as thermal efficiency in other technologies falls with capacity.[19]

[46] Due to the skewed distribution of SOFC degradation rates (which are usually either zero or ~5% per kh) the standard deviation is larger than the mean. Degradation rates were capped at a minimum of zero.

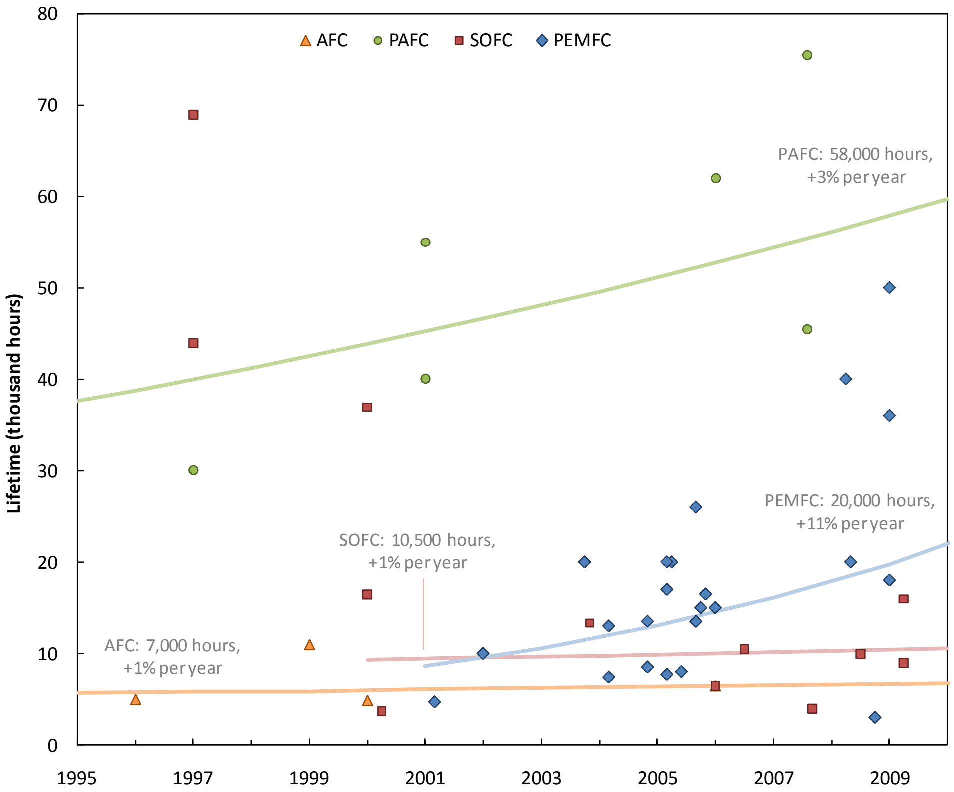

Figure 4.2: The improvement in demonstrated stack and system lifetimes of different fuel cell technologies over the past 15 years. Data points indicate individual results reported in literature, and weighted exponential fits are shown for each technology, with a label giving the rate of improvement, and estimated average lifetime as of 2009.

The longest SOFC lifetimes were demonstrated in the often cited work at Siemens-Westinghouse in the late 1990s.[45, 47, 224] Evaluations of fuel cells which are based on this achievement make the leap of faith that if two cells can operate at steady-state in a laboratory for 69,000 hours, then a complete system in the dynamic environment of a house should be able to as well.[122] The proceeding decade of research has not managed to achieve this stiff technical challenge, and system lifetimes have remained under 15,000 hours since. The latest Japanese roadmap for SOFC technology predicts that 10,000-20,000 hour lifetimes should be attainable by 2015, and that 40,000 hours is not expected until after 2020 for domestic systems.[98, 101] Although manufacturers outside of Japan are more optimistic about these time scales, none have yet demonstrated a product that is close to achieving these targets.[225, 226]

Nevertheless the lifetime of systems continues to improve, and the systems which are currently being deployed will be capable of longer operation than has been seen in demonstrations up until now. It would be short-sighted to only consider the lifetimes shown in Figure 4.2, so the current targets for each technology were therefore used as part of a sensitivity analysis. These would show what benefits each technology should obtain *if* it can meet the current expectations for system lifetime:

- For PAFC systems, approximately 80,000 hours is projected for the new generation of industrial CHP systems [168, 227];
- The Japanese PEMFC roadmap and ENEFARM manufacturers expect 40,000 hours [88];
- For SOFC systems, the near-term Japanese target of 20,000 hours is considered;
- For AFC systems, a 20,000 hour target was arbitrarily chosen,[47] as this was the upper limit seen in past demonstrations [152, 228].

4.3.1.2. Efficiency

Figure 4.3 plots the electrical and thermal efficiency of 48 fuel cell micro-CHP systems, compared to the traditional alternatives available in the UK. It is seen that the efficiency of most fuel cell systems is 5-30% above the best available heat and electricity generation methods; and 20-50% above the average systems currently in place.

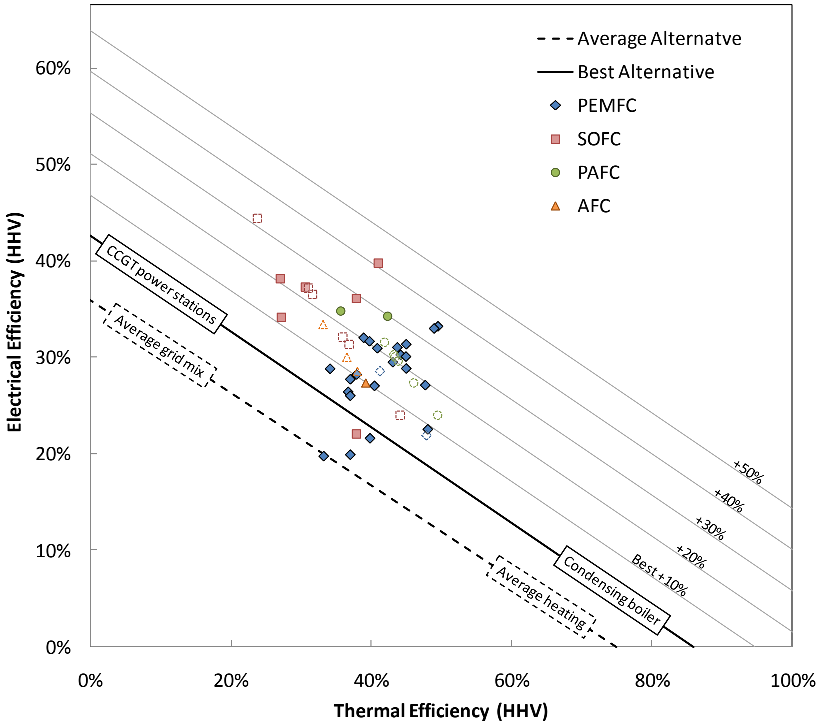

Figure 4.3: Thermal and electrical efficiency of fuel cell CHP systems, plotted against lines that connect the electrical and thermal efficiency of the traditional alternatives available in the UK. Hollow data points represent systems for which only the electrical efficiency was known; thermal efficiency was estimated from the average total efficiency that has been demonstrated for each technology.

Twelve sources were found which had measured the efficiency of complete fuel cell systems (as opposed to only the stack) at different levels of power output. The part-load efficiency of each system is plotted in Figure 4.4 relative to its efficiency at full power. It is clear that across nearly all products electrical efficiency falls as power output decreases, and the thermal efficiency of

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[47] This is no guarantee that current or near-future AFC systems could achieve this lifetime, and was used in the absence of any roadmaps or commercial targets for the technology.

domestic-scale systems is either constant or also falls. The quadratic formulae given in Table 4.3 were fitted to these sets of data using unweighted least-squares minimisation.

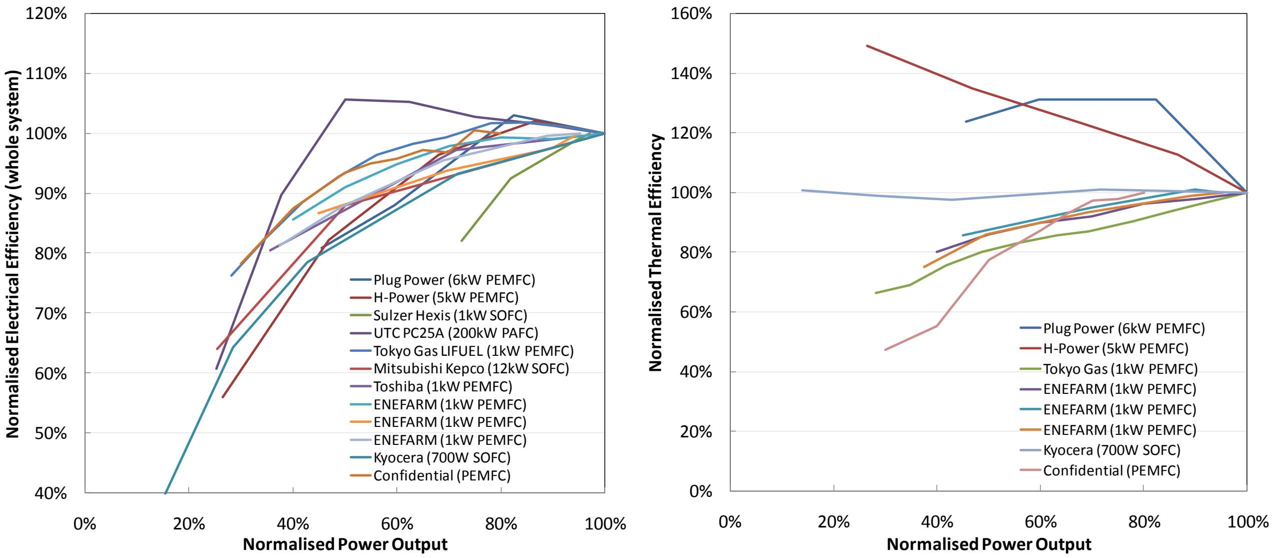

Figure 4.4: Whole system electrical and thermal efficiency (including fuel processing, inverters and parasitic loads) of different fuel cell CHP systems, measured against power output. The efficiency of each system is presented relative to its full-power efficiency.

4.3.1.3. Operating Constraints

While fuel cell stacks by themselves have very good transient performance, the operation of a micro-CHP system is more limited.[229] There are constraints on how rapidly a system can start up and stop, and whether it is even possible to shut down without causing permanent damage. As part of the performance review given in Appendix A, some typical limits on operation were found:

- A minimum operating power of 20-40% of the full output (a turndown ratio of 0.2-0.4);
- A minimum start-up time of around 1 hour for PEMFC systems;[48]
- A requirement for SOFC to avoid shutdown cycles due to mechanical stress in the ceramic cells, therefore the system should hot-idle when no power is required;
- A similar requirement for PAFC systems due to the electrolyte solidifying below 42°C, however idling on load should also be avoided as electrodes corrode above 0.8V.[40]

These constraints were incorporated into the simulation of each technology, but as in previous studies they were not found to have a significant impact on the operational performance of systems.[43, 204] The time and energy required for start-up were modelled more specifically on the characterisation of the Baxi Beta 1.5 Plus system presented in Appendix B, as data from

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[48] Start-up times for 1kW class AFC systems could not be found, and so were assumed to be the same as for PEMFC.

other systems was particularly lacking. The start-up time for PEMFC and AFC was calculated from the time since the unit had previously shut down *(T)* as in Equation 4.3. The amount of energy required to start up was calculated from this using the observation that natural gas is consumed at a rate of 1.5kW during the whole start-up period.

$$Startup\ Time = \begin{cases} 0.5 \ \ for \ \ T < 10 \\ \log(T) - 0.5 \ \ for \ \ 10 \leq T \leq 100 \\ 1.5 \ \ for \ \ T > 100 \end{cases} \tag{4.3}$$

The start-up of PAFC and SOFC systems (in particular) would require substantially more energy due to the time required, however this was not modelled as they were assumed to remain operational over the entire year of simulations. With current systems, this would rely on the centralised electricity supply being uninterrupted for a whole year, as additional equipment is required to support grid-independent operation.[230, 231]

4.3.2. Domestic Energy Profiles

Time-series data of energy consumption measured in individual UK homes was acquired from the two sources mentioned in Section 4.2.2: the BRE Milton Keynes Energy Park and the DTI photovoltaic field trials. Each data set was received in the form of thousands of data files (either in CSV or XLS format), which totalled 600MB for the BRE data, and 7GB for the DTI. Each file contained measurements from various loggers installed in the homes,[49] with one set of readings per line.

Both sources included over 100 homes, making them orders of magnitude larger than the data sets used in previous studies. However neither source was without its faults though, meaning that both had to be used in order for the strengths of one could counter weaknesses in the other.

4.3.2.1. Issues with Data Quality

The energy profiles used in this study had to give a broad, unbiased and accurate representation of the UK housing stock; so there were several aspects of their quality which needed review. Table 4.4 compares the BRE and DTI data sets against the ideal candidate over several categories. The DTI data was generally good, having been collected within the last 5-6 years with high resolution; however it lacked thermal demand from the properties. The BRE data gave gas as well as electricity consumption, but was generally poorer in other respects.

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[49] The BRE data contained readings for the cumulative gas and electricity demand along with date and time; the DTI data gave various readings relating to the solar panels (irradiation, temperature), the AC output of the panel, and amount of power imported and exported – from which the total demand from the building could be calculated.

	Ideal Profile	**BRE data**	**DTI data**
Sample size:	At least 1000 houses[50] 1 or more years of data	130 houses *(102 useable)*, mean 120, range 5-600 days	217 houses *(157 useable)*, mean 417, range 32-678 days
Sample distribution:	Broad and unbiased, representing the whole UK housing stock	A range of 2-5 bedroom low-energy homes built in 1987.[51] Average floor area was 60-120m^2.	A broad range of houses, bungalows and flats throughout the UK.[52]
Data type:	Heat + Electricity	Gas + Electricity	Electricity only
Data resolution:	Highest possible, maximum 1-5 minutes	60 minutes	5 minutes
Continuity:	Continuous and uninterrupted data	Average of 8% corrupt or missing data per profile.	13% of profiles completely corrupted, average of 12% missing or corrupt data in remaining files.
Reliability:	Accurate and consistent data quality	Offsets and anomalies were present throughout. Without filtering, overall results were skewed due to spurious power flows of several hundred MW.	

Table 4.4: Comparison of quality indicators for the ideal data set and those used.[208, 211, 232]

The DTI data was measured at (or better than) the resolution recommended by Hawkes and Wright for energy modelling, and was the most finely-detailed that was available.[130, 131] Electricity data from the BRE set was not directly used, as the 1-hour resolution would lead to inaccurate results from modelling. Having hourly resolution for thermal demand was not commented on directly by Hawkes or Wright, who focussed only on the importance of electrical demand. It was not considered a great problem as large hot water tanks act as a thermal buffer, providing at least an hour's leeway over the exact timing of heat production.[53]

By far the biggest and most time-consuming problems with the data sets were with reliability and continuity. Reliability was generally poor due to the nature of data collection in the field; profiles were missing blocks of data ranging from individual samples to several months, and substantial portions of data were unusable due to corruption.

The BRE data were originally recorded on 5¼-inch floppy disks nearly two decades ago, some of which had since been damaged or lost.[211] The data set was therefore punctuated with gaps and erroneous lines; for example with invalid timestamps, property ID codes, or individual readings. Despite being collected some 15 years later the DTI data was no better, as faults and interference with the logging equipment meant that more gaps and anomalies were experienced. The actual demand of the building was not directly measured, and had to be inferred from three

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[50] If we assume that the results from a simulation model follow a Gaussian distribution when using different profiles, the error in the sample mean will follow $\sqrt{N}/N$ - and thus will fall to 3% when $N = 1000$.

[51] These homes were built to well above building regulations at the time, having double glazing, up to 100mm of under-floor insulation and low U-values for walls and roofing.

[52] While broad descriptions and photographs of each project were published, detailed demographic data (number of occupants, floor area) were not.

[53] Heat demand will generally peak at a 25kW (the capacity of a typical condensing boiler), and so 1 hour of peak demand could be provided by the capacity of tank used with fuel cells (~500L). Therefore, it wouldn't matter if a five minute peak of 24kW thermal demand was smeared to 2kW over the course of an hour, as the fuel cell would not have to provide the 24kW instantaneously as it would do with electricity demand.

other readings.[54] An omission or error in any of these channels would corrupt the demand for that timestep, meaning the proportion of useless data was higher than for the BRE set.

Both data sets needed rigorous processing in order to ensure that they represented the actual energy demand of the houses and that results were not skewed by anomalies. Several dozen programs were written in PHP and C++ to re-order, analyse, display, filter and repair the files. Each program performed a single task (such as searching for gaps, checking heuristics, or removing data entries) and over the course of 4 months the data was processed into its final useable form.

As there were no houses with an uninterrupted year of valid data, a smaller contiguous block had to be acceptable. Days running from 00:00 to 23:55 were required as the minimum uninterrupted block of time, in order to retain the day/night pattern of demand and the ability to merge profiles of different resolutions. An entire year was still required as the ideal profile length, so that the seasonal trend in demand was correctly represented. Shorter profiles would give skewed results – for example 2 months in winter would have higher than average demand, and thus better performance from the fuel cell. A maximum of 14 missing days within the year was accepted, giving <4% deviation from the whole year and still allowing a reasonable number of profiles to be useable. As most of the profiles had been recorded for over a year, they were either split into two separate profiles of one year each (if above 1.5 years), or truncated to one year.

4.3.2.2. Scaling Demand Amount

Despite being relatively large data sets, the demand data only represented a very small sub-set of the UK domestic building stock – just 0.001%. While the DTI data came from a broad range of houses, the BRE data was very specific as all of the houses were the same age and niche design. The data provided on gas consumption would therefore not represent the average or the range seen in UK homes.

An additional complication to this was the fact that gas consumption was given rather than heat demand. Houses in the energy park used varied heating systems such as prototype condensing boilers and mechanical ventilation, and the efficiency of these was not measured at the time.[233] The heat demand from these homes was arbitrarily taken to be 75% of the amount of

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[54] Demand was calculated from the AC output of solar panel + imported electricity – exported electricity.

gas consumed, and therefore the absolute amount of heat demand could not be considered accurate. The variation of this demand over time was still considered valid, as times of heat production and gas consumption would not have been affected.[55]

The average energy demand from UK homes was therefore found in order to give a frame of reference against which the data sets could be compared. The data presented in Table 4.5 were collected from the standard consumer profiles produced by EnergyWatch[56] [234]; four building simulation studies reviewed at the Tyndall Centre [108]; measured data from two field trials [31, 235]; and national statistics gathered by the BRE.[13] The three profiles represented a 20:60:20 ratio of the UK housing stock, meaning their values were treated as the median, 10th and 90th percentiles of energy demand. Table 4.6 gives statistics for the annual energy demands from the DTI and BRE data sets for comparison.

User profile	Annual space heating demand (kWh)	Annual hot water demand (kWh)	Annual electricity demand (kWh)	Annual carbon emissions (kg CO_2)
Low	6,000	2,500	1,500	2,850
Medium	13,000	4,000	3,000	5,700
High	20,000	5,500	5,000	8,850

Table 4.5: Average energy demands and carbon emissions from UK houses. The three profiles roughly corresponded to small flats (low), terraced and semi-detached houses (medium), and larger detached houses (high).

	DTI data	**- - - - - - -**	**BRE data**	**- - - - - - -**
	Electricity (kWh)	**Electricity (kWh)**	**Heat (kWh)**	**Annual HPR**
10th percentile	1,287 (-14.2%)	1,596	8,037 (-5.4%)	3.023
Mean	3,055 (+1.8%)	3,224	12,465 (-26.7%)	4.729
90th percentile	5,332 (+6.6%)	4,714	20,091 (-21.2%)	6.887
Minimum	1,021	966	7,200	0.966
Median	2,493	3,105	12,257	4.473
Maximum	14,074	6,497	29,088	6.497

Table 4.6: Annual energy demands from the two data sets.
Figures in brackets show the relative difference from the user profiles given in Table 4.5.

Houses in both data sets consumed similar amounts of electricity to those nationwide, with the DTI mean differing by less than 2%. The estimated heat demand from the BRE data was somewhat lower than the national average and the range more limited, presumably due to the similar construction of the houses monitored. Figure 4.5 shows that the annual energy demand from each set of properties roughly follows a log-normal distribution,[57] however the BRE data provides a more limited fit to an ideal straight line due to the size of the data set. There is significant variation between the amount of energy demanded in different properties, and a

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[55] The only caveat to this was the use of gas for cooking, although this only accounts for 3% of annual gas demand.[13]

[56] The amount of heat required was taken from figures for natural gas consumption, assuming that 3% of gas is used for cooking, and the remainder is burnt in a boiler of average efficiency (75% HHV).[13]

[57] See [236] for examples of other physical and social phenomena that follow log-normal distribution. In this case the logarithm of annual energy demand from each house approximates to the normal distribution.

general correlation between electrical and thermal demands measured in the BRE houses, as shown in Figure 4.6.

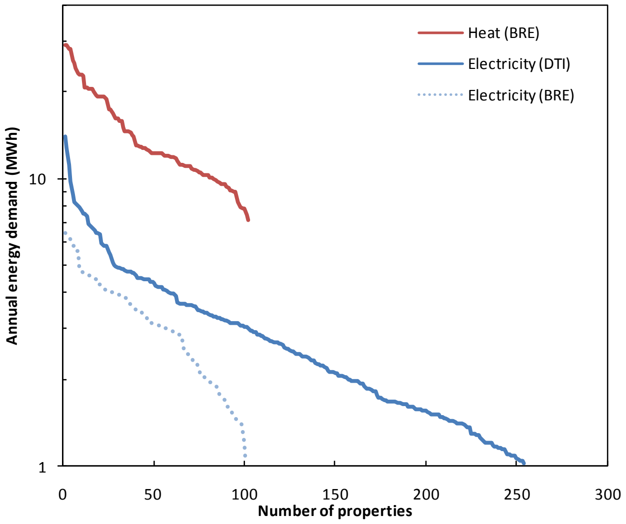

Figure 4.5: Annual energy demand measured from the two data sets, plotted in descending rank order.

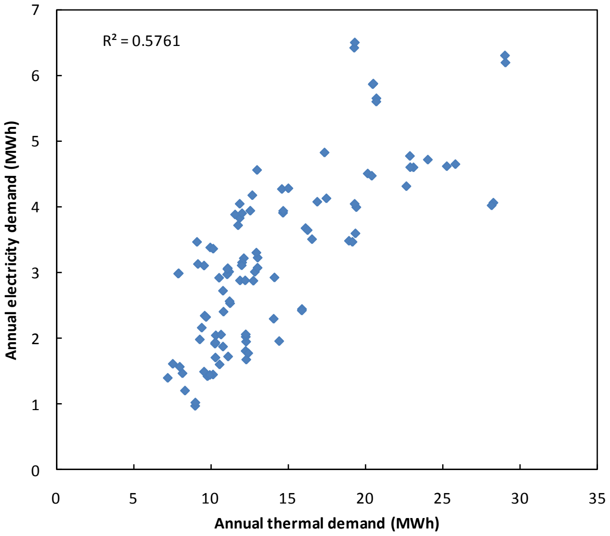

Figure 4.6: Electricity and thermal demands from the BRE data set.

Thermal demands from the BRE profiles (D) were scaled with the following factor: $f = 1.364 + 1.277 \cdot (D - \overline{D})$, such that absolute demand increased by 36.4%, and the standard deviation around the mean was increased by 27.7%. These values were chosen to match the 10th and 90th percentiles to the low and high user profiles given in Table 4.5, and the mean to the average profile. Electricity demand was not scaled, as the DTI data fit reasonably well with the national average demand. Furthermore, applying a simple linear scale-factor to electricity profiles would not be appropriate, as the distribution of electricity demand would not be linearly higher at all times in a larger house. Higher annual demand would come from a complex mix of peak-power items (tumble driers, electric heaters) being used more often, and higher minimum baseload from always-on or standby equipment. These considerations were not expected to apply so strongly to thermal demand, again because of the buffering effect of the hot water tank.

4.3.2.3. Merging the Data Sets

In order to use the best available data from both sets, the BRE thermal profiles needed to be ‘married’ to the higher resolution electricity profiles from the DTI data. No demographic information was available for the houses in the DTI data set, so there were no markers such as floor area or number of occupants that could be used to match profiles. The only common factor between the DTI and BRE data was the time-series of electricity demand in each property.

A statistical method was therefore developed to judge the similarity of electricity profiles by comparing the total annual demand, the distribution of this demand, and the rate of variation over time. The sum-squared difference between each point on the load-duration curve of each house (instantaneous demand ranked in descending order) was used to assess the distribution as shown in Figure 4.7. The change in demand between each time-step was used to assess the variability,[58] and the sum-squared of the forwards-difference ($\sum \Delta^2$) was calculated.

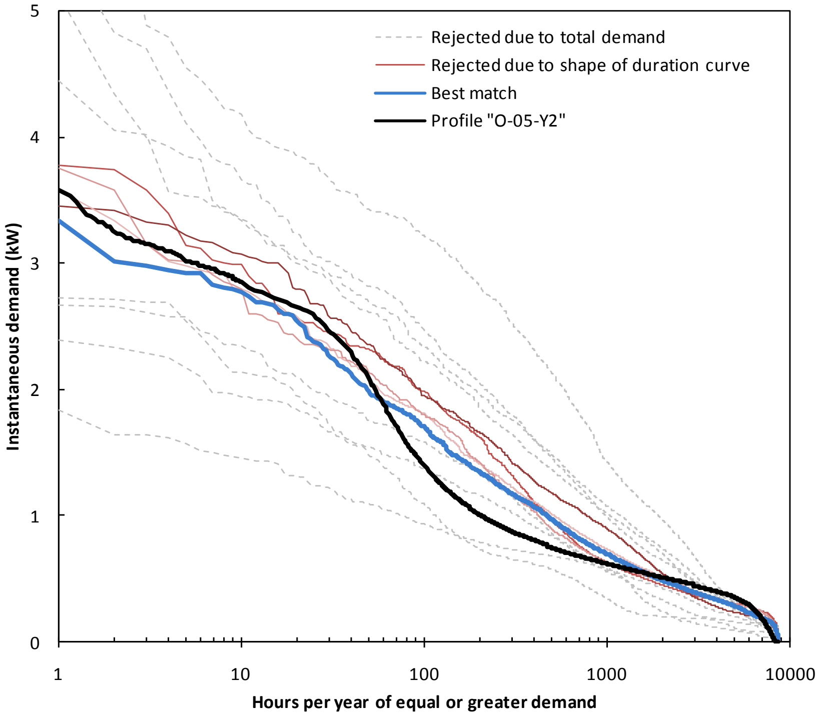

Figure 4.7: An example of matching the load duration curves from a DTI electricity profile (thick black line) and a selection of BRE profiles. Outliers shown as dotted lines were rejected as total energy demand over the year deviated by more than 5% from the DTI total. The five profiles with similar demand levels were analysed based on the shape of the duration curve, and the best match was chosen.

A fuzzy matching algorithm was written to automate this process, whereby the sum-squared difference between each of these three metrics was calculated for each pair of profiles and compared to a maximum allowable threshold. The threshold value was varied by introducing a small amount of random noise, so that the matching process was semi-stochastic and merged more than just the numerically optimal profiles. Broadening the matching criteria in this way was seen as a way to ameliorate the fact that there was no guaranteed way to produce the most accurate representation of high-resolution demand data from the BRE homes. The threshold and level of noise were set according to how many output profiles were desired.

Once pairs of matching profiles had been chosen, the data from each was merged into a single file. The heat demand from the BRE data was up-sampled to 5 minute resolution by simply

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[58] To be comparable with the BRE data, the DTI profiles were down-sampled to 60 minutes for this calculation.

replicating the power demand over each 5 minute window in that hour. The starting position of the BRE data was moved backwards or forwards to give the best alignment to the DTI data as shown in Figure 4.8. As the profiles were usually of different lengths (ranging from 351 to 379 days), the heat demand data was either wrapped around, or shortened to match the length of the DTI data.

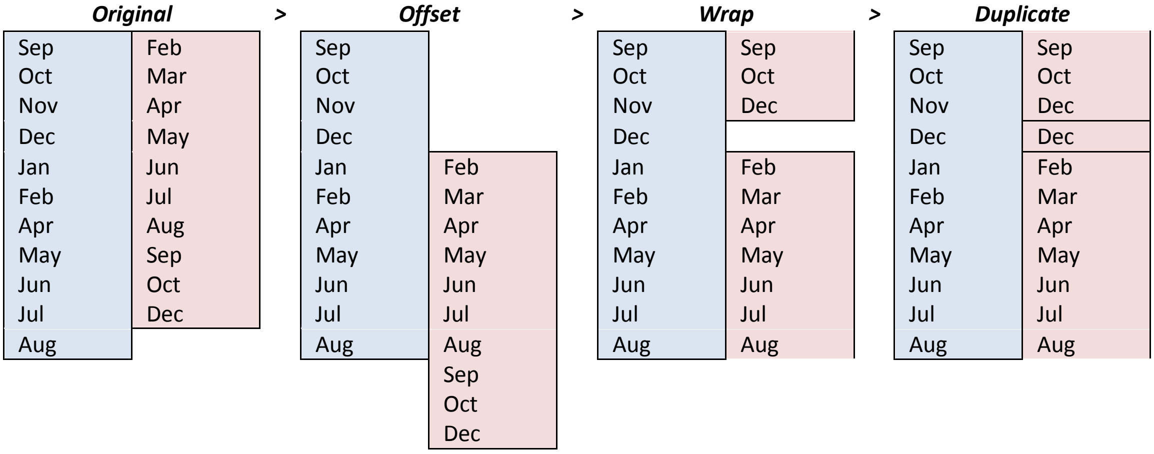

Figure 4.8: Graphical representation of the stages used to match thermal profiles (red) to electrical profiles (blue). For the sake of simplicity, the unit size is shown as a whole month, with March missing from the electrical profile, January and November missing from the thermal profile. The offset was chosen so that the deviation between each unit was minimised, so February was matched with January, so that 7 months of data were aligned.

The results of this process were validated in two ways. The fuzzy matching algorithm was run five times to produce different merged data sets, each with different matches due to the stochastic element. A fuel cell was then simulated with each of these data sets, and yielded results with no significant statistical difference. These data sets were then down-sampled to hourly resolution and compared to the original BRE data (both heat and electricity demand), and again yielded the same results.[59]

4.3.2.4. Characterising the Final Data Set

The final data set used in the following chapters was produced by tuning the tolerance in the matching algorithm to give 1,000 merged profiles. A uniform distribution of the DTI electrical profiles was optimally matched with the scaled BRE thermal profiles. There were typically 4-5 repetitions of each electrical and thermal profile, as the source data sets only numbered 250 and 200 house-years respectively. No two combinations of electrical and thermal profile were allowed to be the same however, so each of the 1,000 merged profiles was unique. Four examples of these are shown in Figure 4.9.

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[59] For example, the fuel cell generated 82±10%, 80±10%, 82±9%, 81±8% and 83±10% of the electricity used by the houses in each of the five data sets (at hourly resolution – without scaled thermal demand); compared with 82±10% in the original BRE data set.

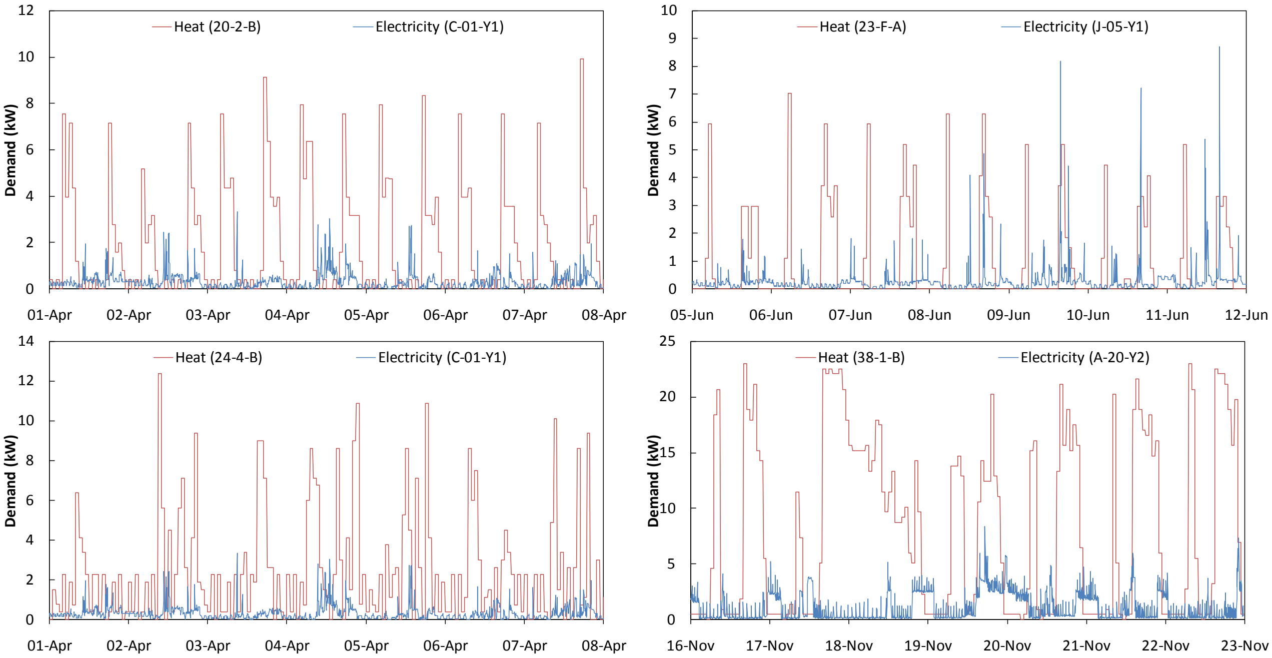

Figure 4.9: Demand data over the course of a week taken from a random selection of demand profiles. The two figures on the left show different thermal profiles matched to the same electricity profile, while the two on the right show the range of energy demands from different houses in summer and winter.

Figure 4.10 plots the annual electrical and thermal demands from each profile in the same manner as before in Figure 4.6, showing the same general correlation between the two. Profiles are seen with higher levels of demand than in Figure 4.6 due to the impact of scaling thermal demand, and because the DTI data included several houses with over 7MWh of annual electrical demand.

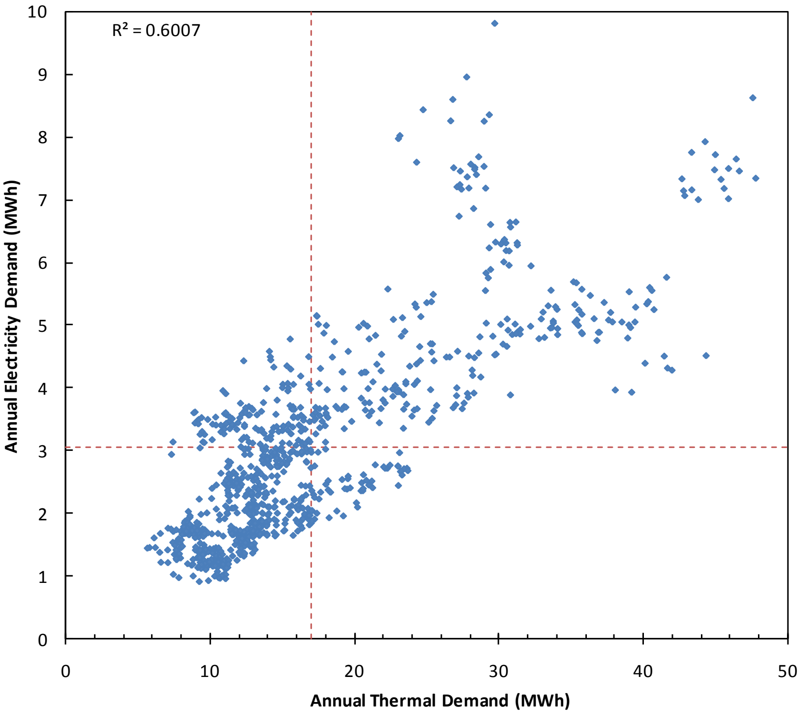

Figure 4.10: Annual electricity and thermal demand from the 1,000 combined profiles, with lines showing the averages.

The annual demands from each profile are plotted in descending rank order in Figure 4.11, showing that both electricity and heat approximate to a log-normal distribution, just as the individual data sets did in Figure 4.5. Annual electricity demand varies by a factor of 12 between properties, and thermal demand by a factor of 6. Electrical demand is reasonably constant throughout the year, however there is a strong seasonal trend in thermal demands, as shown in Figure 4.12.

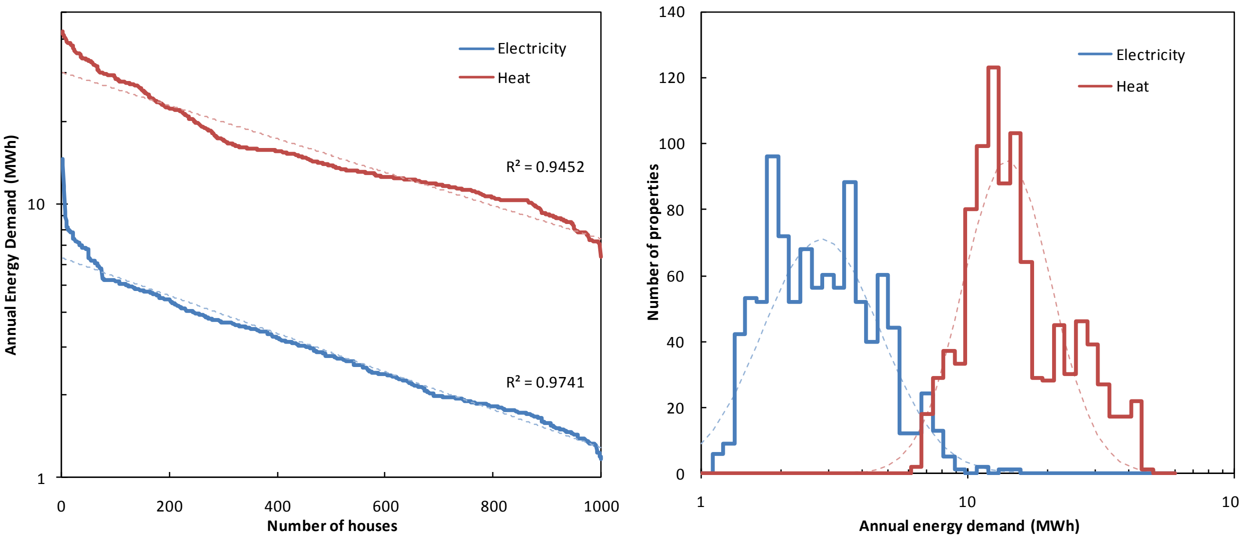

Figure 4.11: Annual energy demand from each house ranked in descending order (left), and histograms of energy demand against number of properties (right). The approximation of this histogram to a log-normal distribution is shown in both plots by the dotted lines. Electricity demand provides a good fit, however there is a slight excess of properties with high thermal demand.

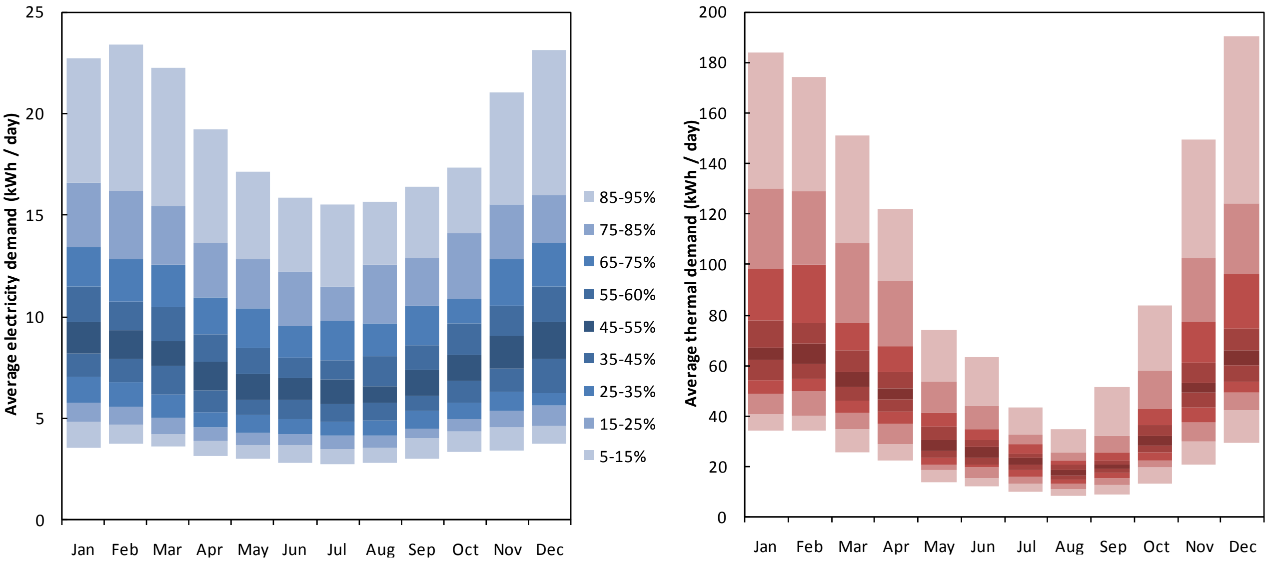

Figure 4.12: Fan charts showing the distribution of average energy demands across each month. Each band shows the range of percentiles from the 1,000 profiles.

Load-duration curves were produced for the individual energy profiles, which are plotted on log-normal axes in Figure 4.13. For each house, the energy demanded at each time step was ranked in descending order, giving the number of hours for which demand in each house is equal or greater than a given value. Many of the houses were seen to use high-power devices occasionally, causing a step change in electrical demand up to around 10kW for a small portion of the year. Possible sources would be immersion heaters to supplement the hot water tank (running for hundreds of hours per year), or items like kettles and hair-dryers running frequently for a short period.[60]

The thermal energy demand per day was not seen to follow a log-normal distribution as closely as electrical demand, as seen by the much flatter curves in the right hand plot of Figure 4.13. Within each property, a similar amount of heat was demanded on the 30-100 coldest days of the year, and only beyond that demand fell log-linearly to a minimum value during summer when there was only demand for hot water. There was reasonably good correlation between heat demand and property size as would have been expected: ~90% of profiles from 2 and 3 bedroom properties (shown in red) demanded less heat than those from 4 and 5 bedroom properties (shown in orange).

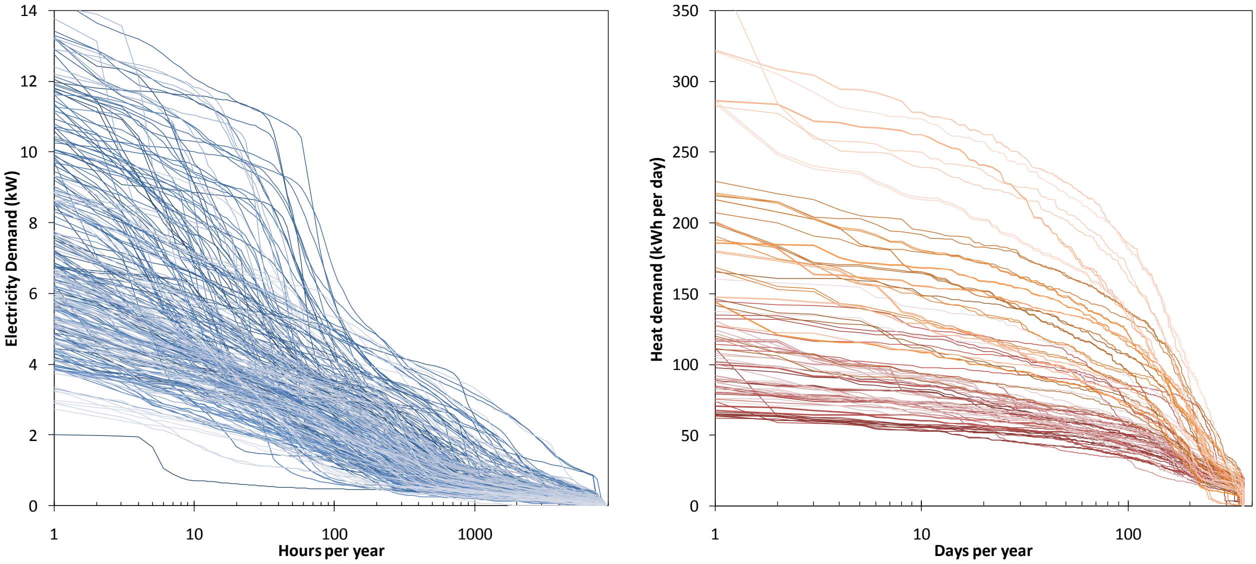

Figure 4.13: Load duration curves for the 273 electricity profiles and 100 thermal profiles that were used. Energy demands are plotted against the amount of time per year where there is equal or higher demand. Thermal profiles were split according to the number of bedrooms in the house, with red lines indicating 2-3 bedrooms and orange meaning 4-5.

If a horizontal line is drawn across the electrical duration curves in Figure 4.13 at a value of 1kW, the point at which this line intersects each curve gives how many hours per year the demand exceeded 1kW. For this number of hours, a typical fuel cell would have to be supplemented with additional electricity from the grid. Subtracting that from 8760 would give the number of hours per year the house could be fully self-sufficient with the fuel cell generator.

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[60] For example, boiling a kettle twice a day for 2 minutes would result in a 2-3kW spike lasting ~24 hours per year.

The number of self-sufficient hours was calculated for each of the 1000 profiles with a range of fuel cell capacities from 0.2 to 2kW. The spread of results is presented in Figure 4.14 as a fan chart. It can be seen that for three-quarters of UK homes, a 0.7 or 1kW fuel cell would be able to provide all of the electricity demand for 85-90% of the year.

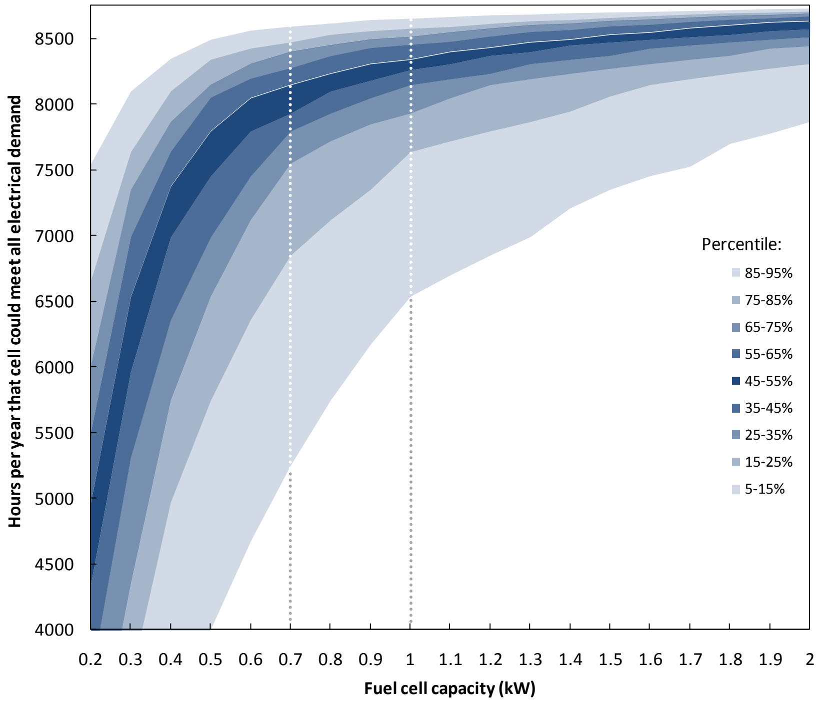

Figure 4.14: A fan chart showing the number of hours of grid independence (no need to purchase electricity) that could be offered by a fuel cell of different output capacities. The difference between 0.7 and 1.0kW fuel cells is highlighted, and only becomes significant (> 500 hours) in the largest 15% of homes.

Similarly, Figure 4.15 shows the number of days per year that a fuel cell would be able to provide the entire heat demand of the house. This shows that supplementary heating is required for a far higher proportion of the year due to the low HPR of the fuel cells relative to UK houses. The difference between a 1kW PEMFC and a 0.7kW SOFC (i.e. ENEFARM and Kyocera) is more pronounced than for electrical self-sufficiency, as the higher HPR of PEMFC systems means they can produce twice as much heat as the slightly smaller SOFC. A 1kW PEMFC system could therefore be expected to provide all of the heat demand for only 35-55% of the year, compared to just 0-30% of the year for a 0.7kW SOFC.

The estimates of 17 and 36kWh heat output per day assume the fuel cell was running constantly at full power. If previously stored heat could be drawn from the hot water tank, these fuel cells would be able to provide more heat (for example an extra 20kWh from a 400L tank). However, if the tank was emptied there would be no stored heat to use on the following day – and it can be expected that demand would be reasonably continuous throughout the winter season.

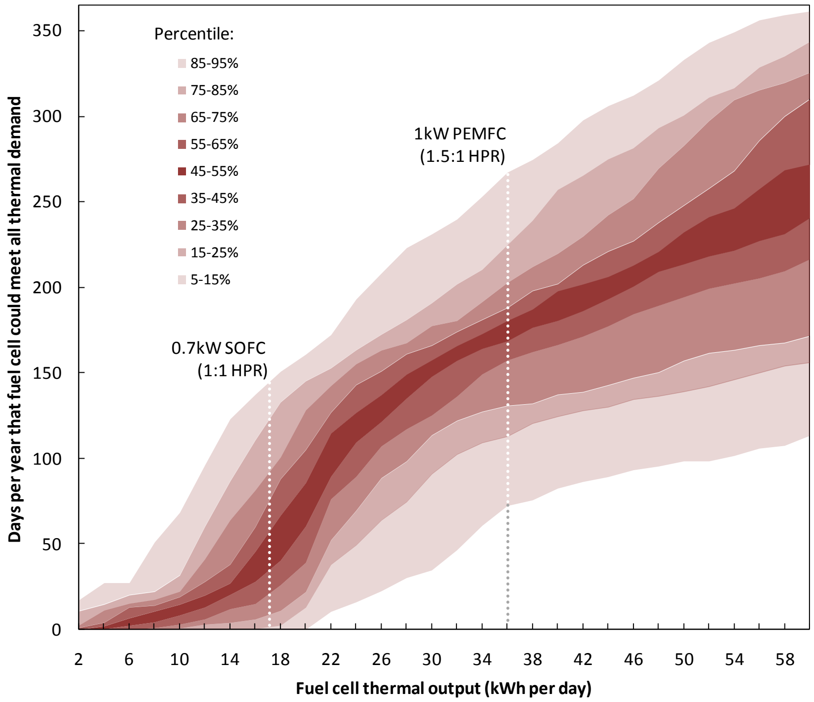

Figure 4.15: A fan chart showing the number of days when no supplemental heating would be required, based on the daily thermal output from a fuel cell.

4.4. Method of Simulating Fuel Cell Operation

4.4.1. Design of the FC++ Simulation Program

Existing simulation models did not match the particular aims of this study or were not freely available to modify, so a new program was written to simulate the operation of fuel cell micro-CHP systems. This program (referred to as 'FC++') was written in Object Oriented C++, and has been released as open source software for future development by any interested parties.[237]

Fast execution was a high priority for the design, allowing large data sets to be simulated with extensive Monte Carlo sensitivity analyses. The models mentioned in Section 3.2 were not designed with high data throughput in mind, and so would have proven more difficult to adapt than starting from scratch. This design philosophy demanded that complexity was minimised and streamlined code was written; which had the added benefits of making the calculation methods transparent and relatively easy for others to use and extend. FC++ can simulate a fuel cell and other equipment running in a house for one year in ~1.5 seconds,[61] compared to 4 minutes for a MATLAB simulation developed by Pawlik *et al.*,[62] and 0.1-10 minutes for the CODEGen optimisation model.[63]

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[61] Using 5 minute resolution demand data on a 2.6Ghz CPU, with approximately 5mb of memory required.

[62] MATLAB simulation using variable step sizes down to a minimum of 1 minute, on a 2.8GHz CPU.[126]

[63] "10 seconds is usually sufficient [for CODEGen to] arrive at a solution for a standard problem. However, for more complex problems that include storage or extensive integer start-up/shutdown constraints, solution times can increase exponentially; usually 10 minutes is sufficient for a tough problem".[238]

To summarise, the program simulates a set of energy generating devices operating in individual houses – for example a fuel cell, boiler, hot water tank, and a link to the national electricity grid. Each device is modelled at a high level, meaning the status and overall efficiency of the fuel cell are calculated rather than individual cell voltages, mass flow rates and temperatures. The important dynamic features of fuel cell performance are captured within the input data, so that part-load efficiency, degradation, transient performance, start-up times and parasitic losses are all accounted for. Using explicit data rather than simulating these effects gives more transparent and robust results, at the expense of requiring the user to have a comprehensive knowledge of the fuel cell (and other devices) they are simulating. This requirement was the driver behind conducting the extensive performance review presented in Appendix A.

The user can specify the types of device that are simulated and their features, such as capacity, efficiency and the strategy (or logic) for operating them. The time-series of energy demands is specified from an external source (i.e. a collection of data files) rather than generated by the program, as in building simulators such as TRANSYS. The program then simulates how the devices would meet this set of energy demands; calculating the instantaneous efficiency of each device, and thus the power flowing between them, and between the house and the outside world. The primary output of this simulation is an estimate of the total amounts of energy (natural gas and electricity) that were used to meet the demands of each house over the course of a year. Some extensions to this include:

- Monte Carlo assessment: repeating the calculations with randomly chosen input parameters (such as efficiencies), each varied within a defined range;
- Integrated calculation of performance and economic metrics, such as fuel cell utilisation and total cost of ownership;
- Simple optimisation of parameters via brute force calculation, for example optimising system capacities and operating strategy to minimise operating costs.

The majority of the 25,000 lines of code used in FC++ are original; however some external libraries and programs have been used:

- **Mersenne Twister** by Makoto Matsumoto and Takuji Nishimura (revised by Rick Wagner), to generate random numbers for the stochastic elements of the program.[64]
- **GenGetOpt** by Lorenzo Bettini, to automate parsing command line arguments;[65]

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[64] http://www.math.sci.hiroshima-u.ac.jp/~m-mat/MT/emt.html and http://tinyurl.com/yaeumqq

[65] http://www.gnu.org/software/gengetopt/gengetopt.html

- **XMLparser** by Frank Berghen, to parse the XML configuration files;[66]
- **CSVParser** by Mayukh Bose, to parse the CSV demand data files;[67]

The program is organised into three general areas which cover the energy generating devices, the control of them, and calculating the results and statistics to describe their operation. Each of these areas is represented by a set of classes,[68] which are depicted by the UML diagram in Figure 4.16.

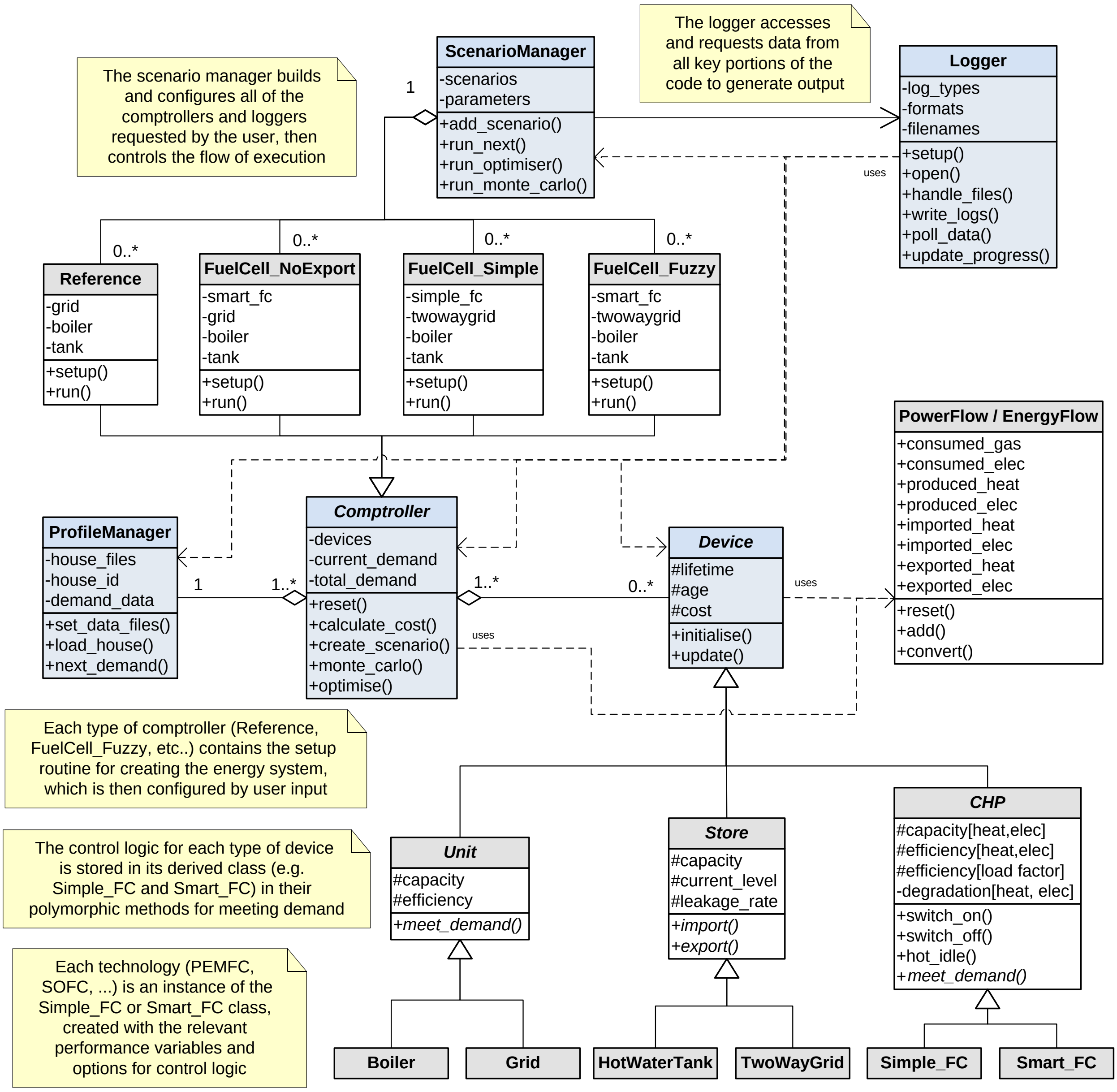

Figure 4.16: A non-extensive UML diagram summarising the core structure of the FC++ program. Each box represents a class, giving its name, attributes and methods, with the most important classes highlighted in blue. Linkages between classes are shown with their usual meanings.[69]

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[66] http://www.applied-mathematics.net/tools/xmlParser.html

[67] http://www.mayukhbose.com/freebies/c-code.php

[68] A 'class' is a structure used to organise the programming code, by encapsulating several attributes (pieces of data) and methods (actions and abilities) into a single object.

[69] For example: a `Smart_FC` is a type of `CHP` which is a type of `Device`; each `Comptroller` contains any number of `Devices` and one `ProfileManager`; various types of `Comptroller` are produced (e.g. `Reference` and `FuelCell_Fuzzy`), which are all stored in the `ScenarioManager`; the `Logger` receives setup information from the `ScenarioManager`, then uses all the other major classes to collect data on the operation. See [239] for a description of UML diagrams.

4.4.2. Devices

Each type of energy generating device is represented by a class, which contains the information and behaviour that is specific to each technology. The class for each device is created with a set of hard-coded default values and options (e.g. the efficiency of the boiler, size of the tank), which are then overridden by the user's configuration file during setup. Three types of device are included in the model: simple units, energy storage and CHP devices – all of which are derived from a single `Device` super-class.

Two types of simple generator are derived from the `Unit` class which output a single form of energy: a condensing gas boiler and a one-way link to the national grid (import only). These hold a value for output capacity and efficiency; part load efficiency was not modelled for the condensing boiler as insufficient empirical information was available. The grid was assumed to be of infinite capacity, and the boiler could either be of fixed capacity, or sized to meet the maximum thermal demand that was required (over and above what was provided from the tank and fuel cell).

Three forms of energy storage were derived from the `Store` class: a hot water tank, batteries, and a two-way link to the national grid. From the point of view of the house, the ability to export electricity to the grid was equivalent to having a remote form of electrical storage with infinite capacity and reserve. This definition produces some counter-intuitive definitions within the model's output files,[70] however it maintains consistency with other devices.

Storage devices can be configured with a value for the capacity (in kWh) and maximum flow rate (kW), as well as a rate of energy leakage (% per hour). The loss of heat from the tank and charge from batteries were modelled as an exponential decay, such that a constant fraction of the remaining capacity was lost in a fixed time period. The default values for these were 2.5-5% per month for batteries, and 5-10% per day for hot water.[235, 240, 241]

The `CHP` class was used for devices with multiple energy outputs, and was treated in greater detail than the preceding device types. As well as the two types of fuel cell mentioned in Figure 4.16 other micro-CHP engines were modelled as part of the development process: an internal combustion engine with fixed output capacity and efficiency; and a Stirling engine with simple

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[70] Statistics on the power and energy flows relate to the storage device itself, rather than the reference frame of the house. Power exported from the house to the grid is classed as `imported_elec` (as the grid imports it from the house) and vice-versa electricity purchased from the grid is classed as `exported_elec`.

heat-following control and the ability to modulate output. The two classes of fuel cell differed in their complexity: `Simple_FC` was capable of modulating output and simple load-following, whereas `Smart_FC` had additional methods to maximise operating hours and strategically decide when to turn on and off.

As mentioned in Figure 4.16, separate classes were not used for each type of fuel cell. From a modelling point of view, each fuel cell was simply a black box that converts natural gas into heat and power, and so each stack technology differed only in its performance (such as efficiency) and the constraints placed on its operation. The differences between each technology could therefore be encapsulated in the configuration parameters defined by the user, which were as follows:

- The capacity and efficiency of electrical and thermal outputs;
- Efficiency at part load, chosen from hard-coded performance maps;
- Rates of electrical and thermal efficiency degradation, and system lifetime;
- The operating strategy to use, chosen from a list of pre-defined options;
- The turndown ratio (minimum operating power);
- The time and energy required to start the system;
- A constraint on whether turning on and off, or hot-idling were permissible.

4.4.3. Scenarios and Control Strategies

Each of these devices is a self contained unit, incapable of operating independently or interacting with other devices. In order to operate, each device must be asked to produce a particular amount of power, and will respond by stating what is possible. An overall system controller is therefore needed to make the devices work together to meet the energy demands from each house. This models the control circuits that are found in fuel cell systems and boilers, and the valves, thermocouples and other sensors that allow them to interact.

The group of devices used in each house and the rules which govern their operation are collected together into classes (referred to as ‘scenarios’) which are derived from the `Comptroller` super-class. Examples of these from Figure 4.16 are the `Reference` and `FuelCell_Fuzzy` scenarios:

- `Reference` contains a condensing boiler, a hot water tank and an import-only grid connection;

- `FuelCell_Fuzzy` adds to this a fuel cell system (`FC_Smart`) and the ability to export electricity to the grid.

Several scenarios can be set up and operated in parallel, with a typical calculation involving one `Reference` and four `FC_Fuzzy` scenarios configured with parameters to model PEMFC, SOFC, PAFC and AFC systems. Other scenarios were used for example to study the impact of having no hot water tank, or replacing the export link with batteries.

The strategies for controlling each set of devices were hard-coded into these scenario classes, so that the user could specify how to operate the system from the configuration file. The `Reference` scenario was simple enough that only one strategy was required: purchase electricity from the grid and produce heat from the boiler. With the `FuelCell_Simple` scenario, the fuel cell could be set to follow the thermal or electrical demand only, or the minimum or maximum of the two.

The `FuelCell_Fuzzy` scenario improved upon this by intelligently choosing the operating strategy to increase the utilisation of the fuel cell and minimise the number of stop-start cycles required.[242] The fuel cell power output was modified based on the loading status of the hot water tank: as the tank approached its maximum fill, output of the fuel cell would gradually reduce to the minimum operating point in an attempt to avoid shutting down; and when the tank was nearly empty, the fuel cell would produce more heat and power than was requested (when possible) in an attempt to replenish the tank, and minimise the use of the less desirable boiler.

The overall effect of these adaptations was that the fuel cell would operate continuously during the heating season, following demand during the day and operating at minimum output overnight. During summer, the fuel cell would generally operate during the day and shut down each evening once the hot water tank had been replenished. SOFC and PAFC were an exception to this rule due to their constraint on shutting down. During summer nights they would typically run at minimum output and revert to hot-idling or dumping excess heat when there was too little demand.

The fuzzy logic element of the controller was very simple to implement in the code; it required one call to the `Tank` class to request the filling status, and then four lines of algebra. The inclusion of this logic was therefore justified as an alternative to the complex learning or predictive algorithms that were discussed in Section 4.2, as it could be replicated in a real world system with a thermocouple and standard integrated circuits costing less than £1.

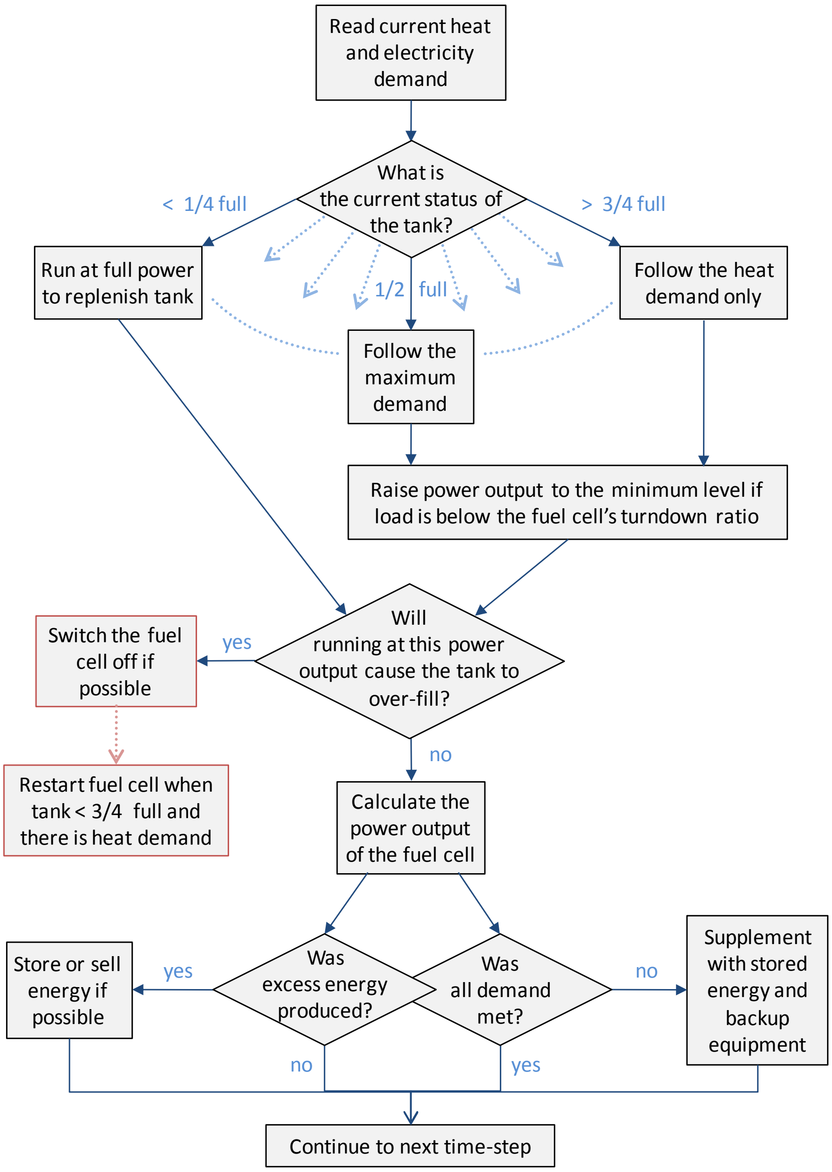

Figure 4.17: A flow-diagram of the energy system control logic.

Figure 4.17 describes the control logic of the `FuelCell_Fuzzy` scenario more thoroughly, including the conditions for determining power output and when to shut down. The `FuelCell_Simple` scenario could also be represented by this diagram, if the first question about the status of the tank led to a fixed response for what control strategy to use. The non-Markov aspects of fuel cell operation that are addressed by optimisation models were at least partially addressed by this fuzzy control; for example, if the fuel cell shuts down overnight it was likely to have restarted again the next morning before there was significant demand.

The impact of the modified control logic is highlighted in the following series of graphs, which compare an identical PEMFC[71] operating over the course of two weeks in winter and summer respectively. The output of the fuel cell (thick red and blue lines) is seen to follow the demand of the house (thin lines) closely in Figure 4.18 – as it was simply set to follow the maximum of electrical and thermal demand. In Figure 4.19, the fuzzy logic is used to increase the running time and minimise the number of shutdowns due to over-filling the tank (shown as a green line).

In both cases, the fuzzy control improves the performance of the fuel cell by maximising its usage, and minimising the energy wasted by starting up. In the final results this increases the primary energy and CO_2 savings by approximately 50%. The financial benefits are not as strongly affected, as the fuzzy control introduces greater mismatch between supply and demand, and thus requires more of the generated electricity to be exported. While exported electricity offers the same environmental benefits as a reduction in consumption, it has a lower economic value than purchased electricity in the UK.[72]

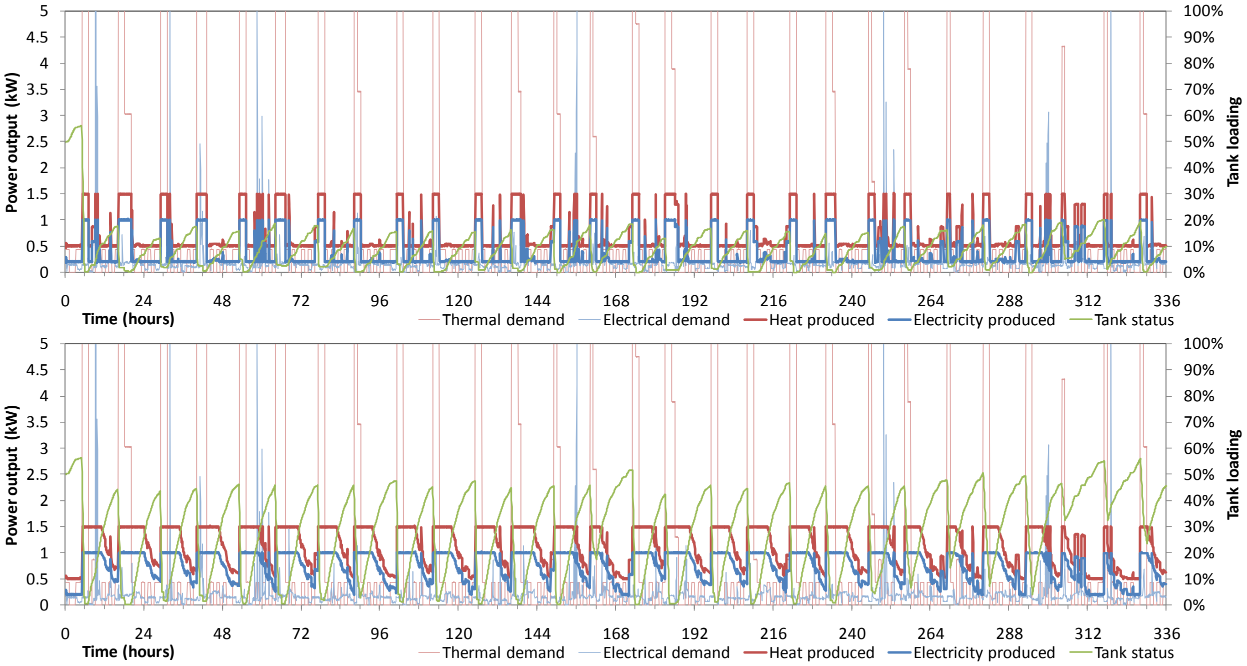

Figure 4.18: The impact of fuzzy control over two weeks in winter. There is a substantial heating peak twice a day, averaging 38kWh/day, and relatively low electrical demand of 4.5kWh/day.

Top: Simple control operates at minimum load for the majority of the time, never raising the tank above 20% filled before it is emptied by the heat demand. The fuel cell produced 46% of the heating demand.

Bottom: Fuzzy control makes the fuel cell operate at full power to maintain the tank at higher levels, and thus covers 72% of the heating demand.

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[71] The fuel cell was simulated with all of the default parameters: 1kW electrical capacity, industry-average efficiency, and a 200L hot water tank.

[72] See Section 6.3 for more details.

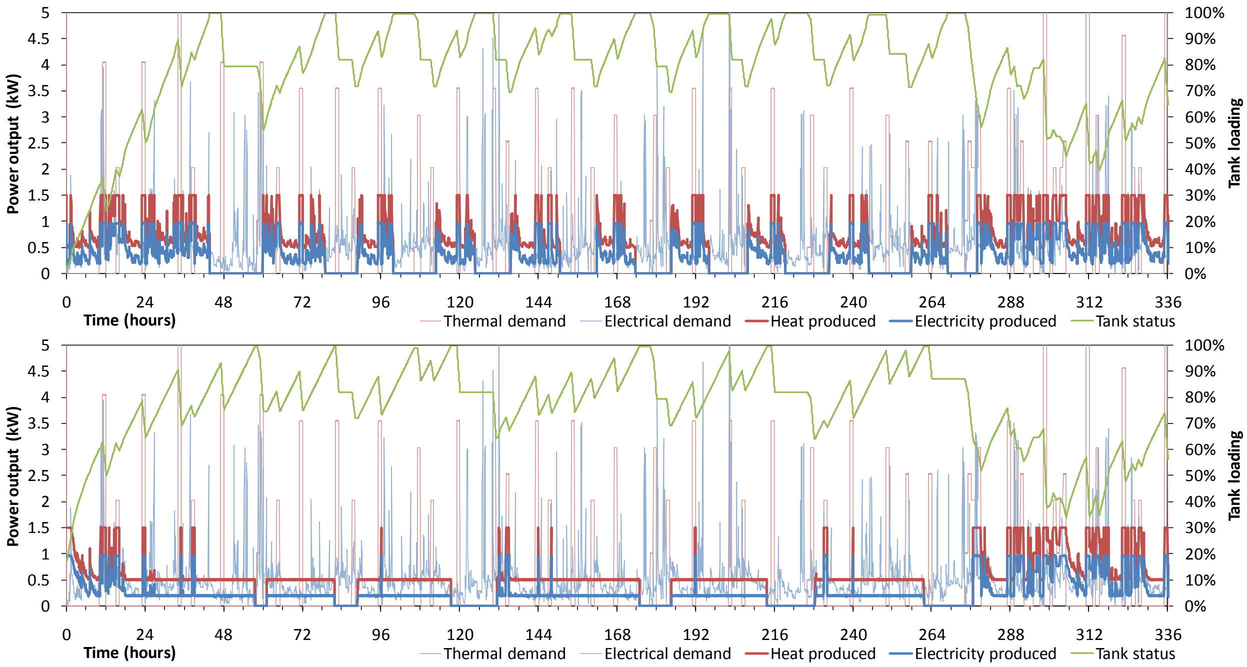

Figure 4.19: The impact of fuzzy control over two weeks in summer. There is limited demand for heat (13 kWh/day) compared to electricity (12.4 kWh/day), therefore the tank often becomes full and the fuel cell must turn off.

Top: Simple control follows the relatively high electricity demand for a few hours until it must shut down, which occurs 10 times in the 14 days.

Bottom: Fuzzy control constrains the fuel cell to minimum output for longer periods, reducing to six start-up/shut-down cycles.

4.5. Concluding Remarks

In order to accurately simulate the operation of fuel cell micro-CHP systems, a review was conducted to uncover the actual performance that has been achieved in practice. Rather than producing highly detailed and specific characterisations of individual systems such as those produced by Annex 42 for example [129, 243], a broad approach was taken that attempted to capture and generalise industry wide performance trends. The field demonstration of a Baxi Beta PEMFC system was used to better understand some of the poorly defined aspects of dynamic system performance. From the review of fuel cell performance included as Appendix A, a number of areas were identified where fuel cell performance is often misconceived or oversimplified in modelling studies.

A similar attempt was made to broadly define the energy demands of the houses in which these fuel cells would operate. The largest available sets of measured domestic energy demands were processed into a useable form, and used to demonstrate the wide spread in results that could be expected from outwardly similar houses. It is argued that just as high resolution measurements are required to capture the fine structure of electricity demand, a broad selection of properties is required to assess the variation and patterns that will emerge from simulations. This variation is shown in subsequent chapters to be substantial, and used to argue that a small group of properties cannot represent the highly diverse ways in which individual households use energy.

A new method of simulating fuel cell micro-CHP operation was developed to accommodate this large volume of energy demand data and the need for Monte Carlo variation of the performance assumptions. A computationally simple yet effective means of optimising the operating pattern was developed using fuzzy logic, which demonstrated a 50% improvement in savings relative to simply following the maximum instantaneous demand. By incorporating part-load performance, voltage degradation and energy consumption during start-up, the model could be used to estimate the efficiency that fuel cell systems would obtain in the field.

Before this model could be used to generate meaningful results it had to be subjected to rigorous testing and validation, as would any new scientific instrument. Confidence in the results of a new method stems from confidence in the method itself, and so it must be calibrated against known standards to ensure that it provides the expected results. The following chapter therefore documents this calibration process, focussing in particular on the method of estimating field performance. Results are compared to those from a previous simulation described in literature, and from extensive field demonstrations in Japan.

From there, the model is used in Chapter 6 to simulate fuel cell micro-CHP systems operating in the UK, using the performance and energy consumption data presented in this chapter. The performance of these systems is used to estimate the financial and carbon savings that could be made across the set of 1,000 homes, making this the broadest modelling study of its kind.

Chapter 5:

EXPERIMENTAL VALIDATION

5.1. Summary

Individual aspects of the fuel cell simulation program such as calculating part load efficiency and performance degradation, or determining the operating point with different control strategies were validated simply by comparing the results to hand-calculated values. However, once all these aspects were combined into the simulation, their interaction became too complex to check manually.

Broader evaluation therefore came from comparison of the model to previous studies, testing the ability to generate statistically similar results from the same input parameters. Micro-CHP models from other authors were used as the first standard, and were followed by actual results from field trials in Japan. Calibration against empirically based sources could not be made on an exact like-for-like basis, as it was impossible to replicate the exact energy demand profiles of the houses that fuel cells were demonstrated in. Comparison against real results generated in the field would however provide the most robust and representative test of the model.

Before the main results of simulation are presented, this aspect of calibration is extended to consider the impact that these field-trial systems would have if they were installed throughout the UK. Two case studies are presented which consider the world's leading PEMFC and SOFC systems as they are (currently operating in Japan), and operated under the different conditions seen in UK homes.

It should be noted that in places the environmental and economic outcomes from modelling are presented, which were calculated using the central set of parameters defined in the following chapter.

5.2. Theoretical Testing and Calibration

A direct comparison between FC++ and a similar theoretical model was made by matching the input data and assumptions given in previous publications as best as possible, and then comparing their results to those from FC++. Minor differences were to be expected as the control strategies were not identical, and original energy demand data from other studies was not available. Any major differences or unexpected results could then be identified and either justified or rectified.

A fuel cell simulation by Pawlik *et al.* [126] was chosen for the comparison as it covered technical, environmental and economic metrics, and provided sufficient detail about the input assumptions to be described thoroughly. In this study a MATLAB model was used to simulate a Viessmann Fuel Cell Energy Center (PEMFC) running in a German detached house, using one year of measured energy demands. To provide similar input data into FC++, 17 profiles were selected from the main set presented in Chapter 4 which had total annual demands within ±10% of the measured demands used by Pawlik, which were 4.45MWh electrical and 22.5MWh thermal. The other input data used by Pawlik is reproduced in Tables 5.1 and 5.2, and was used to create a matching scenario to be run in FC++.

Input Data	
Fuel cell capacity	2kW
Efficiency	$24\%_{el}$ $60\%_{th}$
Part-load efficiency	Constant
Degradation	None
Turndown ratio	20%
Tank capacity	70L
Start-up time	*1 hour*
Boiler efficiency	*86%*

Table 5.1: Technical specifications used in the FC++ scenario. Most data was taken from [126], those in italics had to be assumed as the default values used in the rest of this work.

	Cost (€/kWh)	**CO_2 (g/kWh)**
Gas	0.048	241
Electricity	0.168	600
Exports	0.090	

Table 5.2: The cost and carbon intensity of fuel inputs, taken from [126].

	Pawlik	**FC++**
Proportion of electricity generated by the fuel cell	81%	52 ± 11%
CO_2 reduction	18%	20.3 ± 3.5%
Cost reduction	23%	21.3 ± 3.7%

Table 5.3: A comparison of results from [126] and the FC++ simulation.

The results from running this scenario are given in Table 5.3 above, alongside the results presented by Pawlik. It was seen that FC++ gave similar estimates for the CO_2 and cost reductions, with the standard deviation across the 17 properties covering Pawlik's values in both cases. Pawlik also noted that CO_2 savings from using the fuel cell varied between 9 and 39% depending on the size, location and occupancy of the house it was operated in. The FC++ scenario was run again using the whole data set of 1,000 energy profiles, and estimated CO_2 savings ranging from 9.0 to 32.2%, with an average of 20.7%.

FC++ did however deviate significantly from Pawlik's model in its estimate of the amount of generated electricity that was used on-site – estimating a range of 39-75% compared to 81%. Averaging over the 17 houses, FC++ predicted that 4,445kWh of electricity purchase was reduced to 2,130kWh with the fuel cell installed, and 4,341kWh of the electricity it generated was exported to the grid.

Pawlik only plotted 3 days of energy demand from the German home, so it is not possible to analyse the differences in structure between the annual profile and those used with FC++. The difference in these results could be explained if the German electricity demand was less peaky, and mostly came from sustained blocks of demand of 0-2kW; which would have allowed the fuel cell to provide for more local consumption and export less electricity. This would also explain the fact that FC++ predicted slightly higher CO_2 reductions, and yet lower cost reductions – as exported electricity had the same environmental benefit (still displacing 600g/kWh of CO_2), but lower economic benefits (exported power was only worth half that of avoided local consumption).

It was therefore concluded that FC++ could be calibrated to this MATLAB model by using a scenario with the same set of input parameters, and that the only significant difference between results was due to differences in the energy profiles that had been used. A similar comparison to the CODEGen optimisation model had also been planned, but was limited to comparisons of the results for PEMFC and SOFC systems, which are presented in the following chapters.

5.3. Experimental Characterisation of the Baxi Beta 1.5 Plus

As introduced in Section 2.4.3, two identical fuel cell systems from Baxi were investigated during this project; one in the University of Birmingham's fuel cell laboratory and a second installed into a house in the local area.

An experimental investigation of these systems had originally been planned; characterising the laboratory system to produce data inputs for the FC++ model, then comparing the results from the field system to those from a simulation using the measured energy profile from the actual house it was installed in. However, it was not possible to use either system in this way due to unforeseen technical and contractual problems.

The laboratory system could not be controlled directly, and experienced only limited running time due to interruptions with the demonstration.[244] The only performance inputs that could be used for FC++ were therefore the rated specifications given earlier in Table 2.3.

5.3.1. Demonstration System

The second system was installed into the three bedroom house pictured in Figure 5.1 in April 2008, and was officially unveiled in October that year. It has since operated for 15 months, making it the longest running field trial of a fuel cell system in the UK.

The fuel cell was installed with a 600L Gledhill heat-store in a purpose-built brick shed at the rear of the property. As this was a retrofit installation, it was operated alongside the existing heating system as shown in Figure 5.2.

Figure 5.1: A photo of the 'hydrogen house' in the Black Country. The house was newly built in 2007 to above standard regulations, featuring double glazing and cavity wall insulation, with a floor area of approximately 100m^2.[245]

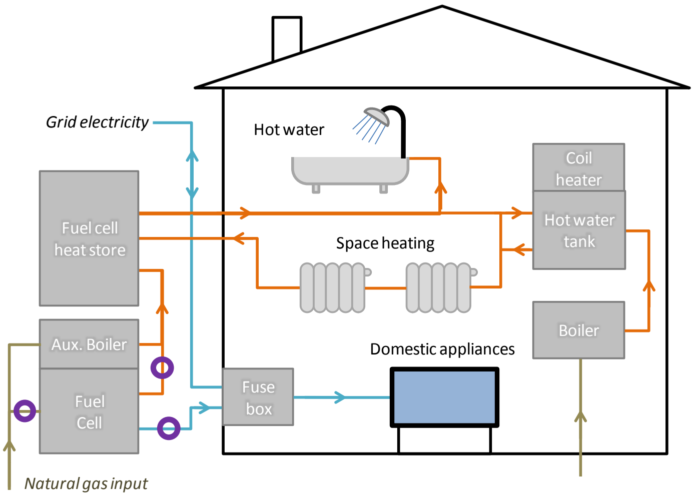

Figure 5.2: An overview of the energy generating systems installed in the hydrogen house. The Baxi Beta and its integrated boiler were thermally connected to the heat store (orange lines), and electrically connected to the house and grid supply (blue lines).

The hydrogen house could therefore be heated from four sources: the fuel cell, its integrated backup boiler, a Potterton Promax condensing boiler, and an electric immersion heater in the indoor water tank; all of which were used in different combinations throughout the trial. The fuel cell's integrated boiler was used for the first few months, and then deactivated in favour of the Potterton boiler. The integrated boiler was found to produce heat that had been requested from the fuel cell, cutting short fuel cell operation and causing unnecessary start-ups.

The three-phase, 400V electrical output of the fuel cell was converted to 230V single-phase to meet local consumption in the house, and electrical interconnection with the grid was made to allow for exports during times of low demand.

The purple circles in Figure 5.2 indicate the three points in the energy system where data was monitored. In the Japanese field trials, data was also taken from the link to the electricity grid and from the backup boiler, meaning that the total electrical and thermal demands of the house could be monitored.[99] As these additional points were not measured in the Baxi field trial, the energy demand of the house could only be estimated using energy bills received every three months.

Data on the fuel cell itself was provided by Baxi in the form of monthly reports which summarised the operations and performance of both the laboratory and field trial systems. In addition to this, a set of time-series data recorded from the field system was made available, covering the period from April 2008 to May 2009. This data set recorded around 8,000 hours of operations, giving the amount of gas input, electrical output, and coolant temperatures and flow, all recorded at five minute resolution.

5.3.2. Analysis of Field Performance

The data was analysed to characterise the performance of the fuel cell, which was written up into a report to the consortium overseeing the trials,[73] and is included as Appendix B. Due to confidentiality agreements, access to this report requires written permission from Baxi-Innotech and the University of Birmingham.[74]

To date, the trial has not allowed the fuel cell to demonstrate its true potential. Energy output has been governed primarily by interruptions to the field trial (both from system maintenance and external factors), rather than by how much energy was demanded by the house. Power was therefore only produced for 2,800 of the 8,000 recorded hours, giving a utilisation of just 19%. Electrical output was less than 100kWh per month for 7 months of the trial, equating to just 3kWh per day (2 hours at full power).

In total, 2.3MWh of electricity and 4.3MWh of heat were produced, at efficiencies of 20% and 37% HHV respectively. The same trends observed in other field trials of micro-CHP were observed (e.g. [31, 100, 101]): efficiency improved as power output rose, and was particularly dependant on the number of operating hours. The fuel cell experienced one month of almost continuous operation during March 2009, demonstrating improved efficiencies and estimated carbon savings of 75kg – equating to 900kg annually if this performance was scaled up.

As this performance during the field trial was not representative of the fuel cell's capabilities, no reasonable comparison could be made to results from FC++. No simulations were performed as the results could not be verified, and would no longer be relevant to the latest commercial system as the Beta 1.5 has since been superseded by the Gamma 1.0.

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[73] The consortium was Baxi-Innotech, the Black Country Housing Association and the University of Birmingham.

[74] To request access to this appendix, please contact Michael Braun <michael.braun@baxi-innotech.de> and Kevin Kendall <k.kendall@bham.ac.uk>

In relation to the fuel cell modelling work, the two most useful and novel findings related to how well the system handled dynamic conditions such as load commutations and start-up, rather than how well it performed in general. There appeared to be no constraint on how rapidly power output from the fuel cell could change over time, at least within the five-minute resolution of the data. The stack was seen to change between the minimum and maximum power outputs (and vice versa) within five minutes, suggesting a maximum ramp rate of at least 150W per minute. The start-up and shut-down of the system was also analysed in detail to reveal the amount of time and additional energy required to pre-heat the system.

This information was used in the development of FC++ to address some of the grey areas that were raised in Chapter 4, and was used to inform the other simulations of PEMFC systems that were performed.

5.4. Validation and Results from Simulating Japanese Systems

Although the FC++ model had been calibrated to another theoretical model, real empirical data from the field was considered the ideal standard to use. A second source of comparison was therefore taken from the real world demonstrations of PEMFC and SOFC systems in Japan. A wealth of information has been published on these systems, which meant that highly specific scenarios could be written for FC++ to describe them and the conditions they were operated under. Both types of fuel cell were simulated with FC++ using their rated performance specifications and a crude approximation to Japanese domestic energy demand, and the results were compared to those from the real-world field trials of these systems.

The aim of this experiment was to test whether FC++ was able to estimate real-world performance from steady-state laboratory measurements. If these estimates were broadly in agreement with those from the field trial, it could be stated with confidence that the simulation method was valid and reliably described the operation of fuel cell micro-CHP systems.

5.4.1. Simulation of ENEFARM and Kyocera Systems Operating in Japan

5.4.1.1. Data Inputs

The ENEFARM PEMFC and Kyocera SOFC systems were introduced earlier in Section 2.4. The manufacturer's specifications for each system were used to model them within FC++, and are reproduced in Table 5.4. The part load efficiency of each system is plotted in Figure 5.3; for the Kyocera system this was quoted with the specifications, but had to be taken from field data for ENEFARM.

	ENE-FARM [81, 93, 104, 198, 246]	**Kyocera [101, 247]**
Fuel cell capacity (kW electrical)	0.7-1.0	0.7
Tank capacity (L)	200	70
Spare boiler capacity (kW)	42	42
Rated electrical efficiency (HHV, full load)	31.5-33.5%	40.5%
Rate thermal efficiency (HHV, full load)	41-47%	36%
Voltage degradation rate (per 1000 hours)	0.25-0.5%	0.25-1%
Turndown ratio	30%	15%
Start-up time	1 hour	-
Start-up energy (kWh)	1.5	-

Table 5.4: Assumptions for the performance of Japanese fuel cell micro-CHP systems.

It should be noted that various models of ENEFARM were produced with different capacities and efficiencies, which had to be accounted for in the simulation. Based on the number of units sold by each manufacturer between 2005-07, a 1.0kW fuel cell was simulated operating in 40% of the houses (which were assigned at random), with a 0.75kW system in another 35% of them and 0.7kW in the remainder.[104, 111]

In the Japanese SOFC field trials three different models have been deployed, of which only the Kyocera was considered. TOTO supplied larger 2 and 10kW units, while Nippon Oil supplied one of the 26 0.7kW systems to the trials in the year that was considered, but data on this system was not so readily available and so its differences was neglected.

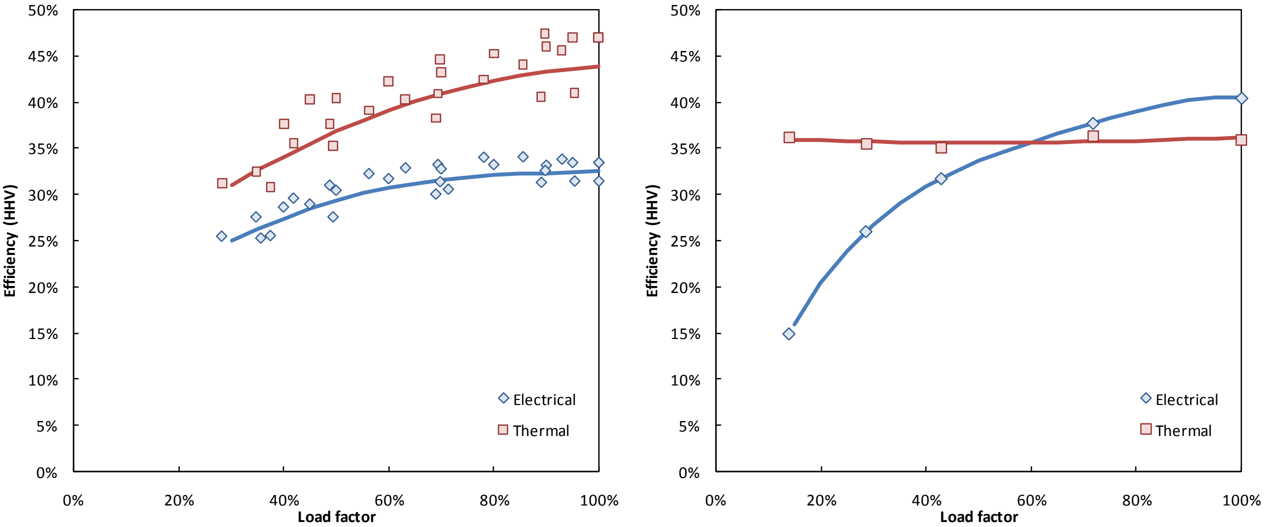

Figure 5.3: The assumed part load efficiency for ENEFARM (left) based on field data from [80, 87, 104, 139, 246]; and for Kyocera systems (right) based on data from [101].

In addition to considering the fuel cells' performance, the FC++ model accommodated aspects of their operation which differed from standard UK conditions. Both systems were constrained to follow the instantaneous electrical demand of the home, as exporting electricity to the grid was not allowed due to Japanese regulations[75].[99, 248] This was modelled by simply limiting the operating point requested by the control strategy to a maximum of the current electrical demand.

The Kyocera systems differed from ENEFARM in that they could not be shut down, and so had to generate heat and power continuously even when there was no demand. This was modelled by adding a thermal dump to one of the standard scenarios, as has been done by Hawkes for example in [124]. A new scenario was written based on `FuelCell_Fuzzy` with a secondary hot water tank which had infinite storage capacity, and would only accept incoming heat when the actual hot water tank was full.

Finally, the efficiency and carbon intensity of the reference system that was defined by the NEF is given in Table 5.5. These values were used to calculate the primary energy and CO_2 savings that were achieved by each fuel cell system.

	Efficiency (HHV)	**CO_2 (g/kWh)**
Heat from gas	78%	236
Electricity	36.9%	690

Table 5.5: Economic and environmental inputs specific to Japanese simulation.[101, 139]

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[75] The impact of this was less severe in Japan than it would be in the UK, as Japanese homes have substantially higher electricity demand throughout the year

A major problem with simulating these systems in Japanese homes was that the available energy demand data was highly specific to the UK. There are substantial differences between energy consumption habits in these two countries as shown in Figure 5.4, with Japanese homes consuming more electricity throughout the year (particularly during summer) and less heat during winter.

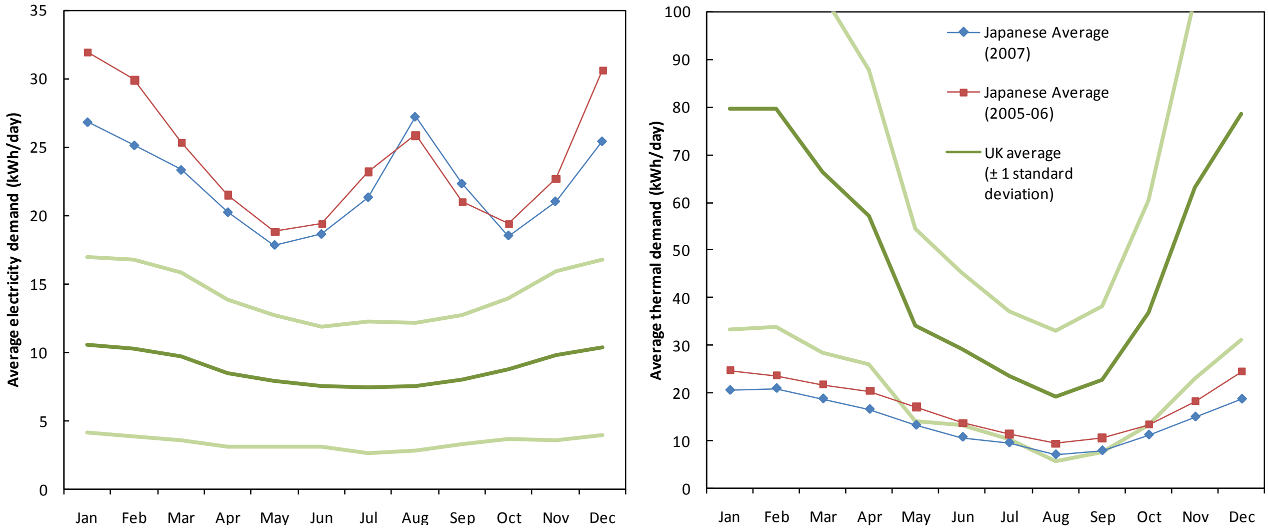

Figure 5.4: The distribution of seasonal energy demand in Japanese and UK homes, showing the monthly average electricity (left) and heat (right) demands. Based on data from the Japanese ENEFARM field trials, and the energy profiles shown earlier in Figure 4.12.[99, 248]

Language barriers and the availability of both time and data prevented specific energy demand profiles from Japanese homes from being found, or the use of building simulators specific to Japan (for example [249-251]). As an improvised substitute, the profiles from Chapter 4 were scaled on a monthly basis to fit the average Japanese demand presented in Figure 5.4.

The structure of the simulated thermal demand was noticeably different from that reported in the field trials. These fuel cells only covered hot water demand in Japan, rather than the space heating and hot water demand that was contained in the energy profiles. The energy profile data was not expected to lead to accurate or methodologically sound results as it went against the principals laid out in Section 4.2.2.[76] This was however the only available alternative, and was only used to compare results from the simulation and field trials, rather than to offer further predictions about fuel cells operating in Japanese homes.

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[76] Japanese electricity demand was dominated by air conditioning used throughout summer, and hot water demand was only for domestic consumption rather than space heating. The shape of both demand profiles would therefore not scale correctly with simple linear factors.

5.4.1.2. Comparison of Results

A set of simulations were run for ENEOS, LIFUEL and Toshiba type ENEFARM systems (0.7, 0.75 and 1.0kW respectively), and Kyocera SOFC systems operating in 1,000 UK homes with energy demands scaled to Japanese levels. The results from these simulations were compared to three sets of annual results from the domestic field trials in Japan which have been published by the NEF:

- 2005-06 data for 420 ENEFARM systems installed in 2005 (1st phase) [138, 248];
- 2007 data for 777 ENEFARM systems installed in 2006 [99, 139];
- 2008 data for 25 Kyocera systems (and 1 from Nippon Oil) installed in 2007 [101, 252].

These three sets of results considered an entire year of operation, and provided data about the amount of energy demanded from and supplied by the fuel cells; allowing a greater number of metrics to be calculated. More recent results from the ENEFARM trials were not included due to the lack of detail that was reported,[100] and results from 2008 Kyocera systems were also excluded as they only presented data from August till December.[101] Both of these sets showed primary energy and CO_2 savings to be ~2-3% higher than in previous years, either due to better operating conditions (i.e. larger houses) or the improved performance of FY2008 models that were installed.

5.4.1.3. Operating Profiles

Figure 5.5 presents a sample of actual operating profiles of ENEFARM and Kyocera fuel cells in the field, taken from a selection of many that were given in NEF reports. These can be compared to Figure 5.6, which gives a sample of one week's simulated operation of each system taken from two randomly chosen houses. It was obvious that the structure of the simulated thermal demand was different from that measured in the actual field trials, as the sharp peak in week-day hot water demand after work (18:00-21:00) was not seen in the simulated data, and thermal demand was more evenly spread throughout the day.

The general features of the fuel cell's operation were however similar to the actual results. In the field PEMFC systems ran for 6-18 hours a day, starting up around an hour after thermal and electrical demand pick up in the morning, and stopping again once the hot water tank is full. The simulated behaviour was naturally similar to this, as the fuel cell tried to turn on once there was sufficient demand and the tank was partially depleted, stopping again when either electrical demand fell below the minimum power output or once the tank was full. This resulted in typical operating periods of 3-18 hours at a time, with occasional periods in winter of over 24 hours.

SOFC systems followed electrical demand continuously, exploiting their high turndown ratio and operating at full power for a reasonable portion of the time. In both the field and simulation, the SOFC can be seen continuing to generate energy when the hot water tank was full, dumping the excess heat that could not be stored.

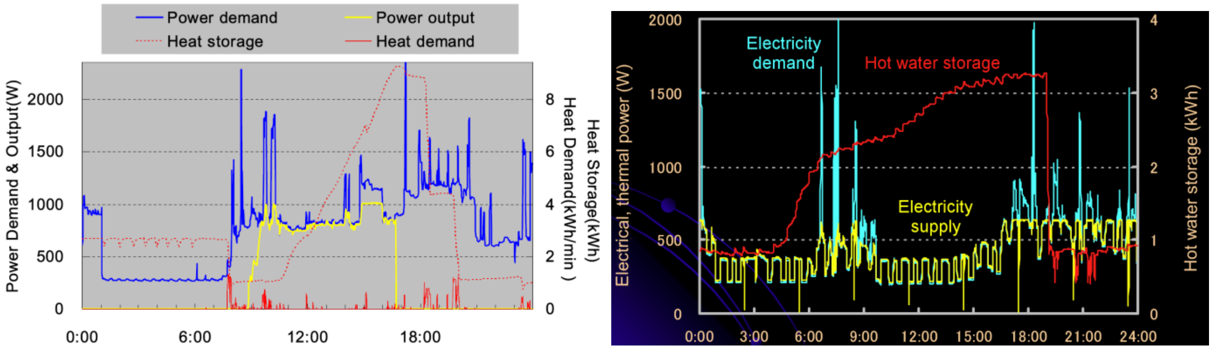

Figure 5.5: Examples of operation profiles for a PEMFC operated by Tokyo Gas (left) and a Kyocera SOFC (right), recorded as part of the field trials and taken from [80, 87, 252]. The PEMFC is seen starting around 9am, an hour after thermal and electrical demands in the property increase, and stopping once the hot water tank is full. The SOFC on the other hand operates continuously to avoid thermal cycles, and must dump heat produced between 5-7pm when there is no available storage.

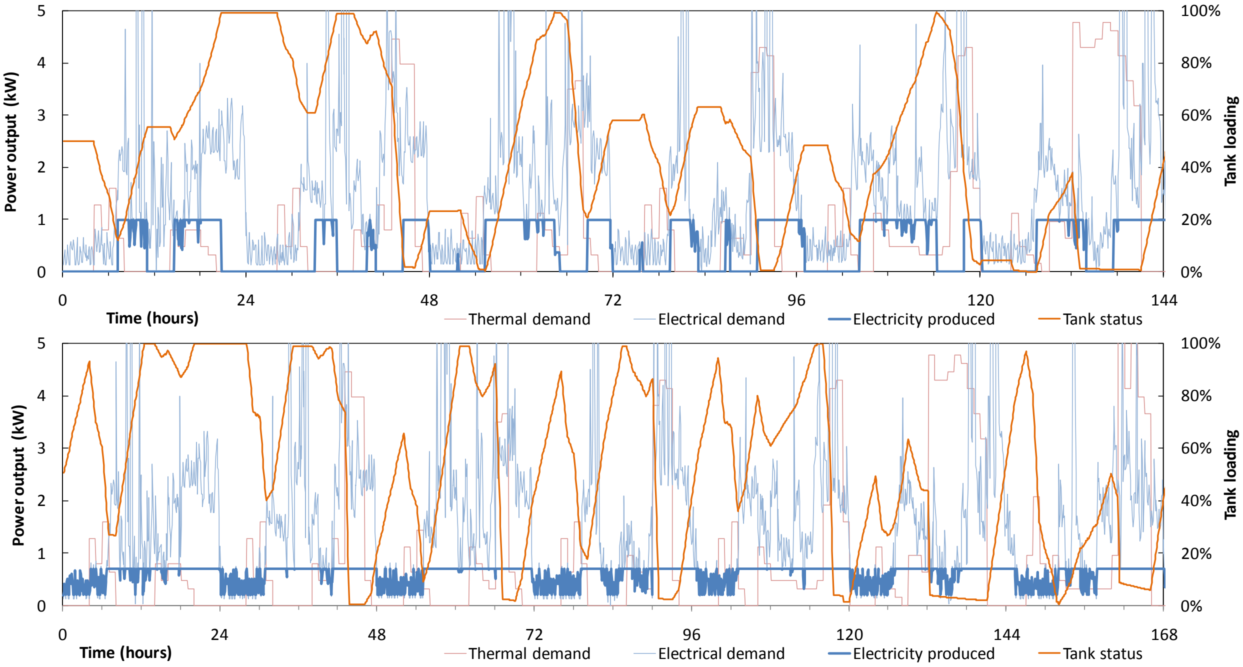

Figure 5.6: Example profiles showing a week of simulated operation for a 0.7kW ENEFARM system (top) and 0.7kW Kyocera system (bottom).

5.4.1.4. Fuel Cell Performance

Results from the field trials included the seasonal average efficiencies experienced in each house, and estimated amounts of primary energy and CO_2 emissions that were reduced by installing the fuel cell. These are reproduced in the following tables alongside the same metrics calculated from the FC++ simulations. Before discussing these results, two conventions used by the NEF need to be explained.

Two definitions of the fuel cell efficiency were given due to the mismatch between energy supply and demand caused by operating constraints of the fuel cell. The gross ‘generating efficiency’ accounted for all energy produced, however not all of this was used in the home and some had to be wasted.[82] The ‘utilisation efficiency’ disregarded this wasted energy and thus was lower than the generating efficiency, as 87.6% of the energy generated by ENEFARM systems was utilised in the homes.[99, 138, 139, 248]

The NEF also used an unorthodox definition for the relative reductions in primary energy and CO_2 emissions achieved by the fuel cells. In most studies (e.g. those in Table 3.2) the absolute reduction in emissions is compared to the total emissions the house would have produced with the boiler and grid. For the 420 houses monitored in 2005-06, this would have been an 846kg CO_2 reduction compared with 7,500kg[77] emissions – an 11.3% reduction. Instead, the NEF compare the absolute reduction to the amount of emissions (or energy consumption) that would have occurred if the heat and power output of the fuel cell had been met by a water heater and the grid, which in 2005-06 was only 3009kg[78] – giving a much higher relative value of 28%.

These conventions are adhered to in the following tables, but were not used throughout the rest of this work. Table 5.6 gives a comparison of the simulated and actual results for ENEFARM systems, and Table 5.7 gives the same for Kyocera systems.

	2005-06 field trial [138, 248]	**2007 field trial [99, 139]**	**FC++ simulation**
Electrical generating efficiency (HHV)	29.1%	30.0%	29.4 ± 2.6%
Thermal generating efficiency	40.7%	42.2%	39.2 ± 5.2%
Electrical utilisation efficiency	26.0%	26.4%	*25.8 ± 2.2%*
Thermal utilisation efficiency	37.1%	36.8%	*34.4 ± 4.6%*
Electricity production (kWh)	2926	2704	2938 ± 997
(proportion of household demand)	(33%)	(33%)	(37 ± 11%)
Heat production (kWh)	4176	3828	3935 ± 1456

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[77] Based on average energy consumption of 8,724kWh electricity and 6,233kWh heat per year,[248] and the emissions factors given in Table 5.3.

[78] Calculated from 2,926kWh of electricity production and 4,176kWh of heat production by the fuel cell.[248]

(proportion of household demand)	(66%)	(74%)	(72 ± 14%)
Average operating hours (per year)	5,454	?	4765 ± 825
Primary energy reduction (kWh per year)	2004	1920	1896 ± 1275
(relative to avoided consumption)	(15.3%)	(15.8%)	(13.4 ± 5.0%)
CO_2 savings (kg per year)	846	792	849 ± 404
(relative to avoided emissions)	(28.0%)	(28.0%)	(28.6 ± 4.1%)

Table 5.6: Comparison of actual results from the ENEFARM field trials and simulated results from the FC++ model.

The electrical and thermal generating efficiencies presented in the last column of Table 5.6 were simulated with FC++ using the start-of-life efficiency at full power, part-load efficiency maps, degradation rates and additional energy consumed during system start-up. The effect of energy utilisation could not be accounted for by the FC++ model without modification,[79] and so the utilisation efficiencies were estimated by multiplying these by a factor of 0.876 – taken from the field trial data. The estimated efficiencies were similar to those recorded during the field trials, and had relatively large standard deviations due to the different input efficiencies assumed for each ENEFARM model.

The other metrics presented in Table 5.6 were calculated directly from the FC++ results, none of which show statistically significant deviation from the field trial results. The absolute primary energy reductions differed by only 0.02-0.08 standard deviations, and the CO_2 savings by 0.01-0.14; which was pleasantly surprising given the poor quality of demand data used. The most substantial differences were with the thermal efficiency which was 0.52-0.59 standard deviations below the actual values, and the number of operating hours which were 0.84 above.

	2007 field trial [101, 252]	**FC++ simulation**
Electrical generating efficiency (HHV)	34.8%	34.9 ± 3.2%
Thermal generating efficiency	36.7%	36.2 ± 0.1%
Electrical utilisation efficiency	34.7%	34.9 ± 3.2%
Thermal utilisation efficiency	22.8%	30.1 ± 3.8%
Electricity produced (kWh)	4331	3835 ± 952
(proportion of household demand)	(69%)	(48 ± 15%)
Heat produced (kWh)	4581	3921 ± 662
(proportion of household demand)	(114%)	(72 ± 26%)
Heat utilised by household (kWh)	2846	3252 ± 1048
(percentage of total production)	(62%)	(83 ± 11%)
Primary energy reduction (kWh per year)	2823	3984 ± 1337
(relative to avoided consumption)	(18.4%)	(26.1 ± 6.3%)
CO_2 savings (kg per year)	1284	1387 ± 467
(relative to avoided emissions)	(35.1%)	(40.7 ± 5.3%)

Table 5.7: Comparison of actual results from the SOFC field trials and simulated results from the FC++ model.

The simulated generating efficiencies for Kyocera systems in Table 5.7 were both similar to those seen in the field trials. The electrical efficiency had a reasonably large standard deviation

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[79] The system controller did not tell the fuel cell to produce energy that had not been demanded unless it could be exported or stored. The exception to this was the thermal dumping scenario written specifically for the Kyocera systems, as these exhibited more substantial losses than ENEFARM.

due to the fuel cell's part load efficiency varying from 40% down to just 15%. It is also notable that the measured (and simulated) electrical efficiency was 5.5% lower than the rated specifications of the Kyocera systems, which was approximately double the fall that was witnessed with ENEFARM systems. This could also be attributed to the strong fall in part-load electrical efficiency (compare the two graphs in Figure 5.3), and to the degradation rates of the SOFC systems which were measured to be as high as 1% per thousand hours.[101] The simulated thermal generating efficiency was close to that reported from the field trials in absolute terms, however the standard deviation was almost zero as the variation over time was minimal, and the part-load profile was virtually flat.

Unlike the ENEFARM simulation, both the generating and utilisation efficiencies were estimated with FC++ by including and excluding the amount of heat that was sent to the thermal dump. During the field trials it was seen that over a third of the heat produced by these systems was wasted, giving the low thermal utilisation efficiency of 22.8%.[252] This behaviour was mimicked by FC++, however the magnitude was greatly underestimated. Thermal utilisation efficiency was estimated to be 7 percentage points higher than experienced in the trials, with only half as much heat being sent to the thermal dump as was wasted during the trials. This was thought to have been an effect of the improvised pattern of thermal demand, which was more evenly spread throughout the day than the actual hot water consumption of the Japanese homes.

The reductions in primary energy and CO_2 emissions were therefore over-estimated by FC++ by a factor of 40% and 15% respectively; although they were still within one standard deviation as the range of results was much greater. To test the importance of the error in thermal utilisation, the FC++ results were modified to give the measured efficiency of 22.8% by reducing the amount of heat exported to the useful hot water tank and substituting it with additional generation by the backup boiler. This post-processing reduced the average primary energy savings to 3,110kWh per year (21.8%) and CO_2 savings to 1,226kg per year (38.1%). While these were still higher than the reported values, approximately half the difference had been accounted for. It would be useful to reproduce these results with actual demand data from Japanese homes to see how close FC++ could approach the actual results of the field trial, and identify what (if any) the source of discrepancy is.

5.4.1.5. Primary Energy and CO_2 Savings

The primary energy reduction rates for the demonstration systems could be calculated directly from the thermal and electrical utilisation efficiencies due to the definition used by the NEF. This was displayed graphically in many of their reports, with two examples shown in Figure 5.7.

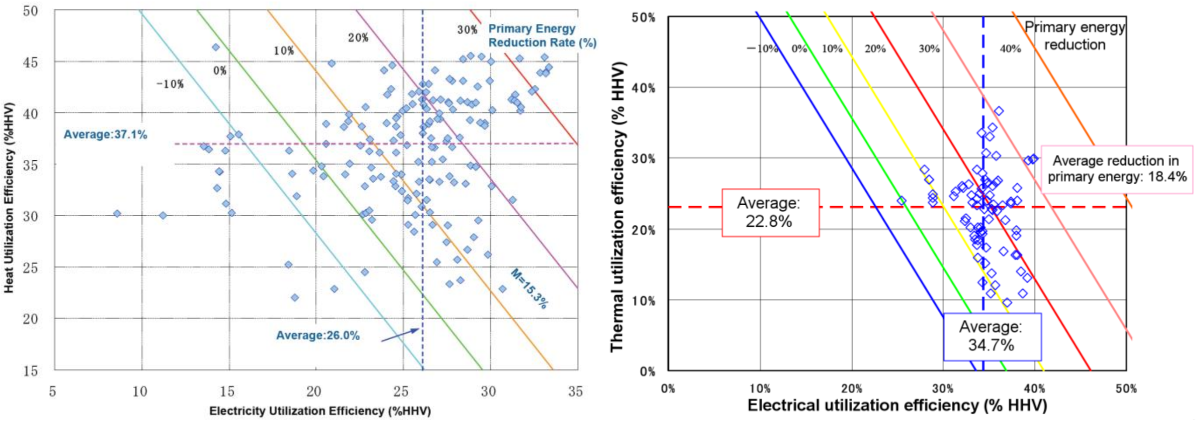

Figure 5.7: The energy utilisation efficiencies of ENEFARM systems in 2005-06 (left), and of Kyocera SOFC systems in 2007 (right). These are plotted so as to give the reduction in primary energy using lines that connect the thermal efficiency of water heaters with the electrical efficiency of the grid, as used previously in Figure 4.3. Taken from [248, 252].[80]

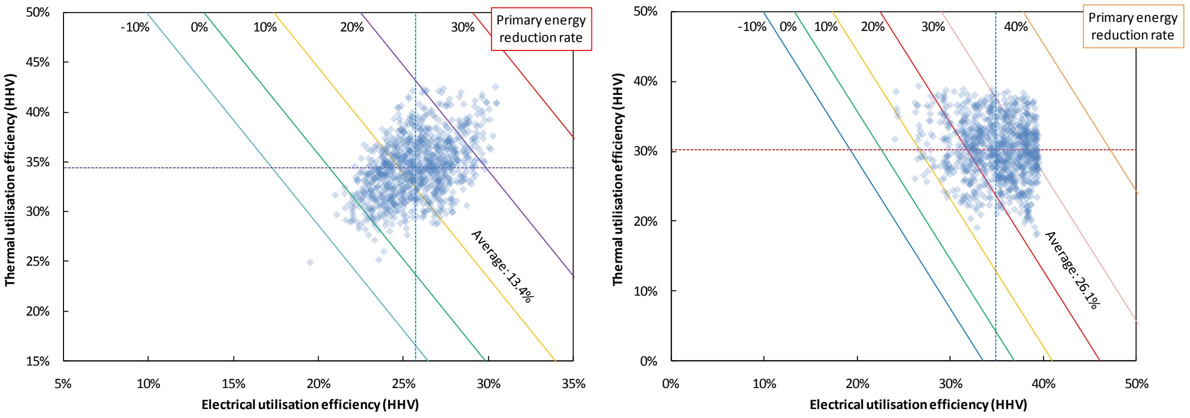

Figure 5.8: Estimated utilisation efficiencies and primary energy reduction rates for ENEFARM systems (left) and Kyocera SOFC systems (right), simulated with the FC++ model.

Figure 5.8 plots the simulated efficiency of the ENEFARM and Kyocera systems on the same axes for comparison. The actual and simulated efficiencies of ENEFARM systems were reasonably close, meaning that a similar rate of primary energy savings was predicted. The range of efficiencies seen in the demonstration was however much greater, as some systems had exceptionally high performance (close to the highest rated specifications of 33.5 + 47%), yet a minority of the houses utilised less than half of the energy produced by their fuel cell, giving total CHP efficiencies under 40%. This range in utilised efficiencies could not be captured by the simulation, and so the spread in results was more limited. The simulated results fell into a well-

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[80] Note that the figure given for the SOFC relates to a slightly different observation period than the data presented earlier in Table 3.2, and so the average efficiencies and primary energy reduction rate are different.

defined normal distribution, dominated by the Monte Carlo variation of starting efficiency and degradation rates.

For the Kyocera systems, the predicted primary energy savings were notably greater than those experienced in the field, as the utilised thermal efficiency was estimated to be significantly higher. In contrast with the ENEFARM results, the simulated spread in efficiencies was higher than experienced in the field, but the actual data set only comprised 26 results as opposed to 1,000 simulated SOFCs. The simulated electrical efficiency exhibits a skewed distribution with a cut-off just below 40%, as some systems ran close to full power for the entire year. The spread in thermal efficiencies was much wider in practice than was simulated, due to the varied amount of heat that was dumped, and many systems in the field trials approached only 10% thermal efficiency.

A final comparison was made based on the estimated CO_2 reductions and their relationship to the thermal demand of the property. Figure 5.9 compares the simulated results for ENEFARM systems against those presented for the 2005-06 field trial data. The two charts have similar structures and average predicted savings, the only difference was the more limited range of results produced by the simulation. None of the simulated systems produced more CO_2 than the traditional alternative, which was experienced in a minority of Japanese homes.

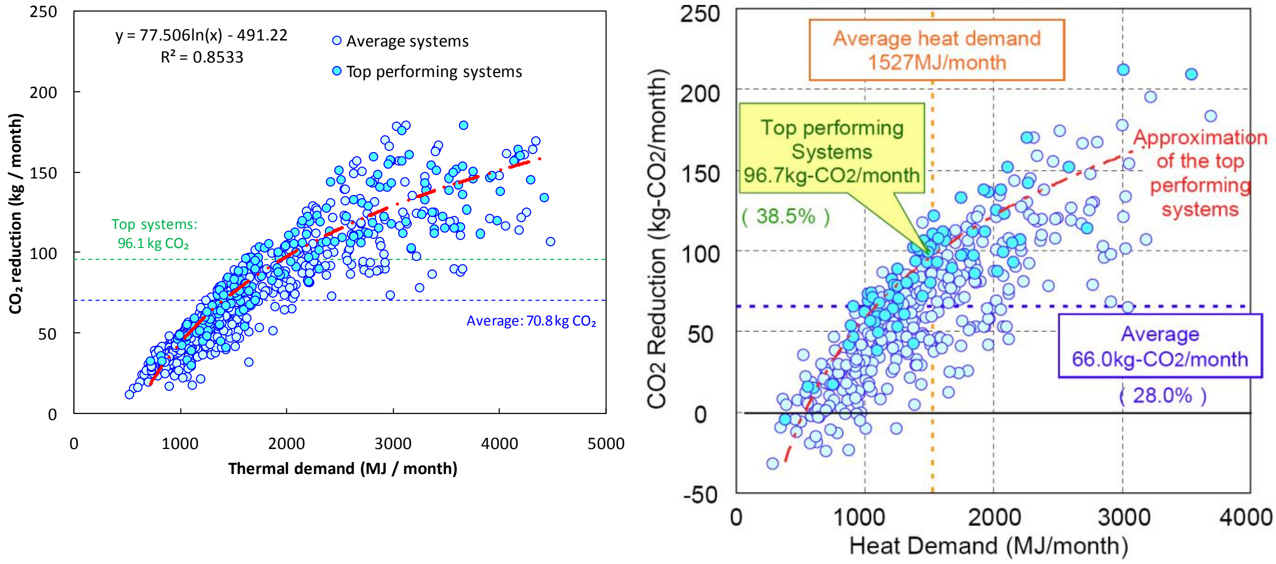

Figure 5.9: Comparison of the simulated and actual CO_2 reductions of ENEFARM systems with respect to thermal demand from each house. With the simulated results (left), the performance of 1kW LIFUEL type systems is highlighted as being the top performer and a logarithmic fit is given to these systems. The actual data (right) is reproduced from [99].

In conclusion, the scenarios written for FC++ to describe the operation of ENEFARM systems appeared to successfully reproduce their operation in Japanese conditions. Results from the simulation matched those from the field trials reasonably well, and left no discrepancies which could not be explained. The simulation of Kyocera SOFC systems required a modification to the model to allow for heat to be dumped, which did not prove to be so accurate. Estimated generating efficiencies were similar to those reported in the trials, but the amount of dumped heat was seriously under-estimated. It was thought that the use of scaled UK profiles for thermal demand was the likely cause, as they offered a poor representation of Japanese hot water demand.

5.4.2. Simulation of ENEFARM and Kyocera Systems Operating in the UK

With the model operation verified and scenarios written to describe ENEFARM and Kyocera fuel cells, the simulations were repeated with these systems operating under typical UK conditions. These simulations would give an interesting insight into the impact that the world's leading fuel cell micro-CHP systems would have if introduced into the UK.

5.4.2.1. Data Inputs

In setting up the UK simulation, the same data inputs for fuel cell performance were used as in Table 5.2, and the energy profile data was reverted back to the original set of 1,000 UK profiles that were characterised in Chapter 4. The economic and environmental parameters used to calculate the cost and CO_2 reductions were also tailored to the current UK situation as given in Table 5.8.

	Efficiency (HHV)	**CO_2 (g/kWh)**	**Cost or value (p/kWh)**
Heat from gas	85.5%	213	3.26 fuel price
Electricity	36.0%	572	10.79 import 5.0 export

Table 5.8: Economic and environmental inputs specific to the UK simulation. These data and assumptions were taken from Sections 6.3 and 6.4.

Two further alterations to the scenarios were also considered:

- The use of larger hot water storage tanks – as 70-200L would be too small for much greater heat demands in the UK;
- The ability to export electricity to the grid – as lower electrical demand in the UK would place a much more severe constraint on running-time if export was not allowed.

Enabling current ENEFARM models to export electricity may require the use of a more complex inverter which is capable of grid synchronisation, adding to the overall system cost. This increase would however be negligible compared to their current sale price, and is expected to be greatly outweighed by the additional benefits that export would give.

5.4.2.2. Simulation Results

Table 5.9 gives the average performance metrics from the seven scenarios that were considered, and Figure 5.10 plots the percentage reductions in the environmental and economic impacts of providing energy for the 1,000 simulated homes.

	ENEFARM			**Kyocera**			
	A	**C**	**D**	**A**	**B**	**C**	**D**
Electrical efficiency (HHV)	29.9%	31.3%	31.5%	30.8%	37.8%	38.9%	39.0%
Thermal efficiency	39.3%	42.7%	43.1%	34.9%	35.1%	36.3%	36.3%
Electricity produced (kWh)	1674	5828	6104	2648	4814	5347	5417
(proportion of demand)	52%	76%	77%	76%	71%	74%	75%
Electricity exported	0%	62%	64%	0%	58%	60%	61%
Heat produced (kWh)	2208	7968	8374	2947	4585	4983	5036
(proportion of demand)	13%	55%	56%	20%	32%	35%	36%
Heat dumped	-	-	-	2.8%	3.1%	1.6%	1.2%
Extra gas consumed (kWh)	2977	9232	9504	5026	7328	7908	7979
Operating hours	3329	8460	8553	8760	8760	8760	8760
Number of cycles	865	47	17	-	-	-	-

Table 5.9: Comparison of performance metrics for ENEFARM and Kyocera systems operating for one year in UK homes. Key to the scenarios: A) unmodified Japanese systems, with 200L tank for ENEFARM and 70L tank for Kyocera; B) with the ability to export electricity and a 70L tank; C) export and a 200L tank; D) export and a 400L tank. ENEFARM systems were not considered with a 70L tank, hence there is no scenario B.

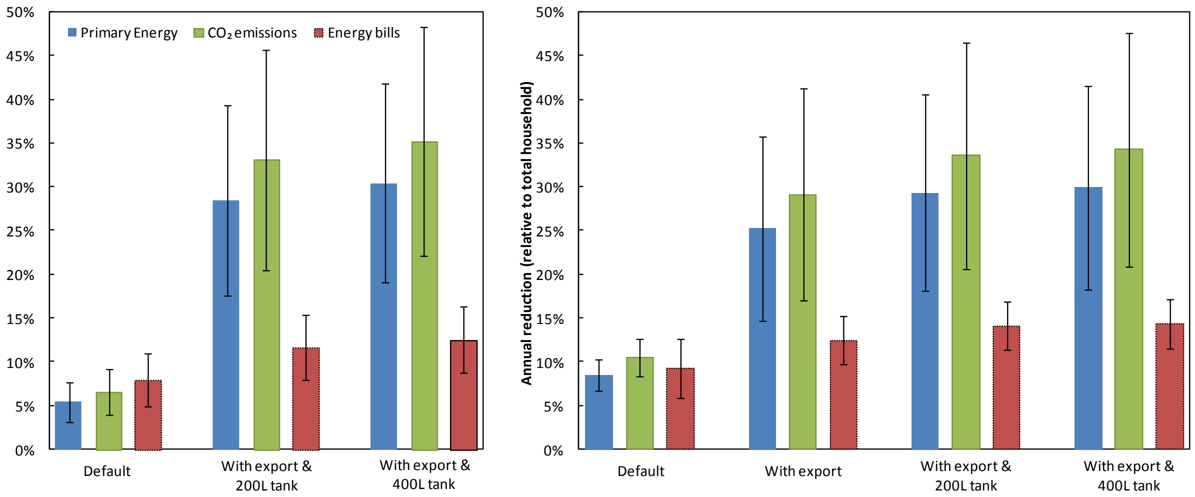

Figure 5.10: The environmental and economic benefits of ENEFARM (left) and Kyocera systems (right), given relative to the total consumption / emissions / bills for each house with the reference scenario.

It is immediately obvious that enabling the export of electricity has enormous benefits to the fuel cell's performance; it enables both types of fuel cell to produce more energy (3.5 times more for ENEFARM), and to operate with higher efficiencies due to fewer shut-down cycles and periods at low operating power. Simulated electrical efficiencies increased sharply for the Kyocera system when exports were enabled, rising from 30.8% in the default UK scenario (constrained by relatively low electricity demand), past 34.8% as measured in the Japanese field trials to a high of 39.1% when the system was able to operate at full load for most of the time.

Increasing the hot water tank capacity from 70 to 200L also had a positive effect for Kyocera, allowing output to increase by 11%; however the utilisation of thermal energy was not such a problem in the UK, as significantly larger thermal demands meant that only 3% of heat had to be dumped, even with a 70L tank. Increasing tank capacity from 200 to 400L had relatively little effect on the performance of either system, as with a 200L tank the majority of 0.7kW systems were already running at full capacity 24 hours a day.

The absolute reductions in primary energy and CO_2 emissions from the default scenario were lower than those measured and simulated in Japan,[81] because local electrical demand was substantially lower in the UK. These rose by a factor of 3-4 with export and a 200L tank, giving relative reductions in the range of 25-35%. These were similar to the values reported in Japan, however the two figures are not comparable due to the different definitions used; the savings in the UK were in fact much greater as it was ~30% of the total household emissions that could be saved by installing a fuel cell.

The absolute emissions reductions for these scenarios are plotted in Figure 5.11. The impact of a ‘better’ reference system in the UK (higher efficiency boilers and lower grid emissions) was clearly offset by the benefits of greater utilisation, and absolute reductions were over double those measured in Japan.[82] The savings from ENEFARM systems can be seen splitting into two distinct bands in houses with higher heat demand, due to the mix of 0.7-0.75 and 1.0kW systems installed. The upper limit on savings is more clearly defined for Kyocera systems, which were capable of operating at close to 100% utilisation in many of the houses.

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[81] ENEFARM saved 1672 ± 1263kWh and 378±278kg of CO_2 in the default UK scenario, and Kyocera saved 2329 ± 1054kWh and 540 ± 222kg.

[82] CO_2 savings were 1.2 times greater for Kyocera and 2.5 times greater for ENEFARM, while primary energy reductions were 1.8 and 3.5 times greater respectively.

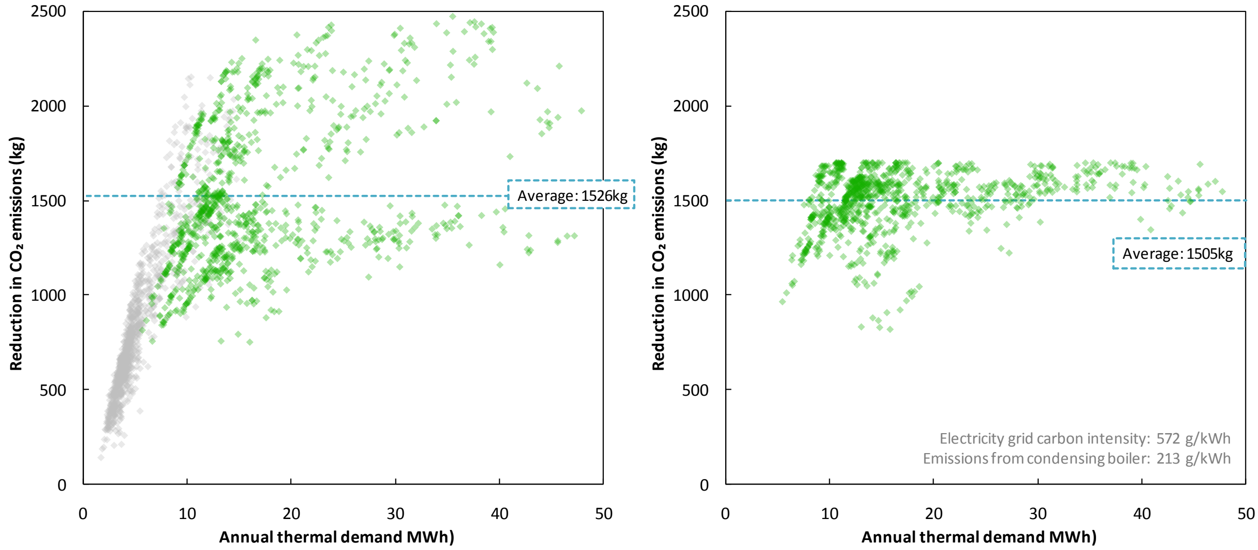

Figure 5.11: Estimated CO_2 reductions from ENEFARM (left) and Kyocera (right) with electricity export and a 200L tank. Results from the Japanese simulation (Figure 5.9) are superimposed over the ENEFARM figure in lighter grey.

From Figure 5.10 it can be seen that financial benefits were more modest than the environmental ones. Approximately 60% of the fuel cells' electricity was exported, earning less revenue than reducing local consumption. Figure 5.12 shows a clear trend between the amount of energy demand and the savings that can be made, and that SOFC achieve marginally higher savings on average, with a particular benefit in smaller properties.

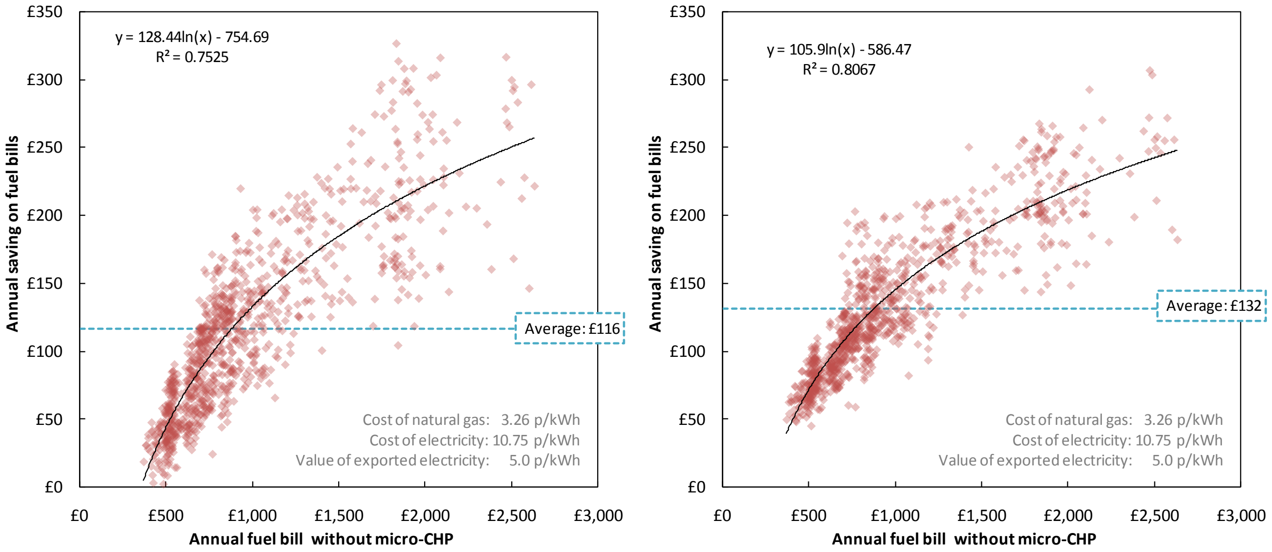

Figure 5.12: Estimated financial savings from ENEFARM (left) and Kyocera (right) with electricity export and a 200L tank. Savings are plotted against the total energy bills for the reference scenario, and fitted to a logarithmic function.

From these simulations, it can be concluded that the UK could provide much better operating conditions for these fuel cells, as the colder climate (combined with woefully inadequate insulation) and potential for exporting excess electricity allow for virtually unconstrained electricity and heat production. Both Kyocera and ENEFARM fuel cell systems would have a significant beneficial impact on UK domestic carbon emissions, reducing household emissions by around a third.

5.5. Concluding Remarks

The simulation method was validated against others presented in literature, and against the empirical findings from field trials of both PEMFC and SOFC systems in Japan. Agreement between the model and these standards was generally good: the simulated operating patterns were comparable to those seen in the field, and the estimated total amount of energy production was statistically similar to the measured values in all cases. The only major deviations were with the proportions of generated electricity and heat that were used on-site, which could be attributed to using different demand data, especially in the case of simulating operation in Japanese houses.

The key finding was that when the model was supplied with detailed specifications of a system's performance at steady state, it was able to predict the impact of the dynamic operating conditions in most situations. The actual generating efficiencies seen in the Japanese field trials were statistically similar to those simulated with FC++, implying that the dynamic features of domestic operation were accurately replicated.

This represents an important step forwards in the techno-economic modelling of fuel cell systems, as it allows those with a detailed knowledge of a system's laboratory performance to speculate how it would perform in the field. This could be used to inform system development, for example by identifying which technical improvements would have the greatest impact on real-world performance.

The results presented in the last section of this chapter were a prelude to the main analysis which is presented in Chapter 6, in which four fuel cell technologies (including AFC and PAFC) are simulated in UK houses, and their impact on domestic carbon emissions and fuel costs is studied in more detail.

Chapter 6:

RESULTS OF FUEL CELL SIMULATION

6.1. Summary

Following on from the simulation of specific products, the FC++ model was used to consider the impact of installing different fuel cell technologies and the multitude of different micro-CHP products that are currently under development.

Four key pieces of information were taken from the model: the amount of natural gas consumed by the fuel cell, the reduction in gas consumed by the boiler, the reduction in electricity purchase, and the amount of electricity exported. The central results were then used to estimate the financial and carbon savings that could be made from operating fuel cell micro-CHP systems in the UK.

The expected range in the performance of fuel cell systems, and the variety of houses they could be installed into were both shown to have profound effects on results. The influence of other input assumptions was investigated in a series of sensitivity analyses, considering the choice of energy tariff, levels of financial support from government, and the sources of electricity that could be displaced by micro-CHP.

6.2. Simulation of Industry-Average Fuel Cell Micro-CHP Systems

Simulations were run with the 1,000 UK domestic energy profiles and the aggregated performance data for each fuel cell technology that was given in Table 4.3. Input parameters for the main simulations were varied over the presented standard deviations using one thousand Monte Carlo trials. The minimum load factor of the fuel cell was taken to be 30% of full power, except for SOFC for which it was 15% (based on Kyocera systems). PEMFC and AFC were assumed to switch on and off according to the control logic depicted in Figure 4.17, and required 1 hour of pre-heating which consumed 20Wh of electricity and 1.5kWh of natural gas. SOFC and PAFC were assumed to operate continuously to avoid shutting down, operating at their minimum power and dumping any excess heat when absolutely necessary.

The backup system used by each fuel cell was considered to be the same as the reference scenario that was used for comparison, which consisted of electricity purchased from the national grid and heat generated by an 85.5±3.5% efficient condensing boiler.

6.2.1. Changes to Energy Consumption

The main calculation consisted of simulating each fuel cell technology with a 1kW electrical capacity, operating with a 400L (20kWh) hot water tank over the course of one year. The simulated changes to annual energy consumption relative to the reference scenario are summarised in Table 6.1, along with aggregate statistics on the fuel cells' operation. Due to the similarities in operating efficiency and constraints, the results of AFC and PEMFC were generally similar, as were those of SOFC and PAFC. The following analysis therefore focuses on PEMFC and SOFC in particular.

	PEMFC	**SOFC**	**PAFC**	**AFC**
Electrical efficiency (HHV)	24.4 ± 1.7%	31.0 ± 2.2%	30.9 ± 1.7%	25.5 ± 1.3%
Thermal efficiency	40.0 ± 3.9%	34.6 ± 4.8%	38.5 ± 2.8%	38.1 ± 3.5%
Electricity produced (kWh)	6042 ± 941	6790 ± 815	6905 ± 911	5989 ± 807
(proportion of household demand)	75 ± 11%	79 ± 11%	80 ± 11%	76 ± 11%
Electricity exported	64 ± 14%	66 ± 14%	66 ± 14%	61 ± 19%
Heat produced (kWh)	9886 ± 1443	7561 ± 825	8554 ± 1053	8962 ± 1177
(proportion of household demand)	67 ± 20%	52 ± 18%	59 ± 19%	64 ± 14%
Heat dumped	-	0.9 ± 1.7%*	1.6 ± 2.3%*	-
Additional gas consumed (kWh)	13107 ± 1645	12951 ± 1124	12244 ± 1093	12967 ± 1448
Operating hours	7872 ± 634	8760	8760	8007 ± 575
Utilisation[83]	76 ± 12%	87 ± 10%	83 ± 11%	81 ± 11%
Number of cycles	63 ± 66	-	-	39 ± 45

*Table 6.1: Operating statistics from 1,000 Monte Carlo trials of 1kW fuel cells simulated operating for one year in 1,000 UK houses. * Note that no heat had to be dumped in 36% of houses with an SOFC, or 27% with a PAFC.*

Figure 6.1 depicts the simulated flows of energy through a typical house using a 1kW PEMFC system. 34.1MWh of natural gas was consumed over the course of a year, which was 13.4MWh more than if only a boiler was used; however electricity purchase was reduced by 2.2MWh, and an additional 3.8MWh of electricity was exported to the grid.

These relative changes in gas and electricity consumption were the main output of the model as they determined the economic and environmental benefits of using the fuel cell. The full set of results is plotted in Figure 6.2, showing the spread of results between properties and Monte Carlo trials. The range of houses produced the observed spread in the amount of gas consumed by the fuel cell, whereas the deviation in results from a straight line was due to the variation in performance assumptions. For any of the individual Monte Carlo trials, the R^2 values for straight line fits were around 0.97-0.99, with the remaining difference caused by the different operating profiles in each house.[84]

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[83] Utilisation is defined as the annual average power output divided by the maximum possible output: 1kW x 8760 hours per year.

[84] The average seasonal efficiencies were influenced by the proportion of time that the fuel cell was operating at high load factors and the number of start-up cycles, which were in turn determined by the shape of the energy profile in each house.

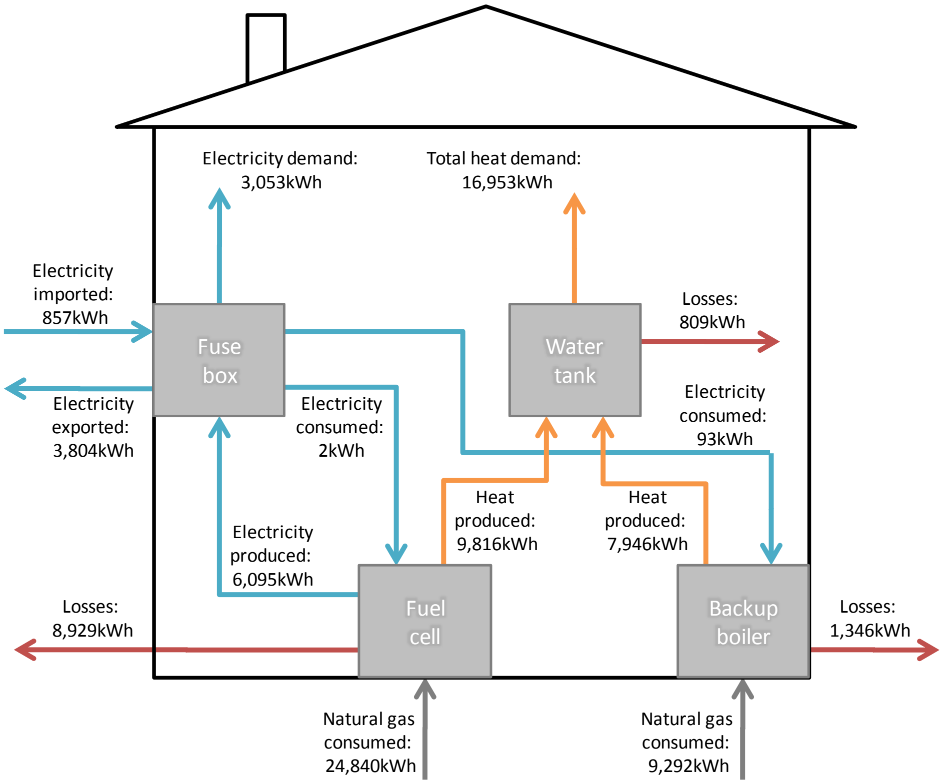

Figure 6.1: Depiction of the energy consumption, losses, and flows between the devices in an average house with a PEMFC installed. The fuel cell consumed much less electricity than the gas boiler as it only required external power during start-up, and consumed its own power when operating. Reference [137] provides a similar diagram for comparison.

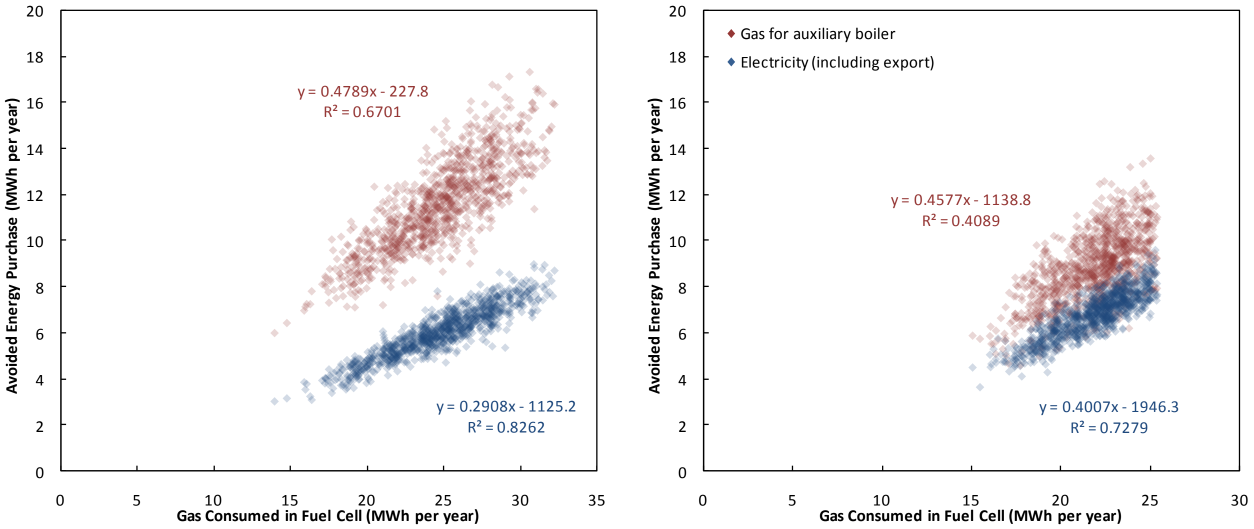

Figure 6.2: Change in energy purchase due to installing a 1kW PEMFC (left) and SOFC (right). Note that only 1,000 of the results are plotted due to technical and visual limitations – 1 result for each house was randomly chosen from the Monte Carlo trials. The parameters of straight line fits to each data set are shown.

6.2.2. Fuel Cell Performance

Table 6.1 gave the average seasonal efficiencies predicted for each fuel cell technology. The efficiency of each fuel cell technology, simulated in each of the 1,000 properties is plotted in Figure 6.3 against the traditional and best available systems in the UK, in the same manner as in Figure 4.3. The predicted efficiencies of PEMFC and AFC systems were broadly the same, with both offering 0-9% improvement over the best available alternative in the UK. SOFC and PAFC were also similar, giving 10-19% and 13-21% improvement respectively. These values for all four technologies were similar but slightly lower than those presented in Figure 4.3, due to the simulated effects of operating in the field.

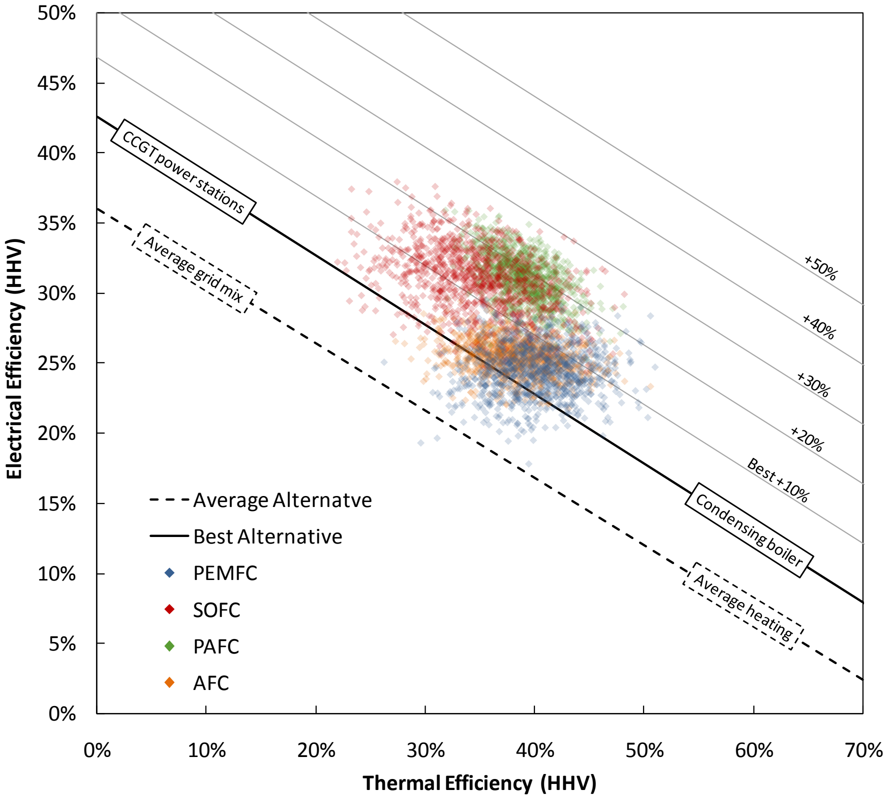

Figure 6.3: Simulated annual average electrical and thermal efficiency of each fuel cell technology, plotted against lines connecting the traditional and best available systems in the UK.

The low part-load efficiency, degradation and start/stop constraints of each fuel cell meant that seasonal efficiency was simulated to be several percent below the rated specifications given in Table 4.3. A breakdown of these losses is depicted in Figure 6.4, giving a comparison of the industry-wide efficiencies input into the model and the seasonal efficiencies calculated by it. All of the dynamic effects had a negative impact on electrical efficiency; however, voltage degradation acted to improve thermal efficiency to the extent that seasonal thermal efficiencies for SOFC and AFC were above the values quoted from laboratory studies.

It is worth noting that many previous simulations of fuel cells do not consider any of these sources of efficiency loss (e.g. [109, 123, 126]), and so are expected to over-estimate the benefits of operating a fuel cell in the real world. When all of these dynamic effects were excluded in FC++, CO_2 reductions were over-estimated by 30-35% (250-400kg per year) and financial savings by £20-40 per year.

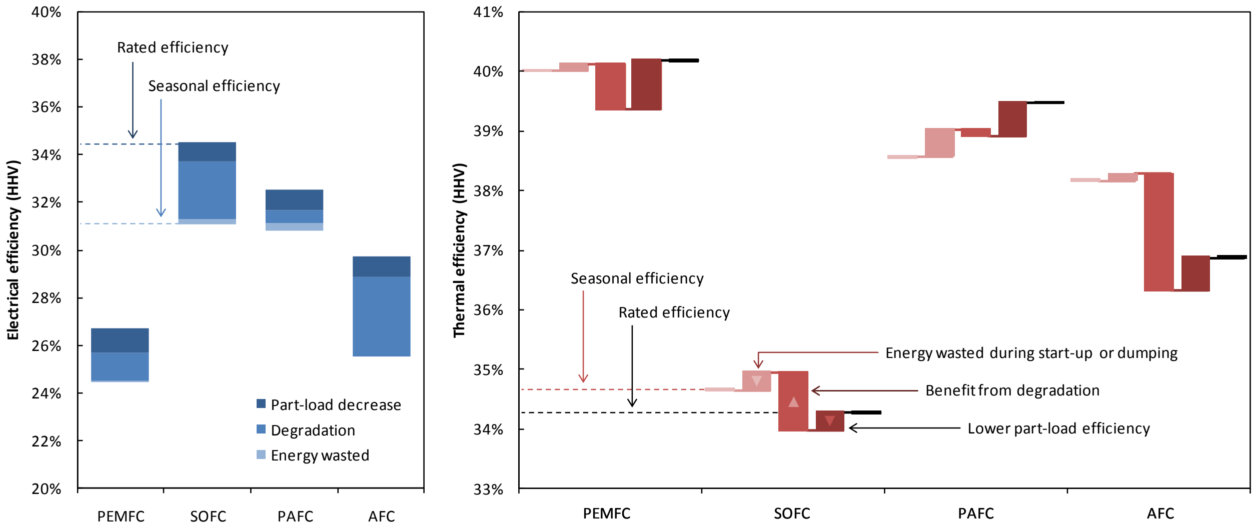

Figure 6.4: A breakdown of the sources of efficiency loss (and gain) caused by the dynamic performance effects simulated within FC++. These acted to lower electrical efficiency (left), so tracing each bar downwards charts the fall from rated input to simulated seasonal efficiency. Tracing each sets of bars for thermal efficiency (right) from right to left shows the rise and fall caused by each dynamic effect.

6.2.3. Influence of Domestic Energy Demands

There was a wide range in the seasonal efficiencies plotted in Figure 6.3, much of which was due to the Monte Carlo variation in input parameters (particularly rated efficiency), and the different houses the fuel cells were simulated in. Figure 6.5 shows that efficiency had only a limited dependence on the total amount of energy demanded by the house. The worst performances for both PEMFC and SOFC were seen in the smallest houses; however the varied patterns of energy demand meant that some of the top-performing systems were also located in houses with low energy demand. A more identifiable trend was seen with the thermal efficiency of PEMFC, which fell in houses with below average thermal demand (<17MWh per year).

The amount of energy produced by the fuel cell also showed only a limited correlation to the annual energy demand of the house. Figure 6.6 again shows that the different patterns of energy demand seen in each property dominate the spread of results. Energy production generally increases with the amount of demand, however R^2 values were below 0.5 in all cases. The only clear trend was that PEMFC output was limited in houses with less than 17MWh per year of thermal demand, resulting in more frequent shutdowns – which in turn led to the lower efficiency shown in Figure 6.5.

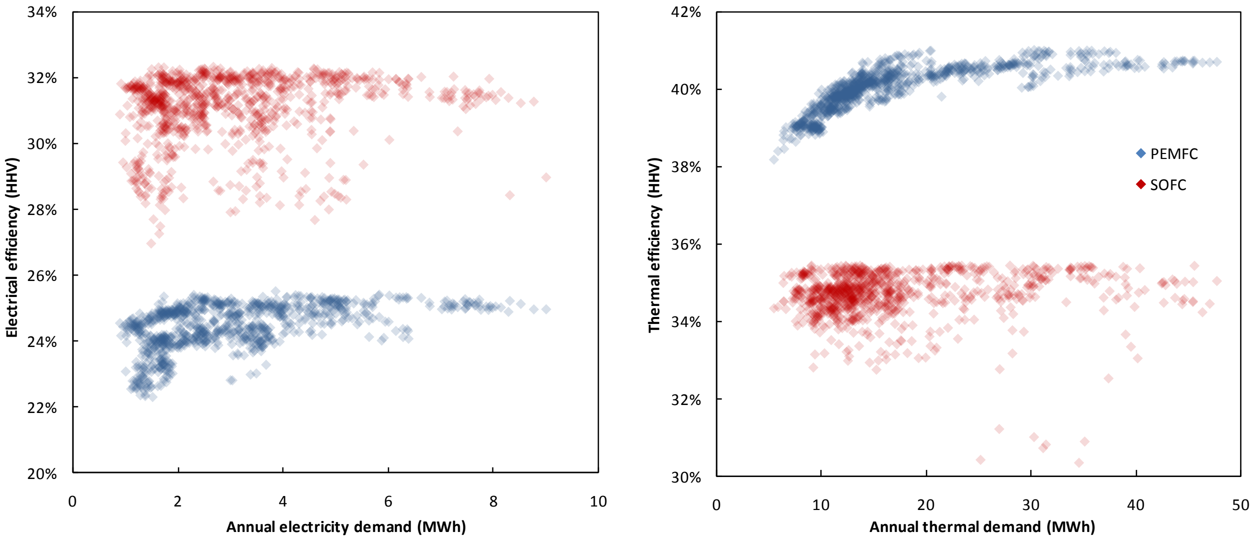

Figure 6.5: Simulated electrical and thermal efficiency of PEMFC and SOFC systems plotted against annual electrical and thermal demand respectively. Results were taken from the central performance inputs, as the Monte Carlo variation swamped any observable trends between houses.

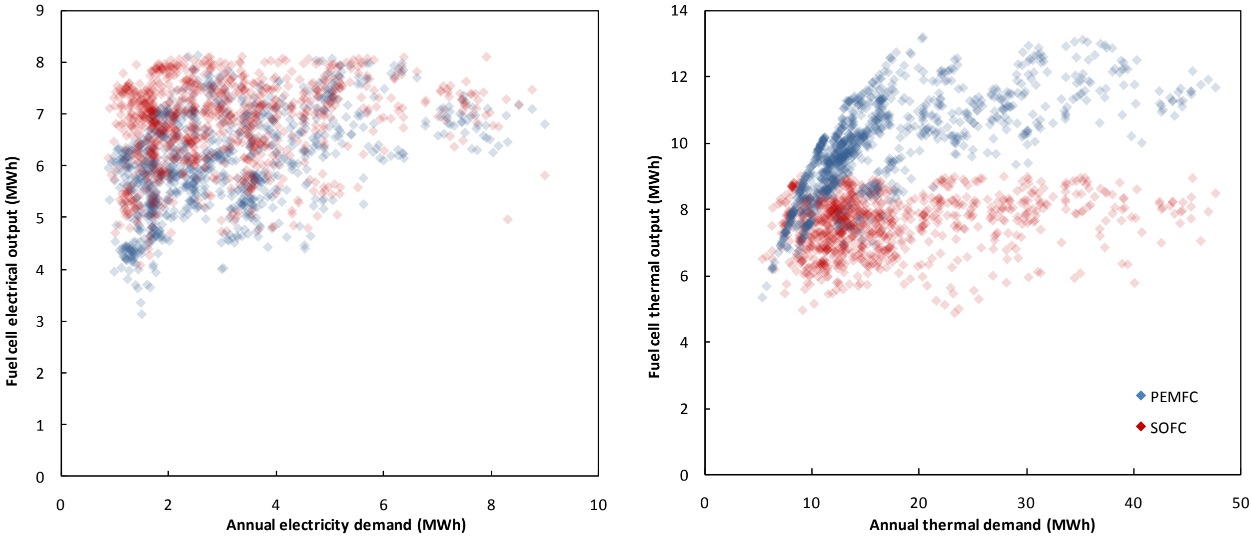

Figure 6.6: Simulated electrical and thermal output of PEMFC and SOFC systems plotted against annual energy demands, taken from the same simulations as used in Figure 6.5.

A similar lack of correlation was seen when the properties were grouped by number of bedrooms.[85] There was no statistically significant difference between these groups in either the efficiency of the fuel cell or the amount of energy produced. For example, it could only be said with 30-35% confidence that a PEMFC produced more energy in a 4 bedroom house than it would in a 2 bedroom house. The traditional means of categorising profiles by annual energy demand or type of construction are therefore likely to produce results that differ more widely within each group than between them, and the general trends that have been observed (such as fuel cells in detached houses achieving the greatest CO_2 savings [20, 109, 126]) cannot be expected to apply in every case.

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[85] While thermal profiles could be classified by the number of bedrooms, it must be remembered that electrical profiles could not be guaranteed to come from the same size of building as they contained no demographic information. The total annual electrical demand in each profile was however similar to that of the houses in the BRE profiles due to the matching algorithm used.

As well as using a limited number of houses, it is common for simulations to use only a selection of individual days. Pawlik found that when simulating a fuel cell in a single house, results deviated by less than 5% if three specific days were chosen (one winter, one summer, and one from spring or autumn) as opposed simulating the whole year.[126] This claim was tested by choosing three random days in December, July and either April or October from each of the profiles, and comparing the results from these days with those from simulating the whole year. Four of the profiles are plotted in Figure 6.7, showing that the heat demand over the three days was higher than the annual average (by 14±11%), and that electrical demand differed widely around the average (by 1±20%).

Using the economic and environmental assumptions from Table 5.8, the use of 3 randomly chosen days resulted in a 440±329kg overestimate in the annual CO_2 reductions from using a PEMFC system (40±27%), and a £55±72 overestimate in annual savings on fuel bills. Using only a limited selection of demand data therefore introduces errors into simulation results of a similar magnitude to using electricity demand with only hourly resolution.[130]

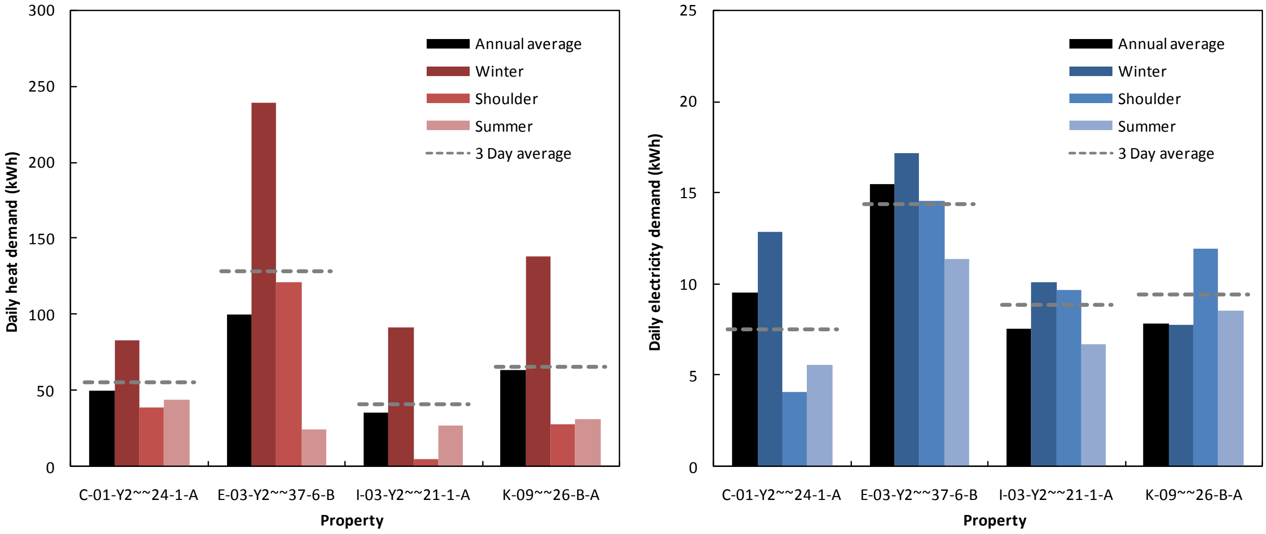

Figure 6.7: Comparison of the energy demanded in four houses during selected days and over a whole year.

6.2.4. *Influence of Component Sizes*

The preceding analysis only considered fuel cells of 1kW electrical capacity operating with a 400L hot water tank. Other devices capacities were simulated to investigate their influence on results, and the optimum combination from different perspectives. The annual reductions in CO_2 emissions and energy costs are presented for 30 combinations of fuel cell and tank capacity in Figures 6.8 and 6.9 respectively. For these calculations, the central performance figures were used with no Monte Carlo variation and only the average results from the 1,000 profiles are presented. While the standard deviation in each data point was relatively large (as in previous figures) the results from each individual house were correlated, so the same trends would be observed.

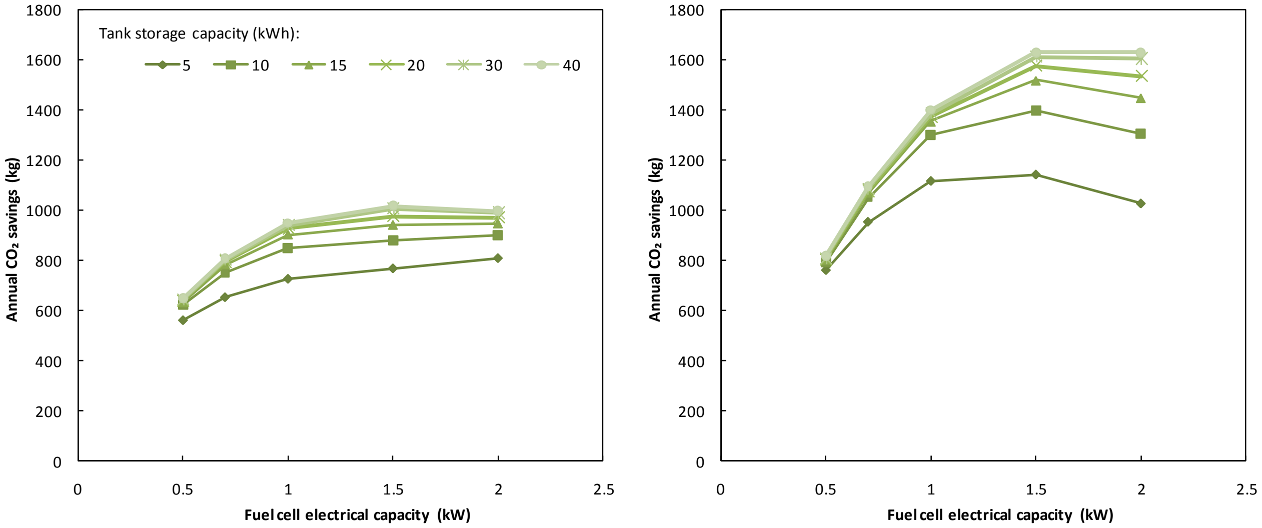

Figure 6.8: Influence of fuel cell and tank capacity on CO_2 savings, for PEMFC (left) and SOFC (right).

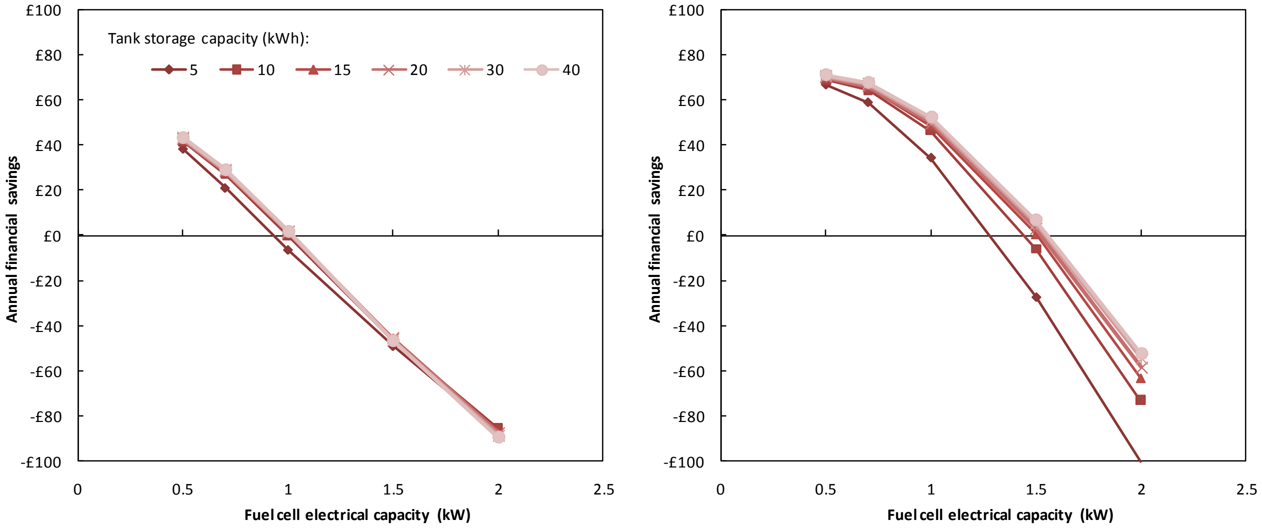

Figure 6.9: Influence of fuel cell and tank capacity on financial savings, for PEMFC (left) and SOFC (right).

The environmental and economic outcomes show markedly different trends as maximising energy production has a positive environmental impact, but is not profitable with the assumed export price of 5p/kWh. The optimum fuel cell capacity was 1.5kW for maximising CO_2 reductions, as smaller systems produced less energy, and 2kW systems either had to shut down more frequently, or dump more unwanted heat. In contrast, 0.5kW or less was the optimum capacity for minimising annual fuel costs, as generating electricity for export resulted in a financial loss to the owner. This result was highly sensitive to the assumed value of exported electricity as shown in the following section, and an export value above 7-8p/kWh would result in higher capacities (>2kW) being the economic optimum.[20]

Using a larger water tank offers better results; however beyond a certain capacity the rate of improvement becomes marginal. The slight increase in heat losses from storing a larger volume of hot water were offset by enabling longer running times, with fewer shutdowns or less dumping. The marginal benefit of using a larger tank however must be balanced against the additional upfront expense and the space required – which were not factored into this analysis.

For PEMFC up to 1kW, tanks above 300L (15kWh) yield diminishing returns, while a slight improvement can be gained by increasing to 400-600L with 1.5-2kW stacks (as done by Baxi for example). SOFC systems show a much greater dependence on tank capacity due to their need to generate heat continuously, as shown in Figure 6.10. Again, a 300L tank appears sufficient for a system up to 1kW, but the penalty for decreasing tank capacity below this is much larger than for PEMFC. 1.5 and 2kW SOFCs would operate best with a 600L tank, with no appreciable benefit in increasing to 800L.

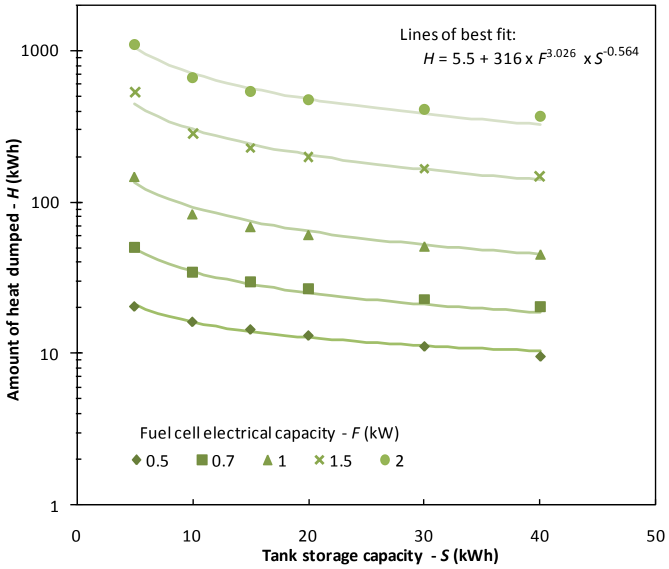

Figure 6.10: Amount of heat dumped annually by each capacity of SOFC system simulated with different tank sizes. The average amount of heat dumped in each scenario is shown by the data points, with a parametric fit to the entire group shown as the individual lines.

6.2.5. Influence of Operating Strategy

Section 4.4 outlined the benefit of using fuzzy logic to decide the fuel cell's immediate operating strategy based on the status of the hot water tank. A 1kW PEMFC system was simulated using the default fuzzy control strategy and the simplified maximum demand lead strategy, both with the central performance assumptions from Table 4.3 and a 400L storage tank. Applying the fuzzy logic resulted in a 54% average increase in the utilisation, equating to an additional 2253 ± 1186kWh of electricity produced per year. The mean reduction in CO_2 emissions was therefore

55% higher (978 ± 250kg per year *cf.* 637 ± 274kg), although this improvement was unevenly distributed across the individual properties. Figure 6.11 compares the results from individual houses with and without the fuzzy control strategy. Fuel cell utilisation was increased by a factor of three in some of the smallest houses, however the improvement was as little as 10% in the largest houses, as they had sufficient demand to not constrain the operation of a maximum-lead fuel cell.

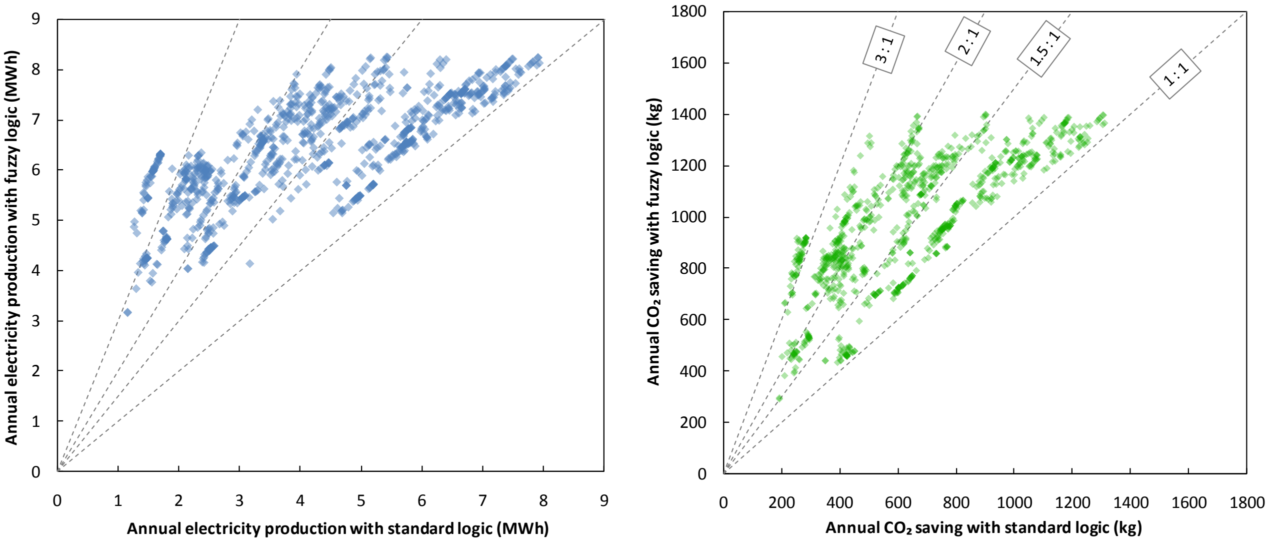

Figure 6.11: Comparisons of the results of simulating a 1kW PEMFC system with a maximum load-following strategy and the modified fuzzy control logic. The amount of electricity produced (left) and CO_2 savings (right) from each of the 1,000 properties are shown for the two scenarios.

A second operating constraint that was contained within the control logic was the dumping of heat from SOFC and PAFC systems that were unable to shut down. Although the amount of heat that had to be dumped from these systems was low,[86] it impacted on the benefits they offered. As the economic benefit was already marginal, the impact of dumping heat had a large relative effect. An alternate operating strategy for SOFC would be hot-idling: keeping the stack supplied with a minimal amount of hydrogen and drawing no current, while using an electric furnace to maintain operating temperature. This strategy was simulated in FC++, and the reductions in CO_2 emissions and energy costs are compared in Figure 6.12.

The fuel cell's electrical efficiency drops as the power required for hot-idling increases, whereas the thermal efficiency drops with decreasing tank size as more heat must be dumped; both of which lowered the benefits from operation. Thermal dumping with the default 400L tank resulted in a 0.5% decrease (in absolute terms) in both CO_2 and financial savings, which would be matched by hot-idling with a standby heat requirement of between 0.75 and 1kW.

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[86] 80-90% of houses with a 1kW PAFC or SOFC would dump less than 2.5% of the heat generated.

Analysis of the part-load efficiency of the Kyocera SOFC (presented in Figure 5.3) and experience with operating a 1kW SOFC stack from Fuel Cells Scotland suggests that 75-100W is required to maintain stack operating temperature. Manufacturers would therefore see a slight improvement in performance if they could incorporate the ability to hot-idle without causing any degradation from redox or thermal cycles.

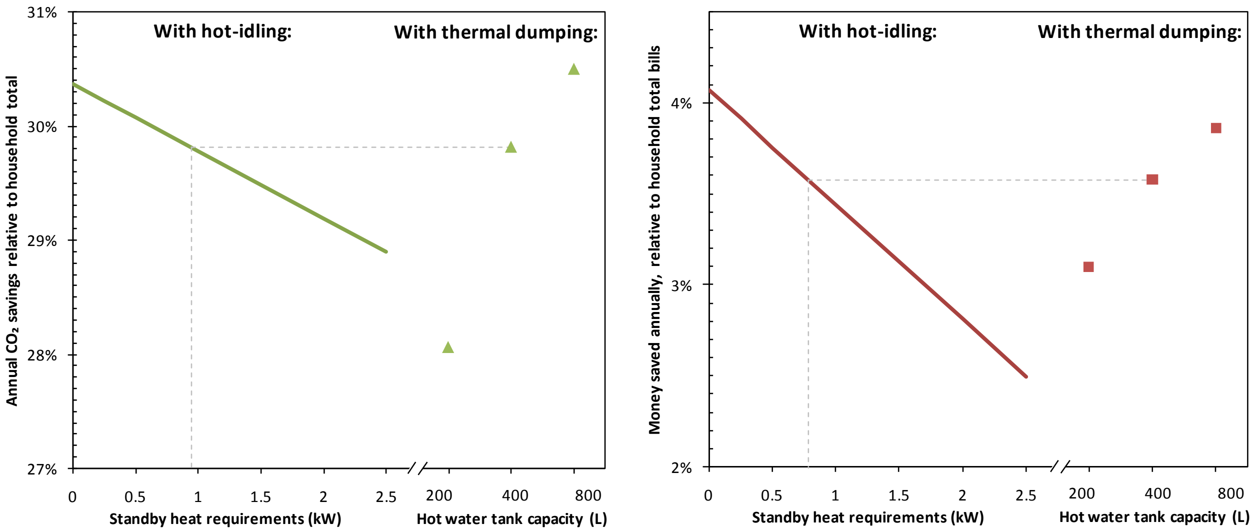

Figure 6.12: Comparison of the environmental and economic benefits of SOFC operational modes. Hot-idling with a 400L tank and a range of standby heating powers is shown as the line to the left of each plot, and thermal dumping with different capacities of hot water tank are shown with the data points to the right.

6.3. Estimated Operating Costs and Savings

The results of the central simulations (1kW fuel cell with a 400L tank) given in Table 6.1 were used to calculate the economic benefit of operation to the homeowner. Previous studies have shown that the magnitude of this benefit is heavily dependent on the ratio of electricity to gas prices (the spark gap), and the value of exported electricity. Data on the range of energy prices available in the UK was therefore sought to keep the simulation relevant to the UK.

6.3.1. Economic Assumptions

There is no single price for electricity or gas in the UK, as different tariffs are offered by the numerous private suppliers. Gas and electricity prices were recorded from the lowest cost tariffs[87] of the six largest suppliers in March 2009, and are presented in Figure 6.13. Electricity rates vary by an additional ±10% between the 14 distribution regions in mainland UK, however only prices for the West Midlands region was considered in this study.[88]

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[87] These were for direct debit payment (as opposed to credit or prepayment) and a mix of internet-only, dual-fuel and fixed-price deals.

[88] Prices in this region were 2.3% below the national average, based on the direct debit tariffs offered by EDF.

The spark gap in the UK was 3.3±0.5, based on gas prices of 3.26±0.24 p/kWh and electricity prices of 10.79±1.99 p/kWh. The bulk of the following analysis uses these average energy prices, with the impact of using different suppliers considered in a sensitivity analysis.

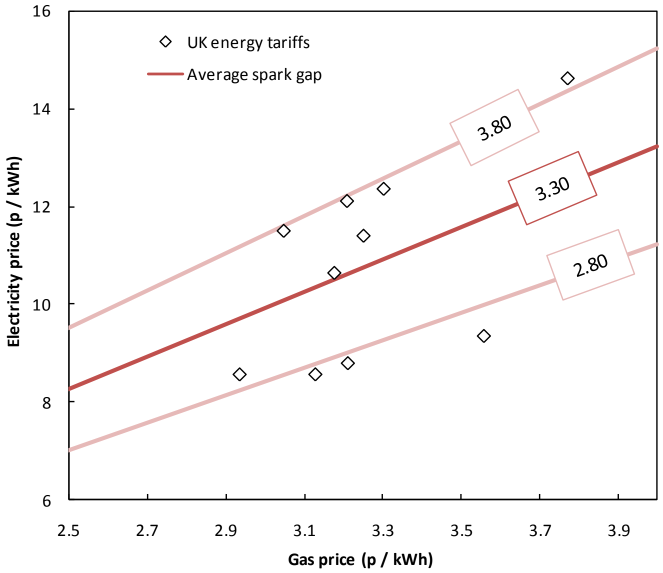

Figure 6.13: Energy prices offered by six major suppliers in the UK, highlighting the range in the ratio of electricity to gas prices.

As 50-80% of the electricity produced by a 1kW fuel cell will be exported,[89] the value of this export is in fact more important to economic viability than the electricity import prices given in Figure 6.13. Customers generally expect that the export price they receive should be the same as the import price they pay; however this neglects the additional costs incurred from distribution, metering and billing.[253] A breakdown of electricity costs estimated by Ofgem suggested that the wholesale cost of generating electricity was around half the rate charged to domestic consumers. By factoring in the distribution losses and other costs that can be avoided, the value of microgeneration to the energy supplier was estimated to be 2.7-5.8 p/kWh,[90] depending most strongly on the wholesale generation costs.[253]

Ten energy supply companies provide export tariffs in the UK, some of which offer substantially higher prices in the range of 12-18 p/kWh.[254] The majority of these are only available for renewable microgeneration: solar PV, hydro, wind, or micro-CHP fuelled on biomass, digester gas or chip fat. Only three companies were found that offer export tariffs for natural gas fired micro-CHP, which are listed in Table 6.2.

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[89] Taken from Table 6.1.

[90] This value was net of the £13-30 additional annual costs estimated for metering and costs to serve – based on 4.2±1.0 MWh of electricity exported per year, taken from Table 6.1.

Company	**Export price (p/kWh)**	**Upfront meter cost**
British Gas	5.0	£300
NIE Energy[91]	7.4	£0
Scottish & Southern	5.0	£0

Table 6.2: Metered export tariffs available for micro-CHP users in the UK as of August 2009.[254] An export meter is required for these tariffs, which can incur an additional cost to the customer.

In addition to the price paid by the energy supplier, the UK government has announced its intention to offer a Feed-in Tariff (FIT) for microgeneration, in line with those offered in many other European countries.[255] A fixed payment per kWh of electricity generated (as opposed to just those exported) will be guaranteed by the government for a period of 20 years from April 2010. Initial tariffs have been published for most technologies, however it is not known at this stage what will be offered for non-renewable micro-CHP, due to uncertainty in current technology forecasts, and the added complexity of crediting the low-carbon heat they also produce. The government however “recognise the important role that micro-CHP over various technologies could play”,[255] and so it is expected that the tariff will be set at competitive levels. A default value of 10p/kWh for generated electricity was assumed in this study.[92]

Two levels of support were therefore considered in the central analysis: the current situation where 5p/kWh is earned per kWh of electricity exported; and with the proposed FIT, where an additional 10p/kWh is earned for every kWh generated (both for export, and on-site consumption).

It is acknowledged that customers could earn more than 5p/kWh for exports if renewable microgeneration tariffs were made available to micro-CHP, however the high rates offered by some suppliers are loss-making promotions designed to attract customers, and are therefore expected to be unsustainable in the long term.[253] As part of the FIT scheme, the government have offered a guaranteed minimum export price of 5p/kWh, in line with the wholesale cost of electricity.[255] The value of both exports and the FIT were varied to assess their impact on the financial viability of fuel cell micro-CHP, allowing recommended levels of support to be identified.

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[91] Available in Northern Ireland only.

[92] For comparison, the proposed tariffs for biomass and CHP from anaerobic digestion are 9p and 11.5p/kWh; whereas those for renewable generation range from 17-36.5p/kWh.

6.3.2. Central Results

If the 1,000 houses considered in this study were heated by a condensing boiler and powered by the grid (i.e. the reference scenario), their average annual fuel bill would be £977 per year. The distribution of these bills is shown in Figure 6.14. Heating contributed approximately two thirds of the average bill, as seen in the breakdown of the average reference bill given in Table 6.3. If the houses had instead used a 1kW PEMFC or SOFC, gas bills would have increased, but electricity bills decreased by a similar amount, and additional revenue from the FIT would be significant.

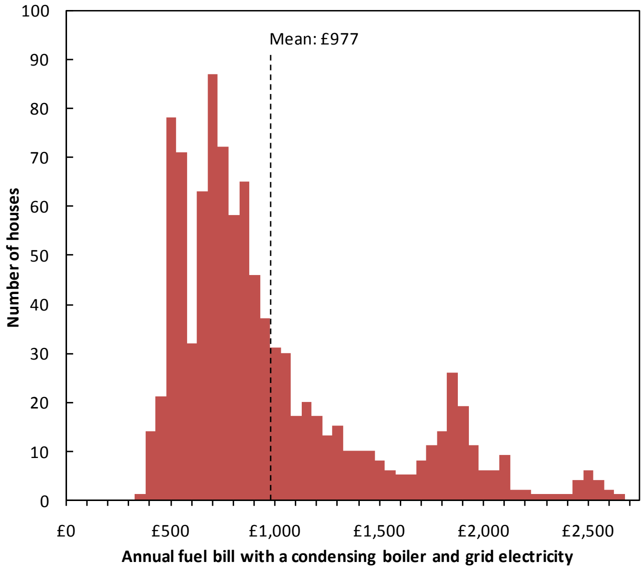

Figure 6.14: Histogram showing the distribution of fuel bills in houses without micro-CHP installed.

	Reference	1kW PEMFC	1kW SOFC
Gas purchase	£648 ± 325	£1070 ± 355	£1065 ± 337
Electricity purchase	£329 ± 187	£92 ± 91	£81 ± 87
Export revenue		-£193 ± 46	-£225 ± 54
FIT revenue		-£604 ± 94	-£679 ± 82

Table 6.3: Breakdown of the average fuel bills for the 1,000 houses from three different scenarios. Average energy tariffs were assumed, with a FIT of 10p/kWh.

For each of the 1,000 properties, the change in energy costs made by installing a fuel cell system was calculated both with and without the FIT support. The savings made in each house are plotted against the corresponding reference bill in Figures 6.15 and 6.16.

The savings that can be made from installing a fuel cell in each case can be approximated with a logarithmic fit to the reference fuel bill. Houses that pay more for energy (because of using more, rather than because of higher tariffs) can expect to achieve greater savings. This is in part because the fuel cell is likely to have greater utilisation, but is primarily because savings are greatest in houses where a high proportion of the generated electricity is used on-site, which offers higher value than exporting.

In the current situation, the estimated savings from operating a fuel cell were in many cases marginal or even negative; the additional cost of natural gas outweighed the value of electricity generated. Average savings across the 1,000 properties were close to zero for PEMFC and AFC systems, although slightly more positive for SOFC and PAFC due to their higher electrical and total efficiencies.

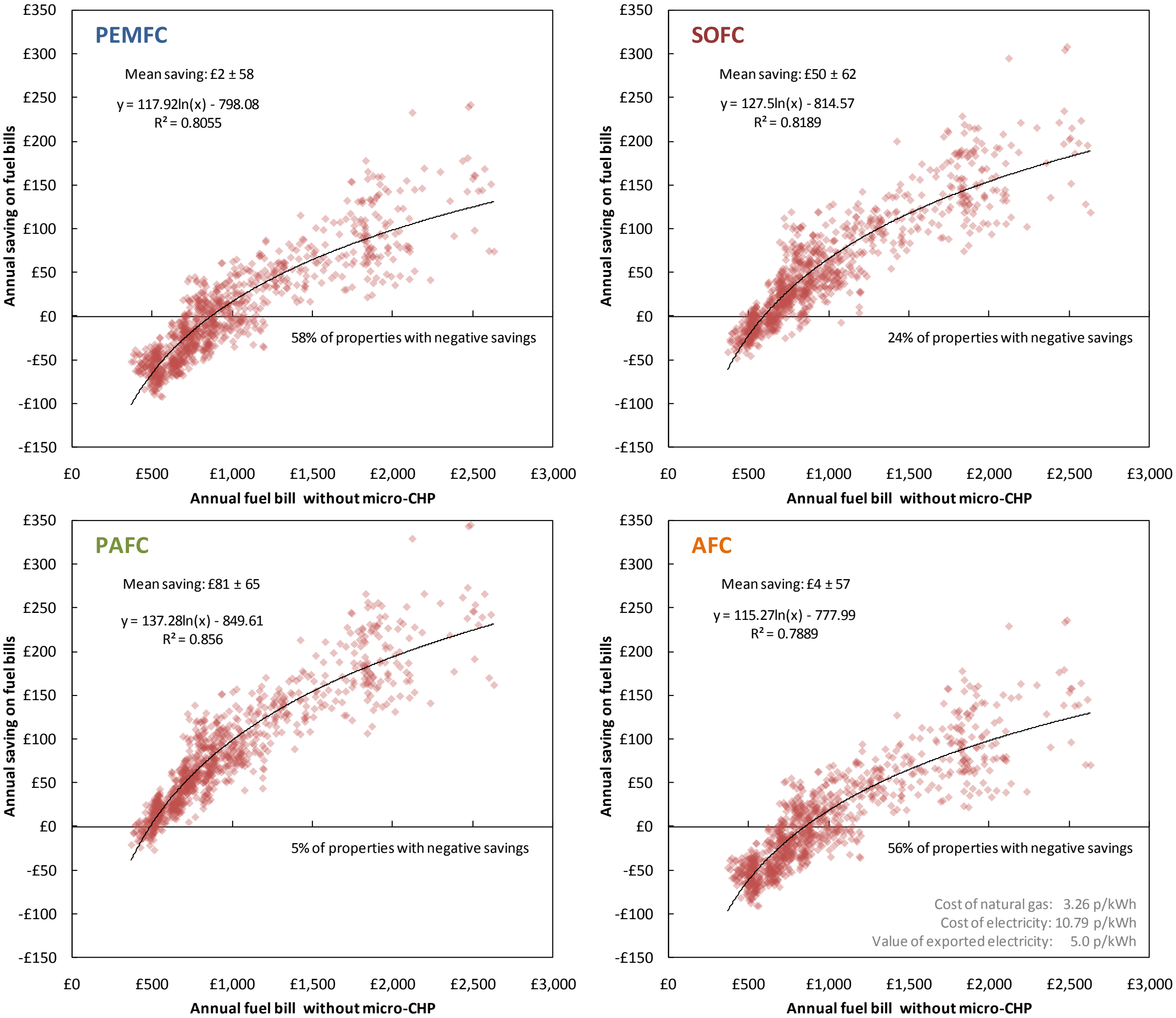

Figure 6.15: The distribution of annual savings made by installing each type of fuel cell system with current tariffs. Each data point represents the fuel bill and savings that were simulated in one of the 1,000 houses.

The proposed feed-in tariff has a profound beneficial impact for fuel cell micro-CHP, making every simulated installation generate revenue for the householder. A generation tariff of 10p/kWh would add £500-800 to the annual savings of each fuel cell, as total electricity production was simulated to be 5-8MWh per year. The average savings of £600-775 per year are comparable to those expected from other microgeneration technologies with the proposed FIT support.[255]

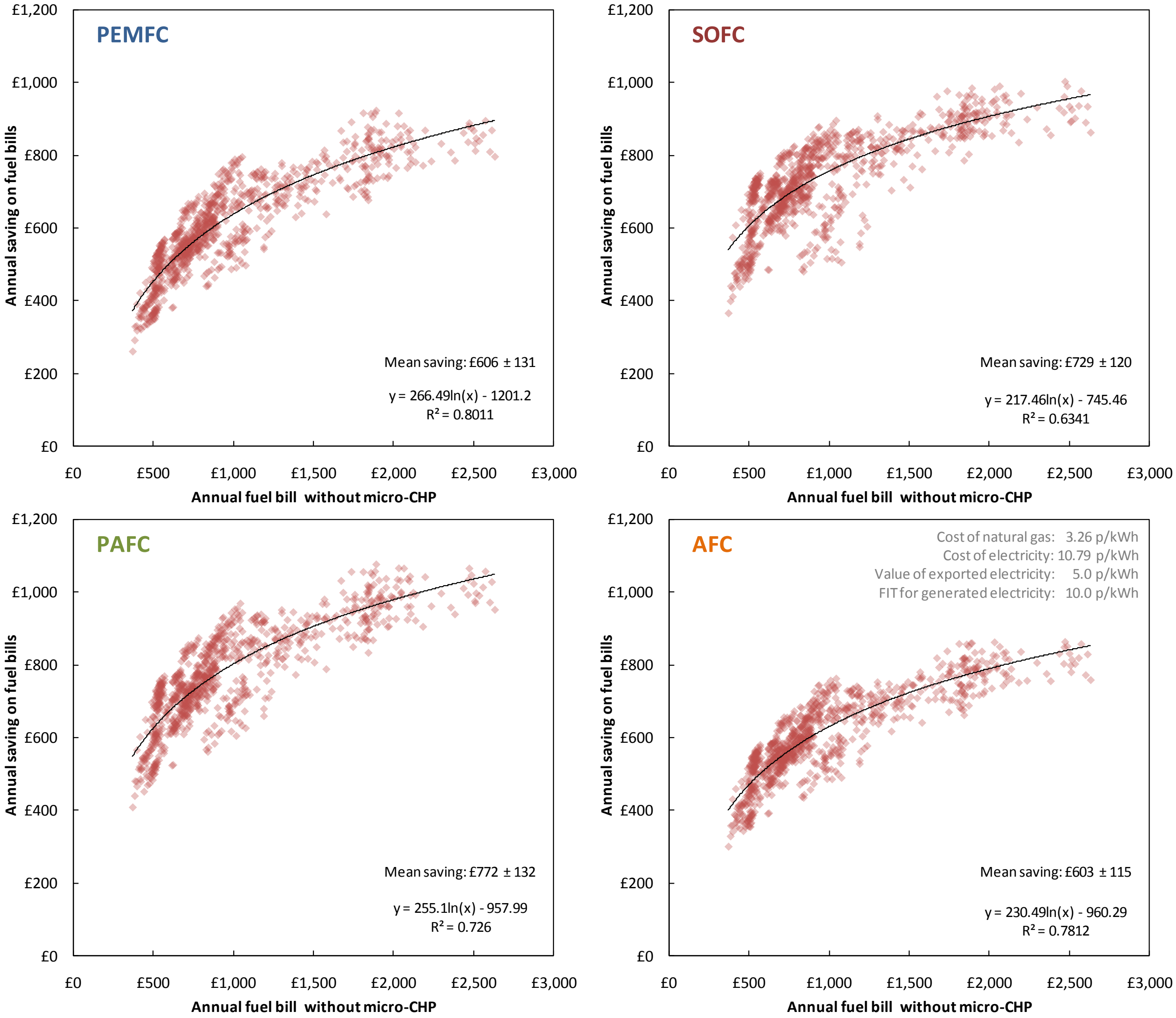

Figure 6.16: The distribution of annual savings made by installing each type of fuel cell system with a proposed feed-in tariff of 10 p/kWh.

Both the magnitude and the logarithmic trend in savings are sensitive to the relative value of local consumption and export, which was 2.15:1 in the current scenario, and 1.38:1 with the FIT. The logarithmic trend between reference energy bills and savings diminishes when export value rises, making Figures 6.15 and 6.16 begin to resemble those from Figures 6.5 and 6.6 – which showed the limited correlation between energy demand and the amount of generation from the fuel cell.

The observed spread of data points in Figures 6.15 and 6.16 is a novel feature of using 1,000 energy demand profiles. The results from previous simulations could be represented as a single data point on these figures, so by considering a large number of properties the wider average was found. Figure 6.17 presents the range of annual savings in each household relative to their energy bill in the reference scenario.

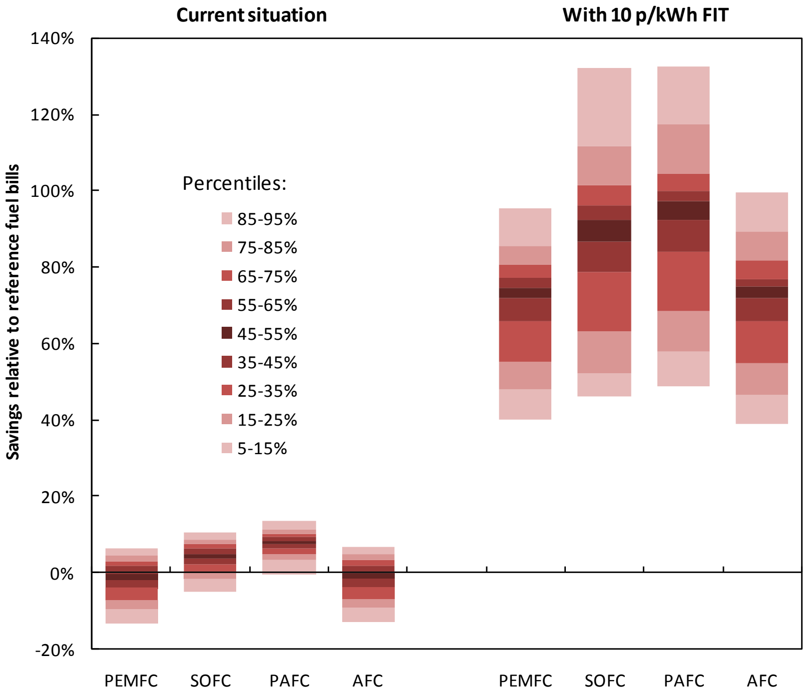

Figure 6.17: Relative savings from installing a 1kW fuel cell, with and without the proposed FIT.

Installing a fuel cell today could either raise or lower bills by up to 15%, with most houses losing money by installing a PEMFC or AFC system. The benefit of a 10p FIT is striking: reductions to the reference fuel bill rise to averages of 65-100%, and in more than a quarter of cases an SOFC or PAFC could save more than 100%. For example with a 1kW SOFC, the £515-620 annual reference bills would turn into a £55-105 overall rebate.[93] These are not necessarily the most profitable cases in which to deploy fuel cells as negative bills were typically seen in houses with low on-site consumption, but they give one example of the potency of a feed-in tariff.

6.3.3. Influence of Energy Supply Tariff

The economic analysis was recalculated using the individual gas and electricity tariffs from different energy suppliers shown in Figure 6.13. Figure 6.18 shows the logarithmic fit to each set of results when using a PEMFC and SOFC system with each tariff, again plotted against the reference bill of each house.

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[93] This average was taken from the 266 profiles with >100% savings, and was made up of: £755-885 paid for gas (fuel cell + boiler), £15-25 for electricity, £245-300 earned from exports and £625-720 earned from the FIT.

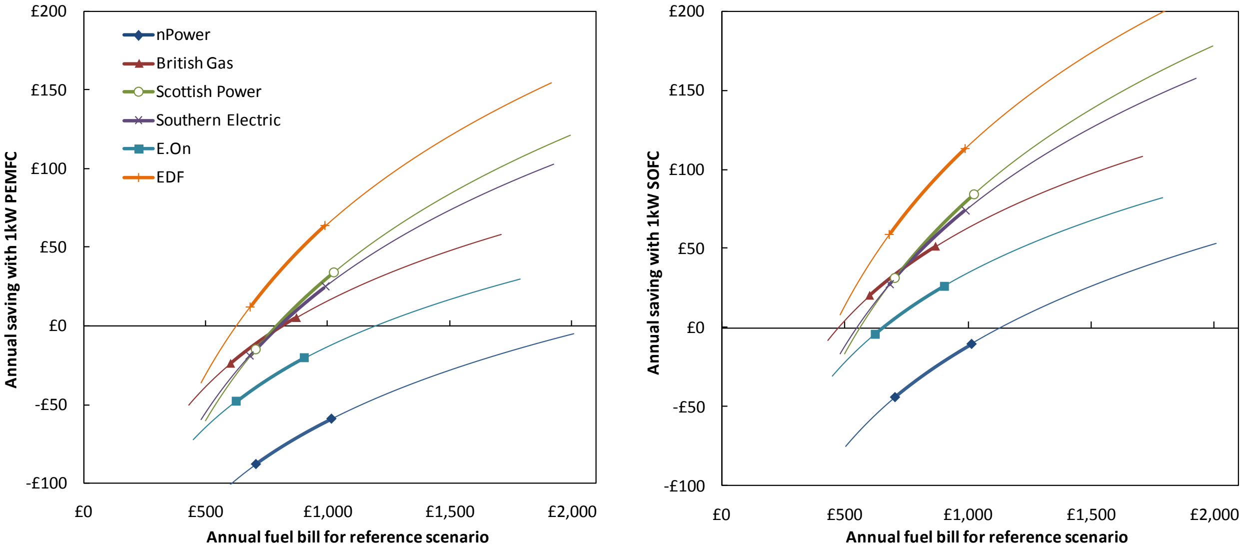

Figure 6.18: Changes to the fuel bills caused by using price tariffs from different energy suppliers, with a 1kW PEMFC (left) and SOFC (right). An export value of 5p/kWh was assumed in all cases.. Thicker bars show the 32-68% confidence interval, while the thinner lines show the 5-95% interval.

The different spark gap offered by each supplier meant that savings could be improved by around £100 in any particular house by changing from the least to the most suitable tariff. For example, as of March 2009, nPower offered a spark gap of 2.63 compared to 3.77 from EDF.

This effect on savings was less important than the underlying difference in reference bills. British Gas offered the lowest energy tariffs from the sampled suppliers; as seen by the fact their curve is furthest to the left in Figure 6.18. Even though users of this tariff would see only a modest saving by upgrading to a fuel cell (£35-50 less than they would with EDF), the resulting energy bills were the lowest of any supplier.[94] Customers would therefore be wise to choose the tariff with lowest gas price, although knowledge of their estimated gas and electricity consumption (e.g. from simulations such as this) would be required to identify the optimal tariff in individual cases.

6.3.4. Influence of Export and Generation Tariff

Due to the high proportion of electricity exported, the economic results show a strong dependence on the revenue earned from exports. Figure 6.19 shows the distribution of savings in the 1,000 houses with export tariffs ranging from zero to 10p/kWh. It is seen that an export value of 6p/kWh is sufficient for virtually all PEMFC and SOFC systems to return an overall profit to the user, and average savings rise to £194±44 and £275±50 per year for 1kW PEMFC and SOFC systems respectively when exports earn the maximum rate.

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[94] Please note this is not an endorsement of any particular energy supplier, as the volatility of UK domestic tariffs means that the relative performance of each supplier is constantly changing.

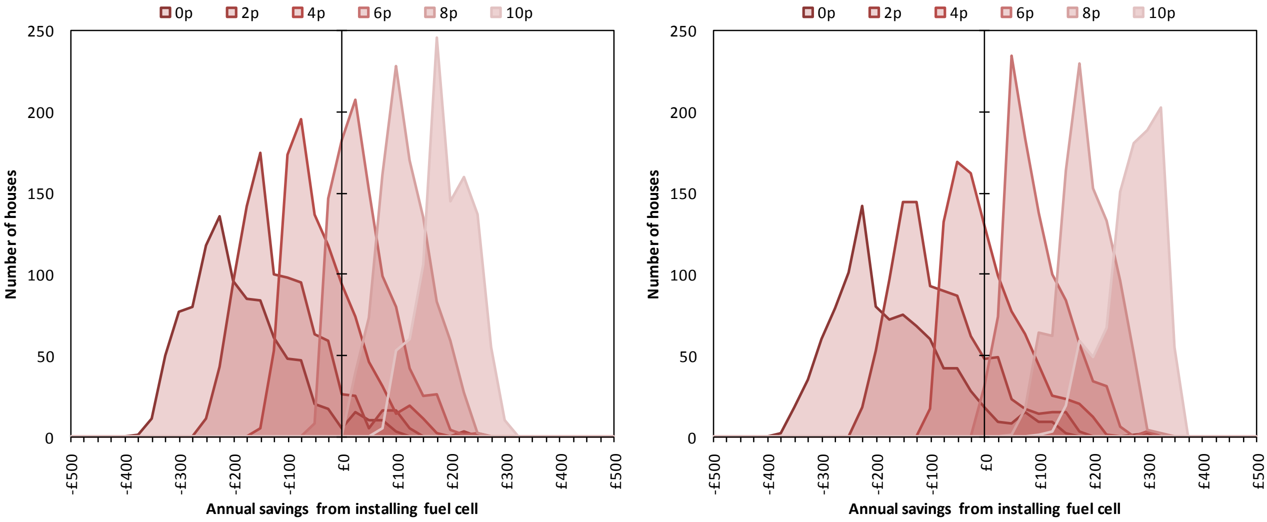

Figure 6.19: Histograms showing the savings attained with different values for exported electricity, for a 1kW PEMFC system (left), and SOFC system (right). No feed-in tariff was assumed.

With the assumed export tariff of 5p/kWh, the majority of fuel cell systems are able to return a net profit, as the savings made by reducing on-site electricity consumption slightly outweighed the losses made when exporting electricity. A typical PEMFC system would save 3.68p per kWh of electricity which displaced on-site consumption, but would cost an additional 2.11p if this electricity was exported. This can be calculated solely as a function of the value of gas and electricity (C_{gas} and C_{elec}), the efficiency of the fuel cell (η_{el} and η_{th}), and the efficiency of the displaced condensing boiler (η_{boiler}),[95] as in Equation 6.6:

$$\begin{array}{r}\text{Relative cost} \\ \text{per kWh}_{elec}\end{array} = \frac{C_{gas}}{\eta_{el}} - C_{elec} - \left(\frac{\eta_{th}}{\eta_{el}} \cdot \frac{C_{gas}}{\eta_{boiler}}\right) \tag{6.6}$$

By setting the relative cost to zero and rearranging, Equation 6.7 can be used to calculate the minimum value of exported electricity that will prevent the fuel cell from returning a loss when all of the generated electricity is exported.

$$C_{elec} = \frac{C_{gas} \cdot \left(1 - {}^{\eta_{th}}/_{\eta_{boiler}}\right)}{\eta_{el}} \tag{6.7}$$

Using the values for seasonal efficiency from Tables 5.9 and 6.1, the required export values were calculated for each fuel cell technology, plus the leading Japanese demonstration systems. Figure 6.20 plots the standard deviation resulting from the range of efficiencies and gas prices in the UK. This shows that 5p/kWh is an insufficient reward for exporting electricity (except with the high efficiency Kyocera system), and that export tariffs of 7-8p/kWh are required to give an incentive for fuel cells to export electricity to the national grid.

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[95] It must be remembered that these efficiencies are the seasonal averages calculated by FC++ or seen in real-world trials, rather than the rated manufacturer's specifications; i.e. the figures from Table 6.1 rather than from Table 4.3.

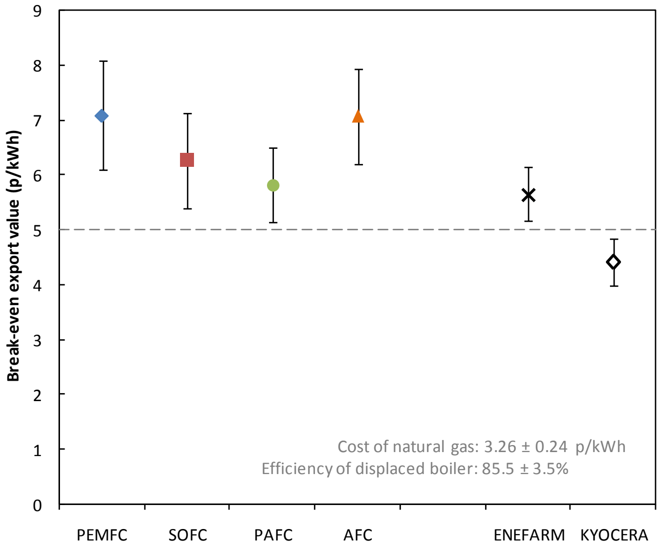

Figure 6.20: The value of exported electricity required for each type of fuel cell to have the same running costs as the reference scenario – if all its electricity was exported. The default export tariff in the UK is shown as the grey line.

While there is a substantial benefit to raising the value of exports, this is eclipsed by the impact of introducing a feed-in tariff which pays for both export and generation used on-site. The annual savings were recalculated with a range of feed-in tariffs from zero to 20p/kWh, with the default 5p/kWh export tariff. Figure 6.21 plots the distribution of savings from a PEMFC and SOFC system. These distributions spread out as the reward increases, as the impact of different utilisations in each house (different amounts of electricity production) becomes magnified.

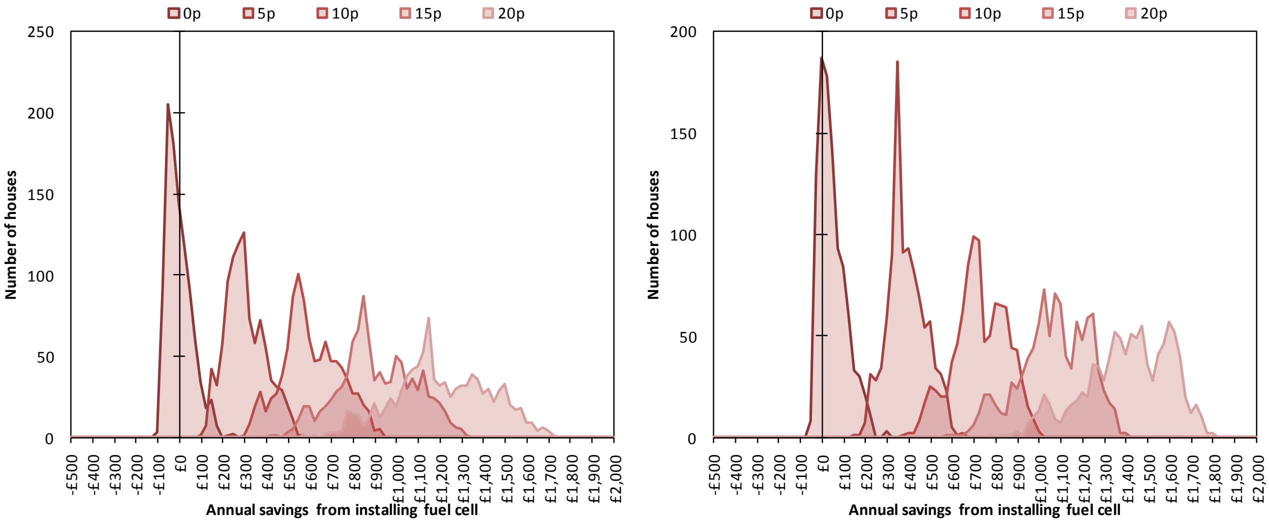

Figure 6.21: Histograms showing the savings attained with different generation rewards with a feed-in tariff, for a 1kW PEMFC system (left), and SOFC system (right).

A feed-in tariff of just 2p/kWh is sufficient to allow most PEMFC and SOFC installations to reduce energy bills, as it would raise the export value to 7p/kWh and give additional revenue to on-site consumption. By crediting both on-site and exported generation, each 1p/kWh increment to the generation tariff has the same effect as adding 1.25-2p/kWh to the export tariff, increasing annual savings by £60-70.

6.4. Estimated CO_2 Emissions Reductions

This section mirrors the layout of the previous one, this time using the central simulations to calculate the reduction in CO_2 emissions that each type of fuel cell could achieve relative to the reference scenario. As with the economic case for micro-CHP, previous studies have shown that the magnitude of these reductions is highly dependent on the carbon intensity of the natural gas fuel and the electricity that is displaced by the fuel cell. Data on the emissions from burning and reforming natural gas, and from generating electricity in the UK were therefore found to begin with.

6.4.1. Environmental Assumptions

The greenhouse gas emissions from burning natural gas were taken from the most authoritative source – the IPCC guidelines for stationary combustion.[187] This gives 182.1±6.7g of CO_2-equivalent per kWh of fuel combusted (HHV), including the global warming potentials of other emissions (NO_x, CH_4, etc.).

Combustion is not the only source of greenhouse gasses however, as energy consumption and methane leakage occur at all stages of the fuel production chain – extraction, processing, transmission and distribution. The additional life-cycle emissions from these activities were estimated using SimaPro 7, a Life Cycle Assessment (LCA) software package from PRé.

Since 2004 the UK became a net importer of natural gas, and by 2008 only 67% of the supply mix was indigenous, with 24% Norwegian, 8% Dutch and the remainder being imported as liquefied natural gas (LNG).[256] Natural gas leakage from distribution pipelines is inevitable, and particularly important as methane has a global warming potential 22 times higher than CO_2 (over a 20 year time horizon). Leakage rates from distribution were assumed to be 0.5-2.0% based on studies of the UK and other infrastructures.[257-260] These stages were modelled using inventories from the EcoInvent 2.0 database, and assessed using the Impact 2002+ indicator. The emissions from sourcing and distribution were estimated to add 7-9% (14.9±2.3 g/kWh) to the total CO_2-equivalent emissions; which was typical among European estimates.[96]

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[96] Other examples of indirect CO_2 emissions are: Italy 6 g/kWh [261]; Netherlands 8.9g [262]; USA 35.5±1.3g [263].

The CO_2 emissions from reforming natural gas were taken to be the same as from combustion, as the number of carbon atoms per kWh of fuel input was invariant. The operating efficiency of each fuel cell technology therefore determined the magnitude of emissions reductions. The emission of other powerful greenhouse gasses (CH_4 and NO_x) from fuel cell CHP systems have been measured in several studies to be around one-tenth those from combustion.[63, 107, 168, 170, 264-266] This was neglected as the resulting reduction in greenhouse gas emissions was <0.1g CO_2/kWh. It should be noted that fuel cells would offer improvements to local air quality, however this was outside the scope of this single-criterion study.

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The displaced emissions from centrally generated electricity were estimated using detailed data from the Digest of UK Energy Statistics (DUKES),[199] as well as environmental performance reports from five major energy suppliers in the UK. The proportion of total electricity generation, average efficiencies and carbon intensities of each type of plant are given in Table 6.4. Carbon intensities were estimated in SimaPro using EcoInvent 2.0 data for UK or European plants, and are compared to estimates published by the International Atomic Energy Agency in 2000.

				Whole life-cycle CO_2 emissions	
Source	**Proportion**[97]	**Efficiency (HHV)**[98]	**Direct CO_2 emissions (g/kWh)**	**SimaPro**	**IAEA [267]**
CCGT	40.6%	45.6% ± 4.5%	423 ± 24	455 ± 25	434-689
Coal	33.7%	33.8% ± 2.1%	1005 ± 71	1088 ± 71	967-1308
Nuclear	15.6%	35.4% ± 4.3%	0	8 ± 1	9-21
Biomass / Waste[99]	2.6%	23.5% ± 2.6%	1853 ± 45	51 ± 9	31-61
French Imports[100]	2.1%	-	-	85 ± 6	-
Wind	1.3%	-	0	11 ± 1	9-48
Hydro	1.3%	-	0	3 ± 1	4-23
Oil	1.1%	28.8% ± 0.6%	991 ± 65	1126 ± 60	802-901
Pumped Hydro	1.0%	74.5% ± 5.0%	-	868 ± 149	-
Others	0.7%	18.1% ± 6.7%	1490 ± 377	1613 ± 540	-

Table 6.4: Composition and carbon intensity of the UK electricity mix for 2007. Greenhouse gas emissions are given for each type of plant, both those from direct combustion, and for the whole life-cycle with fuel sourcing and plant capital.

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[97] Based on annual TWh of energy generated, taken from DUKES Tables 5.4 and 5.6.[199]

[98] Net efficiencies are given, which include the 18.1TWh of electricity consumed by the power stations themselves. Gross efficiencies are 1.02-1.14 times higher than those presented. Averages were taken from DUKES Tables 5.6 and 5.10, and the standard deviations came from the range of individual plant performances given by energy suppliers.

[99] For biomass, whole life cycle emissions are lower than direct emissions from combustion due to the CO_2 absorbed in producing the feedstock.

[100] The French electricity mix in 2006 was 78% nuclear, 11% renewable, 5% coal, 4% gas.[268]

The average gross plant efficiency in the UK was 40.5% HHV, or 36.0±1.9% when transmission losses and consumption by the plants was included, meaning that 2.78±0.15 MJ of primary energy was consumed per MJ of electricity delivered. Sourcing the fuel and building plants also add to this, making the whole life-cycle energy consumption 3.16±0.92MJ per MJ delivered.

The annual average carbon content of grid electricity was estimated to be 647g per kWh delivered, using the data from Table 6.4 and accounting for 6.6% transmission losses.[199] Of this, 572g were direct emissions from combustion, and 76g were from fuel production and distribution, and from construction of the power plants. The figure for direct emissions is in line with recent government estimates,[31, 269] but is higher than the grid average used in the UK government's Standard Assessment Procedure (422g/kWh) and the assumed long-term average rate (430g/kWh).[20, 270]

There is substantial debate over what emissions would actually be displaced by micro-CHP, for example in references [271-273]. It is argued that demand reducing measures would displace so-called marginal plant rather than the average generation mix.[272, 273] Marginal (or peaking) plants are those which respond to instantaneous changes in national demand, varying their output during the day to balance supply and demand. It is unlikely that nuclear baseload generators would be turned off because of micro-CHP systems; instead it would be low efficiency coal, oil and gas generators with higher than average emissions, meaning that micro-CHP could offer greater reductions. The numerous government recommendations for the carbon intensity of electricity generation are discussed by Hawkes in [20], with the conclusion that "there is a great deal of uncertainty regarding appropriate CO_2 rates for residential consumption and generation, and this is a ripe area for research".

Similarly, there are difficult choices to be made when considering how emissions savings from micro-CHP will evolve over time. It can be expected that heat and electricity generating systems will change considerably over the lifetime of the fuel cell, and several studies have suggested that the carbon intensity of electricity could reduce by as much as 70% in this time-frame.[274-276] It is argued that deep and rapid decarbonisation of the grid would have negative implications for fossil-fuelled micro-CHP, however it is only the baseload and average generation mix that is expected to change substantially.[67, 277] Fossil fuelled plants are likely to remain as the marginal generators, as the output of renewables cannot be controlled without excessive storage, and nuclear is inflexible and cannot provide the rapid start-up and ramping rates required. Fitting these fossil plants with carbon capture and storage (CCS) systems could offer a route to lowering marginal carbon intensity, however it remains to be seen whether CCS can demonstrate the required flexibility without incurring cost and efficiency penalties due to the increase in systems complexity.[278]

Other developments could potentially be realised within the same time-scale as centralised grid decarbonisation, such as the use of fuel cells as regional or national marginal generation as part of a virtual power plant, or the development of lower carbon fuel sources such as bio-methane.[277] These further complicate future trajectory of emissions savings, so it was assumed that the carbon intensity of both the fuel cell and the reference system will remain unchanged over the 10-15 year time period being studied.

Six combinations of emission factors were considered, as shown in Table 6.5. Emissions from the average grid mix were used for the central case, and were similar to the marginal emissions that were estimated to be displaced by micro-CHP in a study by Ilex due to the recent switch from gas back to coal in the UK.[273] CCGT and coal plants were included to investigate the impact of displacing the best fossil-fuelled alternative, and the worst marginal emissions.

	Direct emissions	**Whole life cycle**
Natural gas	182.1 ± 6.7	197.0 ± 7.1
Displaced heat	213.0 ± 11.7	230.4 ± 12.6
Grid average	572 ± 28	647 ± 32
CCGT	423 ± 24	455 ± 25
Coal	1005 ± 71	1088 ± 71

Table 6.5: Carbon intensities assumed for the different emissions scenarios. Heat was assumed to be produced with an 85.5 ± 3.5% efficient condensing boiler.

6.4.2. Central Results

The distribution of carbon emissions from the 1,000 properties is shown in Figure 6.14, calculated from the reference scenario with whole life cycle emissions. The average direct emissions from combustion were 5.4 tonnes per year, plus an additional 0.5 tonnes from the fuel life-cycle, which is not typically considered in other studies (e.g. those in Table 3.2). The average direct emissions were in line with other estimates for the UK, which give 5.5-5.8 tonnes per house per year, or 135-145MT for the entire UK domestic sector (~25 million houses).[11-13]

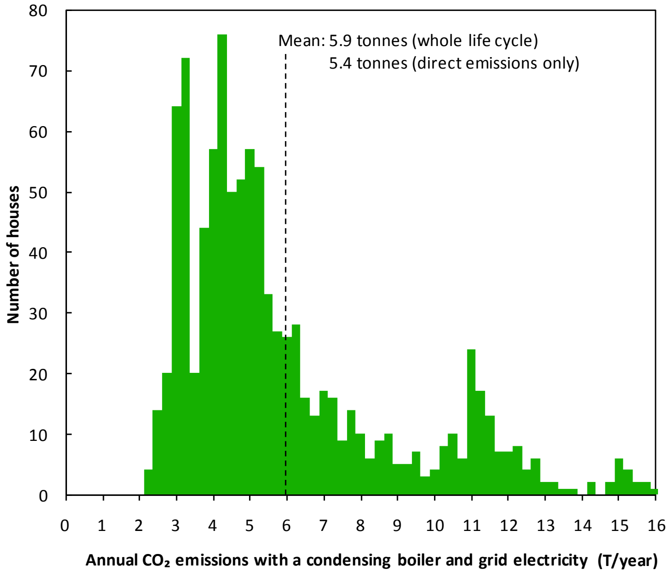

Figure 6.22: Histogram showing the distribution of greenhouse gas emissions in houses without micro-CHP installed.

The average balance of CO_2 emissions from the reference, PEMFC and SOFC scenarios is shown in Table 6.6 below, which gives the breakdown of emissions between the various components of energy use. The fuel cells reduce carbon emissions by displacing centralised generation, both by reducing on-site consumption and exporting electricity for others to consume.

	Reference	1kW PEMFC	1kW SOFC
Fuel cell:		4860 ± 656	4295 ± 409
Boiler:	3916 ± 1964	1638 ± 1751	2172 ± 1876
Purchased electricity:	1978 ± 1125	559 ± 554	492 ± 531
Exported electricity:		-2496 ± 594	-2914 ± 708
Net sum:	5894 ± 2926	4562 ± 2739	4046 ± 2806

Table 6.6: Average carbon balance for the 1,000 houses from three different scenarios, showing the CO_2 emissions produced and displaced by each item (in kg per year). Whole life cycle emissions were assumed, with the average grid mix being displaced.

The emissions reductions that could be made by installing each type of fuel cell are shown in Figure 6.23, plotted against annual thermal demand by convention. No defined trend was seen against either thermal or electrical demand; savings increased linearly until around 15MWh annual thermal demand and then levelled out. The 1kW fuel cells tended to run at full capacity in houses with higher thermal demand, and so no further gains could be made. A reasonable logarithmic fit could be produced when reductions were plotted against CO_2 emissions from the reference scenario – which was analogous to Figure 6.15 where savings were plotted against traditional energy bills.

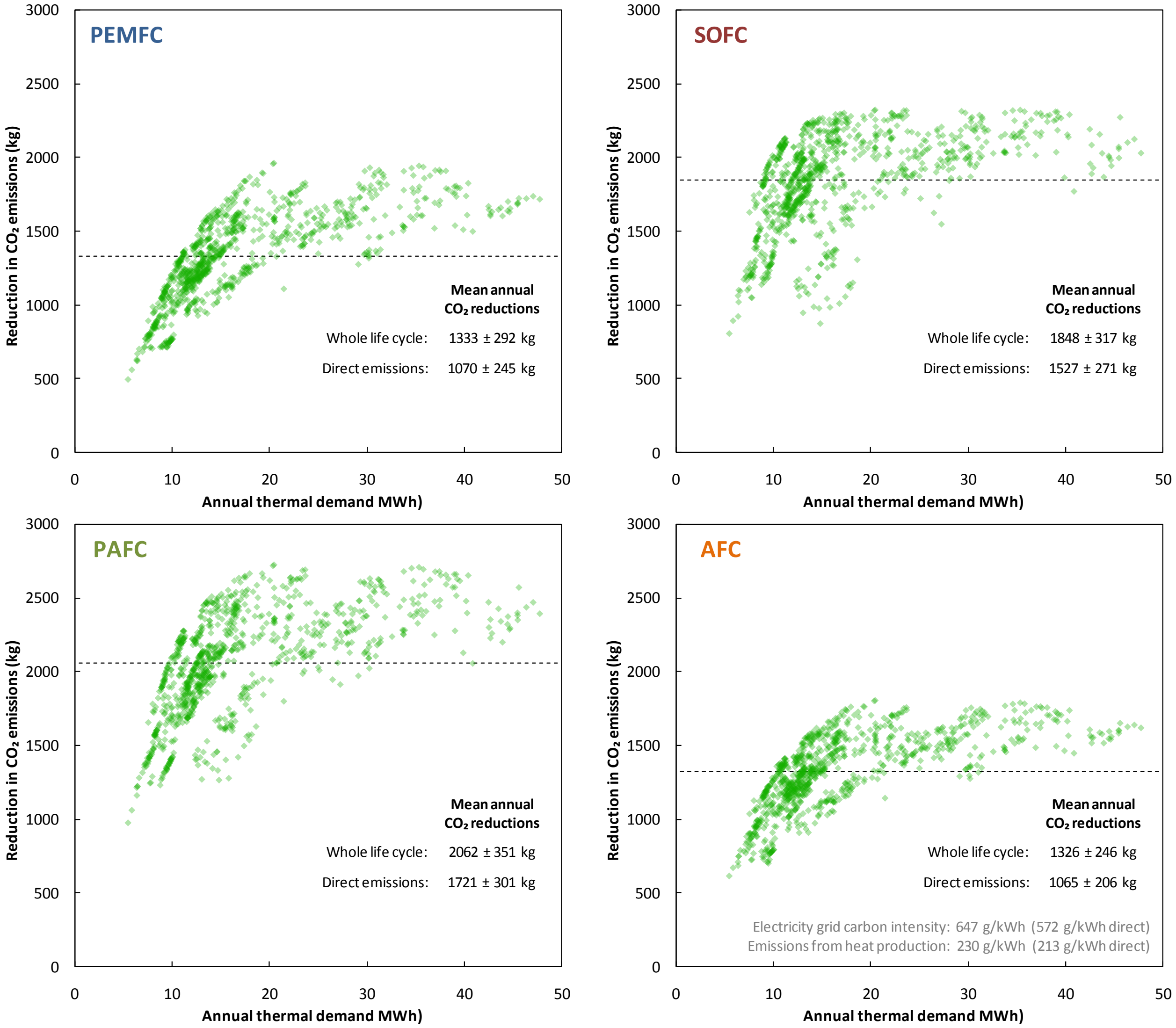

Figure 6.23: The distribution of emissions reductions made by installing each type of fuel cell. Each data point represents annual thermal demand and CO_2 reductions that were simulated in one of the 1,000 houses.

When displacing the UK average grid mix, the CO_2 savings estimated for each fuel cell technology were substantial, averaging 1.3-1.9 tonnes per year, meaning the carbon footprint for energy consumption in each household could be reduced by 25-35%.

The influence of including additional life-cycle emissions is shown in Figure 6.24. The absolute reductions were around 20% lower when only direct emissions were considered, although the percentage reductions were not as strongly affected as the reference emissions were also lower – 5.4 tonnes per household compared with 5.9 tonnes. The average direct emissions for PEMFC and SOFC systems (1.1-1.5 tonnes per year) were comparable to estimates given in other recent simulations of fuel cell micro-CHP in the UK, for example [20].

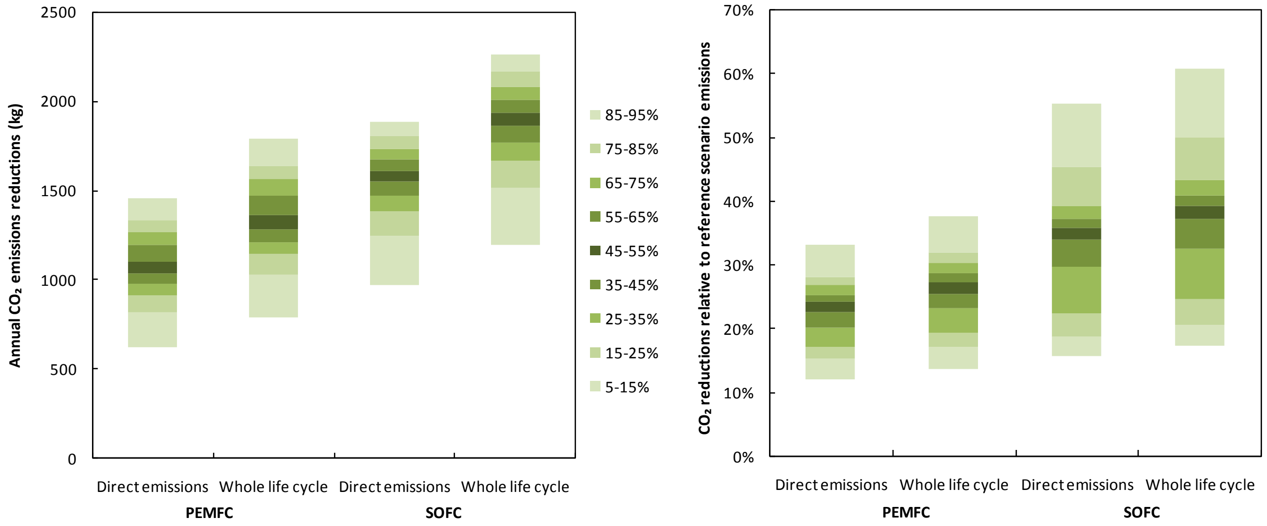

Figure 6.24: Comparison of the direct and whole life cycle emissions reductions from PEMFC and SOFC systems, when displacing the average grid mix. Absolute and relative reductions are shown in the left and right plots, respectively.

6.4.3. Influence of Electricity Supply Mix

As discussed in Section 3.2, the carbon intensity of displaced electricity has a decisive impact on the CO_2 reductions made by installing a fuel cell. Figure 6.25 plots the emissions reductions for the three sets of emissions factors given in Table 6.5.

The choice of which electricity generating technology is displaced is seen to have a far greater impact than the performance of the fuel cell or the house it is installed in. If coal is displaced rather than the grid average, savings are three times higher than those presented in previous plots, whereas if high efficiency CCGT plants are displaced, they are between 3 and 7 times lower.

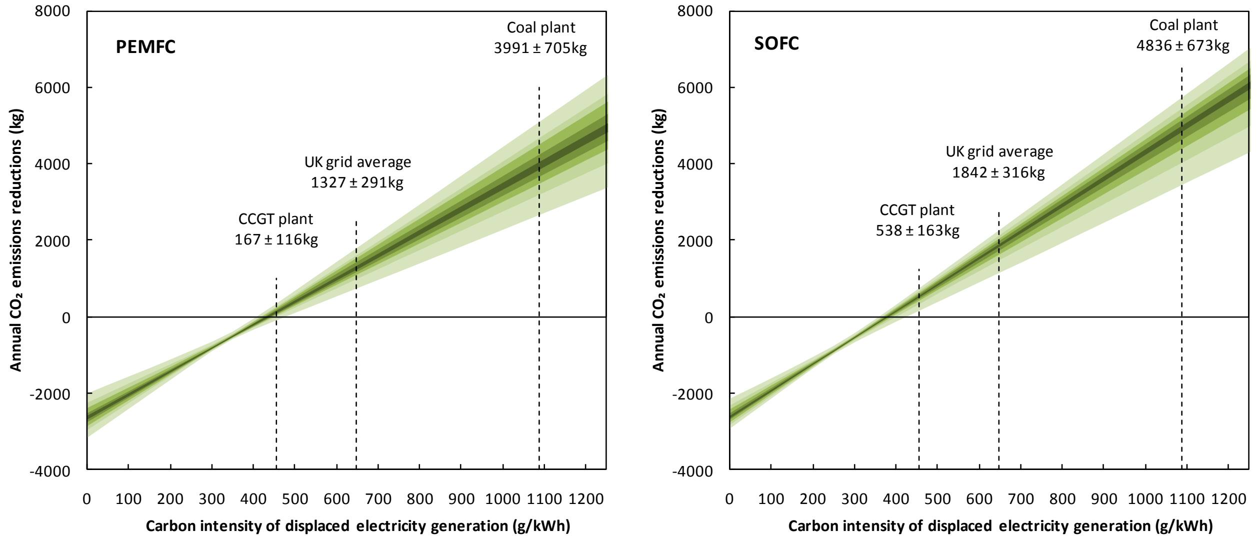

Figure 6.25: Sensitivity of emissions reductions to the displaced type of electricity generation. The range of savings simulated with PEMFC and SOFC systems in each property are shown, and averages are given for displacing electricity from three types of plant, using whole life-cycle carbon intensities.

The positions at which the fan-charts of CO_2 savings cross the zero point on these plots give the carbon intensity of electricity generated by the fuel cell, when the heat output is credited with avoided generation from a condensing boiler. An industry-average PEMFC is expected to produce electricity with 431±19 g/kWh of CO_2, compared with 376±16 g/kWh for a SOFC.

The carbon intensity of PEMFC is similar to that of today's high efficiency gas fired power stations, meaning that in 8-9% of houses (mostly those with low energy demand), a PEMFC would actually increase CO_2 emissions if displacing electricity from CCGT plant. At the other extreme, displacing today's coal plants would give three times greater emissions reductions than displacing the grid average. In 239 of the houses with an SOFC, the reductions would amount to over 100% of the reference emissions.

This does not strictly mean that the fuel cell would be a zero (or negative) carbon technology, as providing energy for these large houses resulted in an average of 5.2 tonnes of CO_2 being emitted. However, as the low-carbon electricity generated by the fuel cell and exported to other homes did not have to be produced by coal fired plants, 5.9 tonnes of CO_2 would be avoided, giving a net saving of 0.7 tonnes as in Table 6.7.

	Absolute CO_2 emissions (kg/year)
Fuel cell:	4266 ± 420
Boiler:	718 ± 324
Purchased electricity:	216 ± 139
Exported electricity:	-5917 ± 882
Net sum:	-717 ± 501

Table 6.7: Average carbon balance for the 239 homes with net negative emissions when using a 1kW SOFC. Whole life-cycle emissions were considered with electricity from coal fired power stations.

This highlights one of the difficulties with defining a 'zero carbon' home that is currently being faced in the UK.[101] The Micropower Council and Renewables Advisory Board accept that in a zero carbon home it will be more cost effective to burn natural gas to cover peak heating demands, provided that the carbon emissions are recovered through electricity export from micro-CHP or renewables.[279, 280] The Renewable Energy Association appear to oppose this view, arguing that it would be better to move away from fossil fuels entirely as "most people would understand a 'zero carbon home' to be one whose total carbon emissions [are] zero".[281]

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[101] The following argument was proposed in a personal communication by Dr. John Barton.

While this may seem like an abstract argument, the “Zero Carbon Homes” policy mandates that all new-build properties in the UK must be zero-carbon by 2016 – meaning whichever technologies are eligible will see enormous growth in uptake. However, there is still no consensus on exactly what ‘zero-carbon’ means at this stage.[282] Initiatives such as the ‘double generation’ promotion by Tokyo Gas (where ENEFARM are sold with solar PV systems) would likely result in zero net carbon emissions from most houses, albeit with significant on-site fossil fuel consumption. Whether or not this will be acceptable under the government’s policy will have a significant impact on the market share that fuel cell micro-CHP will win.[280]

6.5. Concluding Remarks

Four fuel cell technologies were simulated operating in 1,000 UK homes, using the average performance figures collected from an industry-wide survey and measured energy consumption data. Overall, the operating performance of PEMFC and AFC were expected to be similar, as were those of SOFC and PAFC systems; with the latter two obtaining higher electrical, but similar total efficiencies to the former. It should however be noted that the assumptions for AFC and PAFC efficiency were less certain than those for PEMFC and SOFC, as much of the performance data had to be collected from larger industrial CHP units or laboratory studies. It remains to be seen whether these assumed efficiencies could be realised within 1kW-class CHP units based on these stack technologies.

When simulated operating in domestic situations, the efficiency of all systems was found to be markedly lower than their rated specifications due to the impacts of part-load efficiency, voltage degradation and unutilised energy. These dynamic features of fuel cell performance are not universally considered in other modelling studies, yet are shown to lower the attained efficiencies by around 3% in absolute terms – both by these simulations and within field trials. It is therefore suggested that future studies either incorporate these dynamic effects into their simulation of the fuel cell, or base their performance assumptions on the efficiencies attained in the field, rather than those quoted by manufacturers.

Similarly, energy demand profiles were shown to have a significant impact on results, which is neglected when simulations only consider a small number of houses or a selection of individual days. A study that only considers the energy demands from a single property was estimated to give results (such as the amount of energy produced by the fuel cell) that deviate by around 11%

from the actual mean that would be found in all houses of a similar size.[102] The temporal structure of energy demands – how they are distributed throughout the day and between seasons – appears to have the greatest influence on the performance of any particular fuel cell system, more so even than the total annual demand from the house.

This complicates the criteria for selecting ideal houses for micro-CHP. Traditional advice has been to focus on houses of above average thermal demand, and while this will improve the chances of a system performing well, it is not seen to apply to fuel cells as well as to other micro-CHP systems.[19, 31] A method of categorising the pattern in which individual houses use their energy, and a way to tie this down to particular demographics (e.g. the number of occupants, their age and employment status) will be required to improve the understanding of where best to install fuel cells. This area has received relatively little research to date, in part due to the lack of substantial quantities of energy profile data recorded from UK housing stock.

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With average energy prices paid in the UK and a tariff that reflects the economic value of exported electricity, the reductions in fuel bills that could be made with micro-CHP systems are relatively poor. A 1kW PEMFC would save £100 per year in larger homes, giving a reduction of around 8% on fuel bills. Average savings across the whole set of properties were just £2-4 for PEMFC and AFC, and only rose to £51 and £81 for more efficient SOFC and PAFC systems. The estimated savings on fuel bills were sensitive to a variety of factors: the absolute energy prices, spark gap, export tariff, and the value of the proposed feed-in tariff. It can therefore be expected that as micro-CHP takes off in the UK, customers will find it “difficult to identify and switch to the cheapest [energy] supplier”.[253]

For gas-fired micro-CHP to be economically viable, both the electricity used on-site and exported to the national grid must attract higher revenues of at least 7-8 p/kWh, compared to the 5p earned for exports today. In this respect, the UK government’s proposed feed-in tariff will prove to be critical. A generation subsidy of 10p/kWh would be similar to the levels proposed for alternative fuel micro-CHP technologies, and would completely transform the economic

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[102] For example, the mean absolute deviation in thermal and electrical outputs from a 1kW PEMFC were 9.2% and 13.1% respectively, when properties were grouped by total energy demand into bands of 1MWh.

landscape for fuel cells in the UK. Annual revenues would rise to between £600 and £750, reducing the majority of customers' total energy bills by 75% or more.

The carbon intensity of electricity from fuel cell micro-CHP was estimated to be 431±19g of CO_2 per kWh for PEMFC, and 376±16 g/kWh for SOFC; some 29-38% lower than average grid emissions in the UK, and 57-64% lower than coal fired power stations. These values (both for fuel cells and conventional generators) fall by approximately 8% if only direct emissions are considered, however neglecting the other stages in the fuel's life cycle will underestimate what is actually dumped into the atmosphere, and thus the benefits that efficiency improvements such as micro-CHP can provide.

Fuel cell micro-CHP could clearly reduce the "carbon footprint" of UK homes from its current average of 5.9 tonnes per year. There is however great difficulty in placing a value on the magnitude of these reductions, as it is not known which power stations would be displaced by new electricity generation; coal, oil, gas, hydro, imports, etc. Savings could range from a few hundred kg per year if the most efficient CCGT plants were displaced, 1.0-2.2 tonnes if displacing the average grid mix, or up to 3.5-5.5 tonnes per year if coal is displaced. In the latter case, fuel cells could even be classed as "net carbon negative" in some homes, as the emissions from operation would be less than those displaced by avoiding generation from coal plants.

Given that the displaced generator has such a profound impact on carbon savings – not only from fuel cells and other microgeneration, but also from large-scale renewables and demand reduction measures – further research on the types of plant that are displaced by these technologies is highly recommended.

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Following this analysis of the benefits from operating fuel cell systems, Chapter 7 addresses the economic considerations of purchasing such a system. Chapter 8 finishes by bringing these together and putting the operational savings into context, calculating payback times and carbon costs for PEMFC based micro-CHP systems.

Chapter 7:

THE ECONOMICS OF FUEL CELL MICRO-CHP

7.1. Summary

Forty years after fuel cell economics were first assessed,[283] authors are still relying on estimates and targets for system cost.[107, 124, 284-286] This would not ordinarily be considered a problem, as it should be reasonable to assume that targets can be met with consistent progress from industry; however, such limited information is available on current and near-term prices that there has been no way to determine whether the projections given in literature or by manufacturers are feasible, optimistic or completely unobtainable.

Academic and industrial estimates place the cost of a mass-produced fuel cell stack at €200-600 per kW, with an additional €200-400/kW for the rest of the micro-CHP system.[103] These estimates compare well with targets set by agencies such as the US Department of Energy (DOE), which aims to demonstrate fossil fuelled PEMFC CHP systems for under $750/kW by 2011.[143] Similarly, six SOFC manufacturers successfully passed Phase I of the DOE's 'SECA' program by producing 3-10kW systems which could be mass produced[104] for under $800/kW.[149]

Actual sale prices do not fit so neatly with these targets. They are currently 50-150 times higher, even though volume production has begun in some cases. ENEFARM systems are the prime example of this: production volumes are rapidly approaching 10,000 systems per year, yet current prices are around €22,000-24,000.[81, 90, 93, 288] In order to meet the DOE's target, the world's most commercially advanced systems would require a cost reduction of around 95% in just two years.[105]

This void between academic theory and commercial reality raises some important questions for economists and policy makers alike. Three possibilities could reconcile these differences, each with very different implications for the commercial prospects of the technology:

- As the technology matures, learning by doing will allow current prices to naturally fall to the projected levels;
- Current prices are highly inflated and do not represent the underlying cost of manufacturing these systems;

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[103] See Table 3.3 for specific examples.

[104] The capital costs for complete systems were independently estimated at production volumes of around 50,000 per year. Goals for Phase II are $175/kW for the fuel cell stack and $700/kW for integrated systems.[287]

[105] The cost of manufacturing these systems is not precisely known, so a mark-up of 100% was arbitrarily assumed; giving costs of ~€12,000 which need to fall to around €600.

- The projected costs for mass production do not reflect the reality of manufacturing these complete systems.

In an attempt to assess these possibilities, this chapter begins with a review of the available price data for fuel cell micro-CHP systems, focussing on the most commercially advanced systems from Japan and South Korea. ENEFARM systems are analysed in greater detail to reveal the rate at which prices have decreased over the last 5 years, during which production volumes have increased thirty-fold. From this, the first empirically derived experience curves for fuel cell micro-CHP systems are presented, and used to plot the likely trajectory of prices over the following 20 years.

Sections 7.3 and 7.4 are drawn from a paper which was co-authored with Prof. Richard Green,[111] who wrote portions of the text throughout these sections, particularly on the theories of learning-by-doing and pricing behaviour.

7.2. Available Price Data

7.2.1. Current Sale Prices

Since the beginning of this project, one aim has been to find actual prices that manufacturers would be willing to sell their systems for – as opposed to projected, estimated or target costs. It should be of little surprise that this data was most readily available for ENEFARM systems, as their commercial development has now reached the state at which prices are openly displayed on distributors' websites, and orders can be placed by those with enough money.

Price data has also been published in two other field trials of PEMFC systems, however only anecdotal evidence is available for the other technologies, as pre-commercial manufacturers remain secretive. Industrial-scale PAFC systems have been sold for decades and their prices are well known, however these do not give a valid indication of what micro-CHP systems would cost due to the non-linear economies of scale. The cost per kW for smaller scale systems is expected to be several times higher, as seen with other microgeneration technologies.[20]

Table 7.1 collates the actual sale prices of seven modes of fuel cell system which were found during the course of this work. No clear trend can be seen between technologies, as the differences in price are currently dominated by production volumes and system capacity.

Excluding the larger PAFC and AFC systems, it is clear that ENEFARM are offered at the lowest price, which is understandable as they are the most commercially developed micro-CHP system.

	System	Year	Price	Description	Ref.
PEMFC	ENEOS, Toshiba (0.7kW ENEFARM)	Sep. 2009	€22,500	Current sale prices in Japan, including local taxes. System includes a backup boiler and hot water tank, plus other ancillaries.	[81]
	Panasonic (1.0kW ENEFARM)		€23,900		[93]
	GS Fuel Cell, Fuel Cell Power, Hyosung (all 1kW systems)	2008	€80,000	Given as the current system price in 2008. (only available in limited trials in South Korea)	[289]
		2007	€70,000	Given as the individual price for the 70 demonstration units delivered in 2007.	[112]
	Plug Power (5kW)	2001-03	€55,000-85,000	The average purchase and installation costs during the US Department of Defense field trials.	[116, 290, 291]
SOFC	Kyocera (0.7kW)	2009	~€70,000 per kW	Mentioned in the METI technology roadmap and by Kyocera during the demonstration project.	[88, 292]
	Sulzer Hexis (1kW)	2000-05	~€55,000	Mentioned as the cost of demonstration systems. The later Galileo model was described as "less costly", but no price was given.	[148]
PAFC	UTC and Fuji (100+kW)	2001-08	€2800-5400 per kW	The average sale price of industrial CHP systems.	[47, 193, 195, 293, 294]
AFC	(5-10kW)	2006	€10,000 per kW	Quoted price from an anonymous manufacturer for a hydrogen fuelled CHP system.	–

Table 7.1: Known sale prices for fuel cell micro-CHP systems. All prices have been converted to 2009 Euros with the following exchange rates: ¥145, $0.80, 1325 won to €1, and 2.5% annual inflation.

7.2.2. Breakdown of Manufacturing Costs

None of the above manufacturers were willing to give a breakdown of their current prices into materials, manufacturing, overhead and other costs due to obvious commercial sensitivities. The best approximation to current manufacturing costs was therefore found in a forward-looking cost estimate produced in 2004 by the group of ENEFARM manufacturers. This was made at a time when systems retailed for €84,000, and considered the reductions that could be made by up-scaling production volume to 10,000 units per year. The estimated manufacturing cost of the main generator unit is given in Figure 7.1, which includes the major systems integral to the fuel cell, but not the auxiliary boiler and hot water storage.

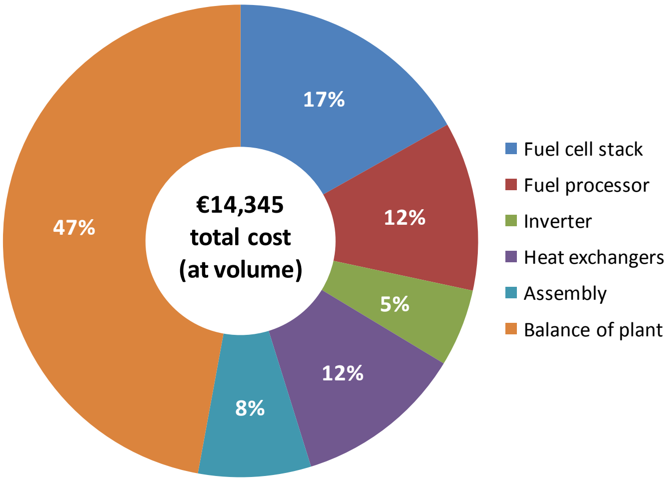

Figure 7.1: The breakdown of the projected manufacturing cost of ENEFARM systems at a volume of 10,000 per year, made by the five active manufacturers at the time. Adapted from [98, 295].

Two aspects of Figure 7.1 immediately stand out. The manufacturing cost of €14,345 is much higher than suggested by any other bottom-up cost estimate, and it is the trivial balance of plant rather than the stack or any major components that contributed the majority of this cost.

The level of cost reductions appears to have been predicted reasonably well, as sale prices have fallen from around €84,000 to €23,000 as annual production volumes rise towards 10,000. It is not unreasonable to expect that current sale prices are founded on a manufacturing cost around the €14,000 mark, as with the additional cost of a gas boiler and hot water tank this would give mark-up rates of around 45%,[106] which is close to the typical low-volume mark-up rate given by Directed Technologies in [141].

The balance of plant consisted of the 30 or so valves, pumps, blowers and sensors that were depicted in Figure 2.2, plus pipe-work and other miscellaneous items.[89, 90] Other cost estimates have not ascribed such importance to these components, as they are thought to be trivial in comparison to the major systems. Directed Technologies were alone in estimating high costs for the non-stack components – suggesting €3,000 for a 3kW system, compared with €200-600 from the other sources listed in Table 3.3.[141] The majority of this cost was for hydrogen regulators, sensors, safety valves, water filters, pipes and pumps, which were “felt to reflect the significant cost contribution of multiple minor components”.[141]

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[106] Based on the estimated component costs given later in Table 7.8 – giving a total manufacturing cost of around €15,800.

7.2.3. Projected Future Prices

In addition to publishing current prices, the manufacturers and agencies involved in the leading fuel cell demonstrations have laid out their expectations and targets for each technology, which are summarised in Table 7.2. It could be argued that these manufacturers are best placed to make predictions as they currently have the most experience with commercialising micro-CHP systems.

Systems		Year	Cost / Price per system	Production volume	Description	Ref.
PEMFC	South Korea	2008	€56,000	100	Expected price during the third and final year of the current demonstration project.[107]	[112]
		2010	€12,000		Target cost stated in the Korean national action plan.	[112]
		2012	€8,000	10,000 cumulative	Target price set by the Ministry of Knowledge Economy.	[289]
	Japan	2004	€14,500	10,000 p.a.	Estimated manufacturing cost for ENEFARM systems made by the manufacturers.	[98, 295]
		2012	€5,000 – 8,000	50,000 p.a.	The METI technology roadmap for production cost of residential cogeneration systems.	[88]
		2015	€3,500 – 5,000	500,000 p.a.		
		2015	€3,500	200,000 p.a.	Panasonic's target price for systems set in 2008.	[296]
		2020-2030	€2,750		The METI technology roadmap for production cost of residential cogeneration systems.	[88]
SOFC	Japan	2008	~€3,800	Mass production	Kyocera's expected retail price for systems (including hot water tank).	[297]
		2015	€7,000 / kW	Several thousand p.a.	The METI technology roadmap for residential cogeneration systems.	[88]
		2020-2030	€2,750 / kW			

Table 7.2: Expectations and targets given by the manufacturers and government bodies involved with world-leading fuel cell demonstrations.

The projections in Table 7.2 are substantially higher than those given by other sources; they are both closer to current sale prices, and have far less aggressive timetables for cost reduction. A striking feature is that neither the Japanese government, nor the manufacturers of PEMFC or SOFC systems expect prices to fall below ¥400,000 (€2,750), even in ten to twenty years' time.

These differences can be explained by the scope of the targets and cost estimates previously mentioned, which do not consider all of the components required for a complete micro-CHP system. By focussing only on the fuel cell stack and/or other major components, these estimates do not give the total cost to the consumer, much of which comes from relatively simple mass produced components for which substantial cost reductions are not possible.

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[107] It is thought that these systems have not been deployed as of September 2009.

If a ‘system’ is defined as what the customer must purchase in order to receive a functional and controllable energy output (as it was in Section 2.3), then it cannot be restricted to just the stack, fuel processor, power conditioning and thermal recovery systems. Current pre-commercial and retail micro-CHP systems unanimously include an auxiliary boiler, hot water tank, ‘intelligent’ system controller, remote feedback systems for the user, and internet based communications for the manufacturer.[108] While none of these components are essential, functionality would be seriously inhibited without them.

7.3. Estimated Rate of Price Reductions

During the Japanese demonstrations of ENEFARM, prices were publicised annually by the manufacturers and the New Energy Foundation (NEF), who oversaw the project. From this and data regarding the number of installations each year, the rate at which prices have decreased was found, and the first experience curves for fuel cell micro-CHP systems were produced.

7.3.1. The Validity of Learning and Experience Curves

“The literature distinguishes between learning curves that are based on cost data, and experience curves, based on data for prices.”[299] Curves based on price data are often used for emerging technologies such as fuel cells, as data on their manufacturing costs is rarely published due to its strategic commercial importance.[110] The following analysis is based solely on price data for this reason.

In a mature (and competitive) market, prices should be close to costs plus an appropriate profit margin. In an emerging market, manufacturers might set prices below their true costs, allowing them to sell greater quantities than cost-based pricing would permit.[110] If this happened during the Japanese demonstration project from which data is taken, the early observed prices (and thus the estimated experience curves) would be lower than the underlying experience curve. They would also have fallen more slowly than the underlying prices if this discrepancy narrowed during the considered period. The conclusion that fuel cell prices will remain high for many years would only be reinforced by correcting for this potential error.

The opposite error would be observed if the fuel cell companies have instead been over-charging the utility companies who purchased their systems, so that the prices included an

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[108] Examples of this include ENEFARM [198], Baxi [231], and CFCL [230, 298].

excessive contribution to overheads such as ongoing R&D as well as the direct manufacturing costs. However, these utilities were essential in securing deployment of their systems, so it is doubtful that the manufacturers would risk the potential for long term cooperation by over-charging. In addition, the scale of the Japanese research budget for fuel cell demonstration meant that only relatively small amounts of extra revenue could be gained.

The very concept of experience and learning curves assumes that the progress of the past will be continued into the future. As fuel cell CHP has not yet reached widespread commercialisation, there is "no certainty that similar cost reductions continue to apply in the future".[299] It is argued that the technology will benefit from 'learning by searching' during the early commercialisation phase, which can offer a different rate of cost reduction to the 'learning by doing' process which influences later development.[161] However, the major driver for cost reduction in both cases will be increasing economies of scale, which will be seen throughout commercialisation.[110] In other technologies, the assumption of a reasonably constant rate of progress has been validated by experience.[110, 164]

7.3.2. Historic Data from ENEFARM Demonstrations

Price data for constructing experience curves was taken from the Large Scale Residential Fuel Cell Demonstration Project which was introduced in Section 2.4. This project is unique in that it has increased the world's stock of fuel cells to such an extent (~30%) that significant reductions in price could be observed.[109]

Two linked pieces of information are required to construct experience curves: the price of a given system, and the total number of systems that had been previously produced. Both sets of data have been published by NEF, and are given in Tables 7.3 and 7.4.[100]

Year	Installations in demonstration projects	Cumulative productions (end of year)
2004	2	85 - 165
2005	480	575 - 675
2006	777	1362 - 1482
2007	930	2302 - 2442
2008	1120	3432 - 3592

Table 7.3: The number of domestic fuel cell systems installed during the Japanese demonstration projects.[98, 300] The range of cumulative installations includes between 10 and 30 additional systems being produced per year.

Year	Government subsidy	Average sale price	Range in sale price
2004	-	€84,414	*±10% assumed*
2005	€41,379	€53,103	€46,897 - 65,517
2006	€31,034	€40,138	€32,414 - 54,483
2007	€24,138	€33,172	€25,172 - 51,034
2008	€15,172	€22,690	€18,621 - 34,483
2009	€9,655	€22,983	*initial launch prices*

Table 7.4: The progression of government subsidies, with the average, the lowest and highest pre-subsidy prices paid each year (all per system).[98, 100] No adjustment has been made for inflation, which was 0% between 2003 and 2007, and only 1.4% in 2008.[301]

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[109] At the end of 2007, the cumulative number of small stationary installations (CHP and backup power) was thought to have reached 7,000.[31]

Table 7.3 gives the number of fuel cell systems that were installed in demonstration projects[110] between 2004 and 2008, along with an estimate for the total number of ENE-FARM systems that had been produced. The cumulative totals included the 43 systems which were demonstrated in 2002 and 2003,[98] and an estimate for the number of other systems that had also been built, but were not installed into domestic properties.

Based on information gathered by the FC-DIC[111] and Hastex [304], it was estimated that approximately 80 systems were produced between 2000 and 2004 which were not used in the demonstration projects. Due to the uncertainty in the data, the rate of producing non-demonstration systems since 2000 was taken to be between 10 and 30 systems per year. This 'additional' production rate is denoted as r = 20±10 systems per year. The justification for including r, and its impact on results are discussed more fully in [111] (given in Appendix C).

It should be noted that there had been significant activity outside of Japan before these demonstration projects began. Around 4,000 fuel cells had been produced world-wide by the start of 2002, mostly for small portable applications or industrial power.[305] The experience gained in producing these other fuel cells was not entirely relevant to the development of domestic CHP systems, as they typically used a different type of fuel cell stack (i.e. PAFC), or did not have fuel processing and heat extraction systems.

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The prices paid for complete fuel cell CHP systems during the demonstration (including the fuel reformer, hot water tank and other balance of plant) were reported to the project overseers as a condition of obtaining the government subsidies. Table 7.4 gives the sale price received per unit by the manufacturer; subsidies were paid direct to the buyers, reducing their net cost, but not (directly) increasing the manufacturer's revenues. The system price in 2004 (towards the end of the small demonstration project), and the announced sale prices and government subsidies for 2009 are included in the first and last rows of the table. A total budget of €42 million has been allocated for 2009, enough to cover 4,335 systems at current subsidy rates.[94, 306]

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[110] The Large Scale Residential Fuel Cell Demonstration Project ran from 2005 to 2008, and was preceded by a smaller demonstration which ran from 2002 to 2004.

[111] The news archives of the Fuel Cell Development Information Center (FC-DIC) contain several examples of press reports from manufacturers, the Japan Gas Association and Tokyo Gas who all engaged in laboratory testing of these fuel cell systems.[104, 302, 303]

As in Table 7.1, Japanese Yen have been converted to Euros for convenience, using the average Interbank rate from 2004-2008 (¥145 per Euro). A fixed conversion rate was used over the entire period of study, rather than separately considering the average rates for each of the six years. Systems were purchased in Japanese Yen during a period of very little inflation, and were not subject to foreign currency fluctuations.

7.3.3. Data Fitting Method

The price of the n^{th} fuel cell to be produced (P_n) can be represented by a function of the experience gained up until producing this unit (X_n). Calibration of this function requires a pair of linked parameters: the price of a particular unit from the past (P_{base}), and the experience that was gained up until its production, (X_{base}). This starting point, along with a factor for the rate of price reduction (b), can be used to predict the price of the n^{th} unit as shown in Equation 7.1.

For every doubling of the cumulative number of systems produced, the price is assumed to decrease by a fixed percentage known as the learning rate, L. This can be calculated from the rate of price reduction as in Equation 7.1.

$$P_n = P_{base} \cdot \left(\frac{X_n}{X_{base}}\right)^{-b} \quad \text{and} \quad L = 1 - 2^{-b} \tag{7.1}$$

The cumulative number of fuel cell systems produced was used as a proxy for experience, so that the cumulative experience gained after producing the 1000th system (X_{1000}) equals 1000. This proxy is used in [142, 155], rather than the total installed capacity (in MW) which is often used for energy generating technologies (e.g. [159, 161]). This reflects the fact that most of the cost and complexity of the system is in the auxiliary components rather than the stack itself, and these do not scale strongly with output capacity within the micro-CHP scale (0.5-3kW).[98] ENE-FARM models have a 0.7-1kW electrical capacity, optimally sized for the energy demands of a typical house. This capacity is therefore unlikely to increase rapidly with technological progress, as is seen with wind turbines for example. The total installed capacity can therefore be assumed to scale linearly with experience, with X_{1000} equivalent to 1MW electric.

Each of the historic prices given in Table 7.4 was the average for the whole year, rather than for a specific unit; so for example €33,172 was the average price of all units from P_{1303} to P_{2232}. This complicated the calculation of the parameters, as the objective was not simply to minimise the deviation between four particular values of P_n and the empirical data. Instead, the integral of P_n

over each year's range of *n* (the total predicted price of all installations in that year) had to be fitted to the respective historic price for that year multiplied by the number of new installations that occurred.

The data from 2008 was excluded from the fitting procedure as it was believed to be spurious; as highlighted in the following results section. In addition to this, a sensitivity analysis was performed around the inclusion and exclusion of data from specific years, and was presented in [111]. The range of *n* used for the 2009 sum was based on the Japanese energy utilities' projected figures of 5,000 sales in the first year of commercialisation.[94, 95]

7.3.4. Derived Experience Curves

Table 7.5 presents the core data set for this analysis, derived from Tables 7.3 and 7.4. The first column gives the cumulative sales reached at the midpoint of each year, based on the midpoint assumption of 20 additional non-demonstration units being produced per year. The average sale price throughout that year was taken directly from Table 7.4, and the relative change from the previous year was calculated for both this and the cumulative sales. Finally, a 'simple' learning rate was derived for each year, based on the data from adjacent years.

	Midpoint of cumulative sales during the year	**Average sale price per system**	**Number of installations relative to previous year**	**Average price relative to the previous year**	**Simple year-on-year learning rate**
2004	103	€84,414			
2005	336	€53,103	3.257	0.629	23.8%
2006	990	€40,138	2.949	0.756	16.4%
2007	1872	€33,172	1.891	0.826	18.7%
2008	2919	€22,690	1.559	0.684	44.7%
2009	5796	€22,983	1.986	1.013	-1.3%
		From 2007 to 2009:	3.096	0.693	20.2%

Table 7.5: The cumulative number of installations (assuming r=20), and the average sale price observed at the midpoint of each year (October 1st). The relative change in both numbers from the previous year is given, along with the derived learning rate observed during that year.

The simple learning rates for the first three years are comparable, but the rate more than doubles in 2008, and then turns negative in 2009, as the prices announced for 2009 were actually higher than the average during 2008. Taken at face value, this implies that no learning (or even 'un-learning') is expected this year. Two possible causes were proposed in [111]: a step change in manufacturing costs between 2007 and 2008 due to new production facilities coming online, and competitive behaviour in the run up to commercialisation that would detach prices from their underlying costs.

The bottom line of Table 7.5 gives the relative changes calculated over the two years from 2007 to 2009. These are seen to give a simple learning rate that is consistent with the earlier years of the demonstration project.

Four sets of experience curve parameters were chosen to represent the historic prices and the likely numbers of units produced, and are listed in Table 7.6. Two 'average' curves were fitted to the data-pairs from Table 7.5, using different estimates for the additional production rate. 'Lower bound' and 'upper bound' curves were fitted to the same data, using the highest and lowest prices reported in Table 7.4 respectively.

	Lower Bound	**Average I**	**Average II**	**Upper Bound**
Additional Annual Production *(r)*	+10	+10	+30	+30
Reference unit *(X_{base})*	3432	3432	3592	3592
Reference price *(P_{base})*	€36,659	€25,781	€25,439	€20,316
Experience parameter *(b)*	0.254	0.306	0.348	0.379
Learning rate *(L)*	16.2%	19.1%	21.4%	23.1%

Table 7.6: Derived parameters for the experience curves which account for additional experience gained from producing R&D systems.

In Figure 7.2, the data points from Table 7.5 are plotted on linear axes with the four learning curves. The 'Average I' is for example given by $P_n = €25{,}781 \times (n/3432)^{-0.306}$. The horizontal error bars on the historic data show the range of installations which are covered by each year's price data, while the vertical bars show the low and high extremities of the installed prices for each year.

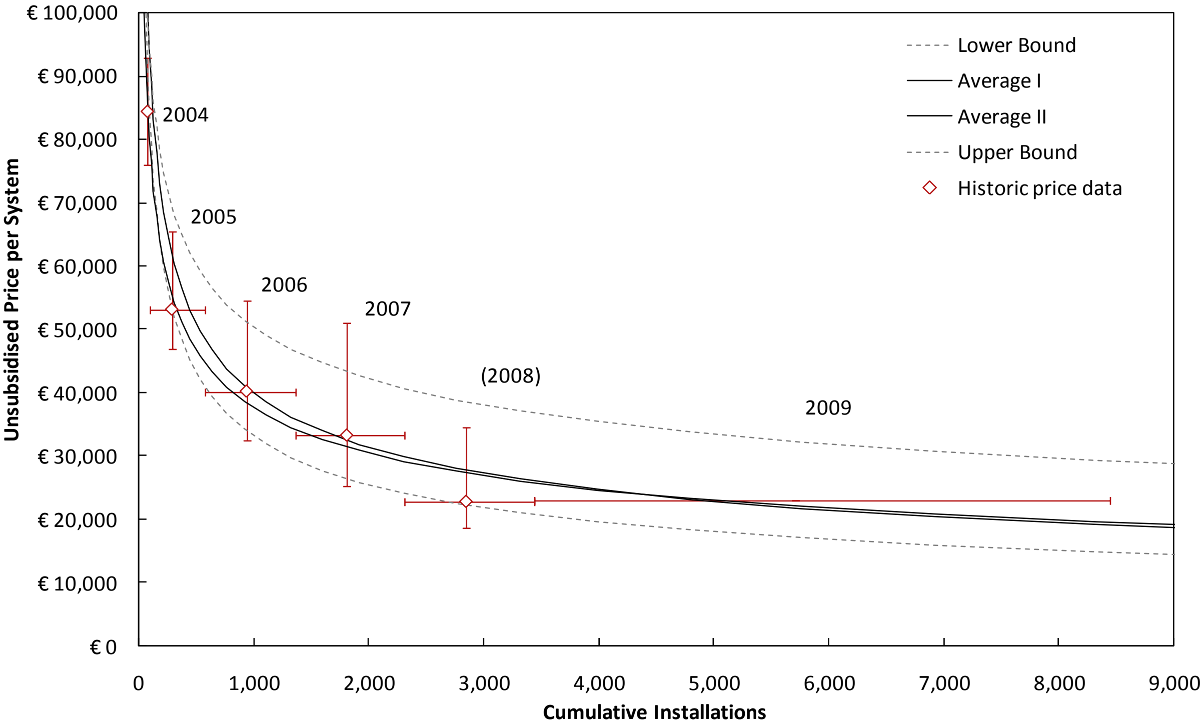

Figure 7.2: The four experience curves plotted against historic price and installation data.

7.3.5. Validation against Manufacturers' Projections

To critique the chosen parameters, Figure 7.3 shows these experience curves projected forwards to 10^7 installations, plotted against the manufacturer and government forecasts given earlier in Table 7.2. Most sources gave a price for a given annual production rate, which was translated into cumulative experience using the estimated growth rates that are introduced later in Table 7.7.[112] Some sources only gave estimates for installation levels specific to one particular company, which were adjusted by the average market share held by that company taken from [111].

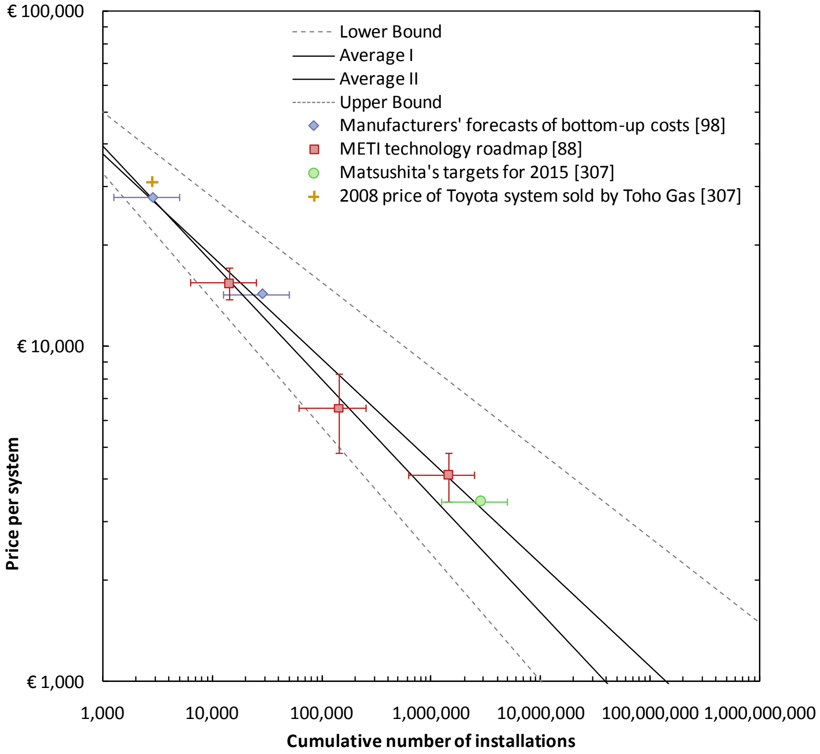

Figure 7.3: The experience curves which account for additional experience gained, plotted against projected and target prices for ENEFARM systems taken from [88, 98, 307].

All of these forecasts lie within the range of the four experience curves, and most have uncertainty ranges which cover the two 'average' curves. The publicly available information is presumably a subset of that used by manufacturers to create their forecasts, and so it is not surprising that these curves are consistent with the manufacturers' forecasts. While it had been expected that manufacturers and others with a vested interest in fuel cells would be optimistic with their forecasts,[113] they were all within, or at least close to, the range of the two average cases. If there was appraisal optimism, it lies within the learning curve methodology, rather than the use made of the available data.

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[112] For example, it was assumed that an installed base of 25,000 fuel cells (12,500 – 50,000 range) was required to realise a production of 10,000 more in the following year.

[113] For example, early predictions by manufacturers suggested that systems would be available for just €3,000-6,000 by 2004, as shown in [111].

The calculated learning rates of 16.2-23.1% (with a likely range of 19.1-21.4%) fall in the centre of the values observed with other technologies, given previously in Section 3.3. These learning rates lean towards the conservative end of previous estimates used for fuel cell technologies, but are still well within the ranges presented. The most notable deviation from previous studies is with the current (reference) price, which at ~€25,600 per kW is at least an order of magnitude higher than used in previous studies.

The initial sale price of the ENEFARM systems (€22,000-24,000) is slightly lower than the estimated reference cost for the 'average' curves, although not outside the lower-bound limit presented. It could be expected that this initial price will hold for some time after the release date. The more conservative 'Average I' curve predicts that prices would fall to the average ENEFARM price (€22,983) after 5,040 cumulative installations. This would require around 1,500 installations during 2009, which is well within the 5,000 sales predicted by manufacturers.

7.3.6. Validation against Other Systems

Some limited data was available on the price and deployment of other systems, although not enough to construct separate experience curves. The two other PEMFC systems listed in Table 7.1 plus a confidential source could be added to the ENEFARM data to see how the experience of other manufacturers lined up.

The contracted price of 1kW systems from GS, FCP and Hyosung were given for the three years of the South Korean demonstration project, along with the number of units to be delivered – 40, 70 and 100 respectively.[112] No effort was made to account for additional production before 2006 as was done with the ENEFARM systems, due to a lack of background information prior to these trials. Also as noted in Table 7.1, it is believed that the 2008 price was a prediction, although it may have already been agreed between the manufacturers and KOGAS (the main contractor for the project).

Limited data was also available on the Plug Power systems installed by the US Department of Defense between 2001 and 2004. Economic data including purchase and installation costs were given in the final reports from individual sites and project wide summaries.[116, 290] It is known that 59 systems were installed as part of the Residential Demonstration program, with another 84 installed during the same period under the Climate Change program.[308] Data is less clear before this, but it is thought that as little as three systems had been sold previously.[309] It should be noted that these systems are not directly comparable with ENEFARM or those from South Korea, as some were directly fuelled by hydrogen and thus did not require a fuel processor, some did not use heat recovery and operated as electricity producers only, and all had a higher output of 3-5kW.

The prices and cumulative experience for these other systems are plotted against the ENEFARM data in Figure 7.4. A weighted fit to all four data sets results in $P_n = €28{,}136 \times (n/3500)^{-0.267}$, giving an experience curve that is similar to the 'Lower Bound' presented in Table 7.6, with an average learning rate across all four systems of 16.9%.

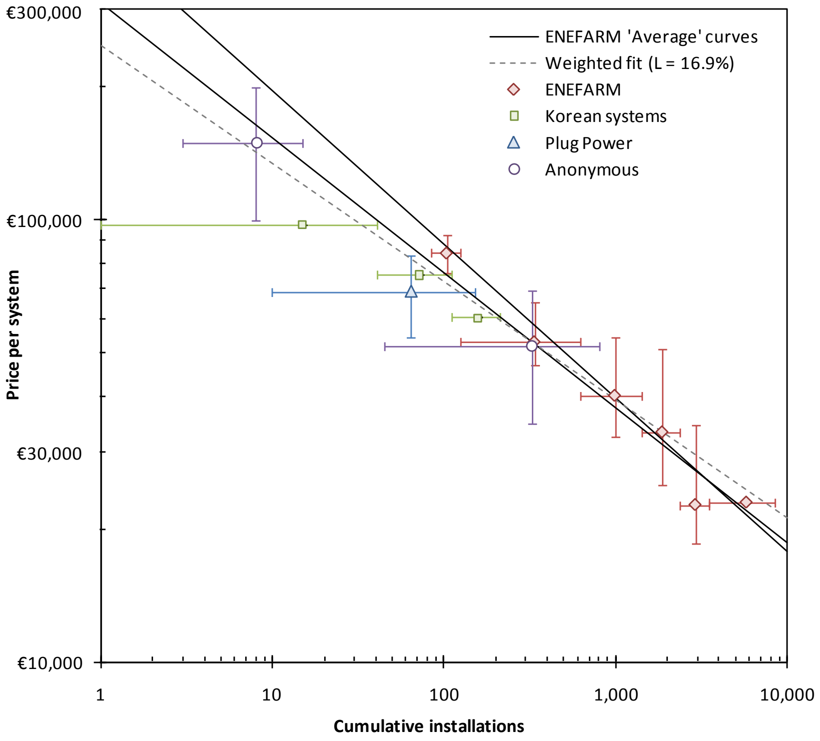

Figure 7.4: An alternate experience curve fitted to price data from ENEFARM and other PEMFC systems.

This lower combined learning rate has several possible explanations:

- ENEFARM manufacturers may have exhibited above-average learning effects, either due to their extensive collaboration, or price distortions introduced by competitive pricing behaviour during the four year demonstration;
- The other three data sets all begin with less cumulative experience than the ENEFARM data set. If the first-system prices from these other manufacturers were naturally lower than for ENEFARM, the gradient of the weighted fit will have been reduced. This may have been possible for the Korean and anonymous manufacturers, as they began producing systems two to four years after the ENEFARM;

- Failing to account for additional production with these other systems may have shifted their data points to the left in Figure 7.4. Assuming that 20 Korean systems were produced before 2006 would, for example, shift all three data points into the range covered by the two 'Average' curves.

It is impossible to conclude which of these best describes the situation at this early stage; however in any case it is evident that PEMFC systems from other manufacturers follow a broadly similar trend to those predicted for ENEFARM systems. Much of the discrepancy between the PEMFC prices given in Table 7.1 can therefore be explained by the different stages of commercial development of each product and the volumes at which they have been manufactured. What this does not reveal however is how SOFC and other technologies' prices compare to those of PEMFC. Until more data is available on the pricing and historic levels of production for these systems, it remains to be seen how prices will compare as these technologies mature.

7.4. Estimated Future Prices

Experience curves by themselves give the decrease in price as the number of installations increases, but it is also useful to consider how prices may decrease with time. The curves presented in Table 7.6 were combined with a range of projections for how many systems would be produced and sold each year, giving a timescale for the future price reductions of ENEFARM systems.

7.4.1. Projecting Future Deployment

The future rate at which fuel cells will be produced was modelled with the archetypal technology diffusion curve, which has been observed for the deployment of several technologies.[310] The rate of installations over time was modelled with the sigmoid function (or S-Curve) depicted in Figure 7.5.

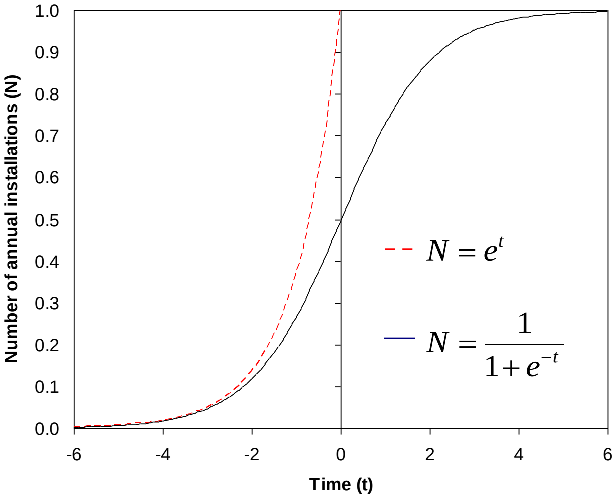

Figure 7.5: A schematic example of the 'S-Curve' used to model technology deployment rates over time, plotted against an exponential growth curve.

Some modifications to the basic function were required to accommodate the specified rate of growth, G, and maximum installation rate, N_{max}. The point at which installation rate saturates was defined simply by multiplying the numerator by N_{max}. A scale factor is needed for the horizontal axis so that during the stable growth phase, ($t < 2$), N rises by the desired growth rate (G) each year. This scale factor (f) can be approximated to $f = \ln(1 + G)$. Finally, the starting point on the horizontal axis (t_{now}) must be found from the current number of annual installations (N_{now}), as in Equation 7.2 – giving the final modified sigmoid function as Equation 7.3.

$$t_{now} = -\ln\left(\frac{N_{max}}{N_{now}} - 1\right) \tag{7.2}$$

$$N = \frac{N_{max}}{1 + e^{-ft}} \tag{7.3}$$

Historic data on the growth of domestic fuel cell deployment are still tentative as the commercial launch of the technology has only just begun. The world-wide growth rate for all types of stationary fuel cells (as opposed to vehicle or portable) was 30-50% per year between 2003 and 2007.[305] Growth rates during the Large Scale Demonstration have ranged from 50% to 1000% based on the numbers in Table 7.3, however these values were predetermined by the government via the number of individual subsidies they offered each year.

For comparison, the "Eco Cute" heat pump and "ECOWILL" CHP engine are two low-carbon domestic energy products that have been rapidly introduced into the Japanese market, with financial backing from the government and electricity or gas companies respectively. Installations of both technologies have more than doubled annually during their first four years on the market, although the growth rate for Eco Cute dropped to 73% during 2007 as its market share grew beyond 1 million.[23, 104, 311] In contrast, the sustained growth rates of many energy technologies such as wind and solar PV centre around 20% per year.[162]

Three scenarios for the deployment of fuel cell CHP are introduced in Table 7.7. Each scenario assumed a different number of installations will take place during 2009, ranging from a moderate increase on 2008 numbers (following the trend from previous years) to the four-fold increase that is forecast by manufacturers and utilities. The three scenarios used growth rates that have been observed with different groups of low-carbon technologies (wind and solar, fuel cells, heat pumps), to reflect the wide spread in deployment numbers that could be expected. Saturation of different markets was modelled, providing upper limits for the annual installation rate. The limit for the 'slow' case was loosely based on the assumption that fuel cells might win a 10% market share in Japan, the 'medium' case on a 10% share in the next most attractive market of Europe, and the 'rapid' case on a 50% share across the entire world. Saturation of these markets would be reached when the only new installations replaced old fuel cell units at the end of their life. With a ten-year system lifetime, this annual installation rate would therefore be 10% of the installed base. The rate of deployment modelled by these parameters is illustrated in Figure 7.6.

Growth Scenario	**Slow**	**Medium**	**Rapid**
Installations during 2009	1,250	2,500	5,000
Growth rate *(G)*	20%	40%	80%
Maximum annual installation rate (N_{max})	10^6	10^7	10^8

Table 7.7: Growth parameters used for future deployment scenarios, loosely modelling penetration of the Japanese, European and global markets respectively.

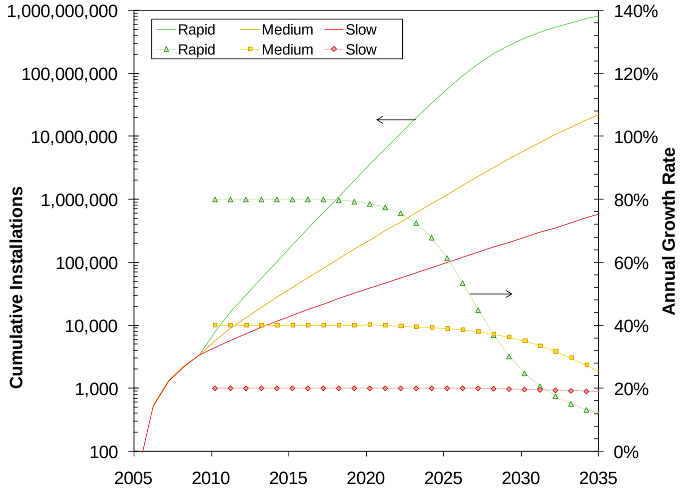

Figure 7.6: The assumed growth rates and cumulative number of fuel cell installations in the future.

7.4.2. Bottom-Line System Cost

Experience curves predict that prices will fall indefinitely so long as the number of systems produced continues to rise. A bottom-line price (or price floor) was therefore introduced to prevent the future price from falling below a sensible limit. Other authors have used the materials cost of the fuel cell as this limit,[155] however this would not give a suitable estimate for the cost of a complete system (see the arguments in section 7.2), as the experience curves presented in the previous section related to the cost of the complete ENEFARM system, including the main generator, auxiliary boiler, hot water tank and other equipment.

The minimum possible cost of these ENEFARM systems was therefore estimated and applied to the learning curve model. Table 7.8 gives a breakdown of the estimated costs, with a comparison to the values given from previous sources.

	Assumed values	**ENEFARM (2004) [98, 295]**	**Literature sources [56, 141, 144, 146, 149-153]**	**DOE Target [143]**
Fuel cell stack	€200-600	€2,400	€200-600	$750
Major components	€200-400	€5,300	€200-400	
Balance of plant	€300-600	€6,600	€3,000	
Auxiliary boiler	€700-1,000	-	-	-
Hot water tank	€400-800	-	-	-
Installation	€1,000-1,500	-	-	-

Table 7.8: Estimated costs for manufacturing each component of a fuel cell micro-CHP system at high volume.

Values for the fuel cell stack and other major components were taken from the literature sources given previously in Table 3.3, assuming high volume manufacture of 10,000 to 500,000 systems per year. The ancillary balance of plant was based on the estimates by Directed Technologies and the ENEFARM manufacturers, accounting for the substantial cost reductions that have been achieved so far on portions of the BoP.[114]

None of the previous sources have considered the auxiliary components of a micro-CHP system, so the cost of a boiler and hot water tank were taken from [312] and [313-318] respectively,[115] while other auxiliary components such as the human interface and internet communications were excluded. The additional cost of a heat store was included even though around half of UK homes already use a hot water cylinder with their heating system.[319] These traditional tanks are unlikely to be compatible with fuel cell systems, which require larger and more efficient heat

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[114] A two year collaborative effort between the ENEFARM manufacturers and around 20 BOP manufacturers managed to reduce the cost of certain components from €2,800 to €760 – falling slightly short of the €550 target,[89, 90] and so a 5-10 fold reduction in subsequent years was proposed.

[115] These were based on the lowest trade prices (excluding tax) seen for these components, as it was assumed that they would be bought from existing suppliers rather than built in-house by the fuel cell manufacturer.

stores with dual coil inputs (one for the fuel cell coolant loop and one for the boiler), and separate storage temperatures for hot water and the space heating buffer.[20]

Table 7.8 also includes an estimate for the potential cost of installing the fuel cell, which would add to the total cost faced by the householder. This was not included in the experience curves however, as the underlying price data for ENEFARM systems did not include installation costs. Installation cost was subject to speculation as only a limited number of systems have been installed to date. The average cost of installing 5kW PEMFC systems during the US DOD field trial was around €9,000 per system; with individual sites ranging from €3,000 to €20,000.[116, 290] The cost of installing ENEFARM and Kyocera systems is not known, however it is likely to also be high as these systems have to be installed outside on specially laid concrete platforms, as were the US systems. These installation costs should however fall dramatically, assuming that continued development will reduce size to the point where systems can be installed indoors (as expected for the CFCL BlueGEN for example).[230]

At a minimum, it was assumed that installation costs would be similar to those for a condensing boiler, as the plumbing and gas connections would be comparable. Electrical interconnection to the house and national grid would also be required, so the estimates made in [20] were increased by one-third to €1,000-1,500 for installation into new-build houses, equating to 1-2 man-days labour.[116]

Summing together the values from Table 7.8 gives an estimated minimum cost to the consumer, excluding profits, delivery and tax. The main generating unit is estimated to cost €900-1,400 based on literature estimates, which is slightly higher than the average cost of a condensing boiler.[312] The minimum price of the whole micro-CHP system was estimated to be €2,200-3,000, increasing to €3,400-4,300 with installation costs. This is very high compared to other high-volume estimates, as it covers the entire system that the customer will have to purchase.[117] It is also better aligned with the projections given in the METI roadmap (Table 7.2) which projects €2,750 as the minimum expected future price for Japanese PEMFC systems.

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[116] These estimates were £750±250 for installation of a condensing boiler into a new-build property, and £1500±250 into older houses.

[117] It should be remembered that this system will be capable of replacing the need for a traditional boiler, and thus the marginal, or incremental cost of the fuel cell will be lower. This is discussed further in Section 8.2.

It is worth noting that in the previous publication of this work, a bottom line price of €750 was used to represent the materials cost of the fuel cell system and boiler, which was considered to be "low enough to have only a minor impact on results".[111] The analysis was therefore repeated with the new bottom-line price.

The minimum price (P_{min}) could either be modelled as a hard limit below which prices could not fall, or incorporated into the experience curve so as to move the zero point upwards as in Equation 7.4. This second option was used in the learning curve model as it gave a more natural structure to price reductions; the learning rate gradually decreased as the price approached its minimum, rather than instantly dropping to zero as shown in Figure 7.7.

$$P_n = P_{min} + \ (P_{base} - P_{min}) \left(\frac{X_n}{X_{base}} \right)^{-b} \tag{7.4}$$

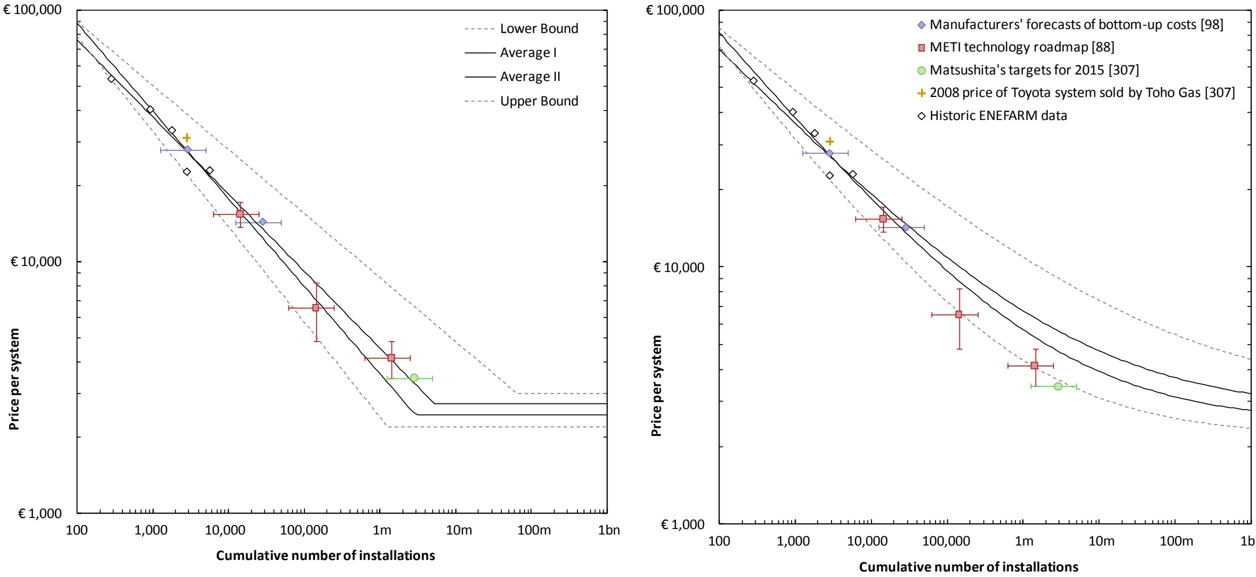

Figure 7.7: Comparison of methods for incorporating the bottom-line cost of manufacture. The experience curves from Figure 7.3 are shown with a brick-wall lower limit (left), and an exponential approach (right).

7.4.3. Projected Future Prices

The three scenarios for fuel cell deployment from Table 7.7 were used to estimate the time required to achieve a given unit price. The four experience curves from Table 7.6 were mapped onto the growth of cumulative installations, giving a projection for the potential price of fuel cell CHP systems over the coming 30 years. The resulting twelve curves are plotted in Figure 7.8, and are compared with other estimates in Figure 7.9.

From Figure 7.8, the rate at which fuel cells are deployed over the coming decade is evidently as important as the learning rate that can be achieved. For example, the rapid expansion seen with other Japanese low-carbon technologies could give prices in the region of €10,000 by 2013, whereas slower growth would result in prices almost double this.

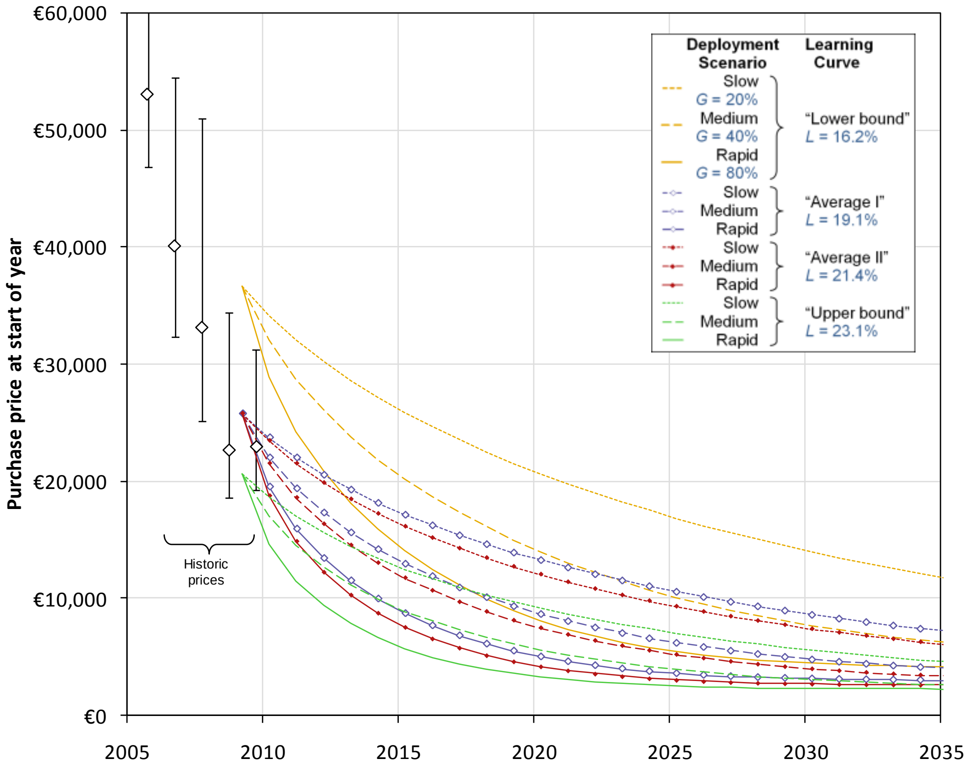

Figure 7.8: The development of estimated fuel cell prices with time, for every combination of learning curve and growth scenario.

The range of prices projected ten years from now are given in Table 7.9. The dependence of these prices on the learning rate and growth rate was fitted to: $P = 140 \cdot G^{-0.622} \cdot L^{-2.222}$, where the growth rate (G) and learning rate (L) are in the 0-1 range as in Table 7.9. Each doubling in the growth rate was therefore expected to result in prices being 40% lower than they would have been in 2019.

		Learning rate			
		16.2%	**19.1%**	**21.4%**	**23.1%**
Growth rate	**20%**	€21,609	€14,027	€12,839	€9,819
	40%	€15,137	€9,485	€8,246	€6,229
	80%	€9,176	€5,727	€4,759	€3,672

Table 7.9: Projected fuel cell prices in 2019, for each combination of experience curve and deployment rate.

7.4.4. Validation against Manufacturers' Projections

Figure 7.9 uses a fan chart on logarithmic axes to give an alternative impression of the spread in possible outcomes, and the forecasts from Table 7.2 are shown again for comparison. Ten equally spaced percentiles are represented by each band, with the 'average'/'medium' scenarios falling in the darkest central bands, and the outlying combinations of low or high learning rate and growth rate in the lighter bands. These are seen to spread apart as they are projected further into the future, as both the assumed amount of experience gained and its effect on prices diverge. If each combination of scenarios was equally likely, this chart gives the probability distribution of out-turn costs.

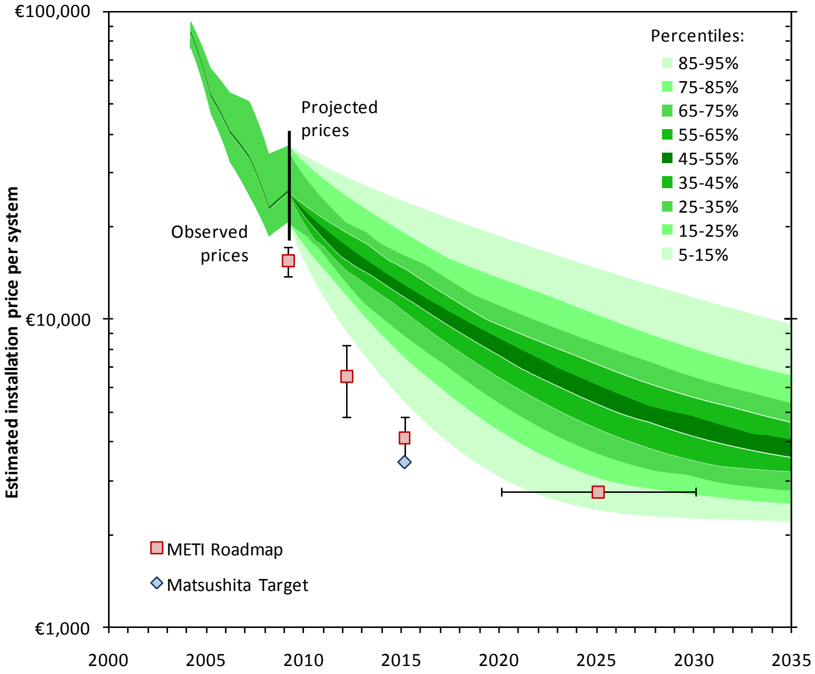

Figure 7.9: The spread in estimated fuel cell prices plotted as a fan chart, against past and present industry projections taken from [88, 307].

The lower limit imposed on the future price of the fuel cell system only impacted on the most optimistic deployment scenarios, forcing the price to remain above €2,200 once one million systems had been produced. The kink seen towards the lower end of the chart is caused by this bottom-line price, combined with the drop in growth rate predicted for the rapid deployment scenario due to saturated market post 2025 (from Figure 7.6). In the original analysis presented in [111], the lower bottom line cost of €750 had less of an impact on the most optimistic projection; which was projected to decrease slightly more rapidly (just covering the upper-limit of the 2012 and 2015 METI ranges), and then experienced a less sharp kink from 2025 to 2030.

The forecasts from Table 7.2 generally follow the most optimistic combination of experience curve and deployment scenario. Figure 7.3, which gave these forecasts against cumulative installations, showed that they were based on similar learning rates to the 'average' curves. This implies that manufacturers assume their sales will slightly exceed the 'rapid' deployment scenario – doubling year on year up until at least 2015. While this trend has been observed on a short time scale with similar technologies in Japan, it remains to be seen if it could be sustained for longer than a decade.

Neuhoff warns against combining optimistic growth rates with learning curves, arguing that faster growth rates can limit the diffusion of learning effects, as there is insufficient time for the gained experience to filter down into new facilities and the methods they employ.[162] Such rapid deployment of fuel cells could therefore result in a lower than expected learning rate over the coming years.

7.5. Concluding Remarks

Fuel cells are currently very expensive. The cheapest ENEFARM systems sell for over €20,000, and other systems cost upwards of €50,000. While public debate remains focussed on the expensive platinum content of PEMFC cells, the high costs seen today can be attributed more accurately to system complexity. It is the auxiliary components and 'trivial' balance of plant that make up the majority of estimated system costs; approximately 80%.

Prices are however falling rapidly, demonstrated by the 57% reduction seen during the past four years of ENEFARM sales. This can be expressed as a 19.1-21.4% decrease for every doubling of installed capacity. This learning rate is broadly in line with solar PV and other energy technologies,[118] and can be expected to result in prices falling to €10,000 within 10±5 years.

Based on the observed prices and learning rates, it is not thought that fuel cell micro-CHP could reach the widely held targets of €1,000 or less until tens of millions of systems have been deployed. In fact, it is argued that it would be impossible for a complete micro-CHP system to meet these targets, as the cost of the auxiliary boiler, heat store and installation would all individually cost more than this. The way in which mass-production cost estimates and targets are interpreted (applying to complete systems, as opposed to stacks or bare generators) is misleading, and could give a false impression of what is possible in the foreseeable future. It was estimated that including all of the auxiliary components and installation would give a

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[118] See Figure 3.1 for a comparison.

minimum bottom-line price of €3,400-4,300 for a complete micro-CHP system; €1,000-2,200 above that for a traditional condensing boiler.

The question of whether fuel cells will receive strong uptake is highly influenced by their upfront cost, but this will not be the only consideration in an individual's decision to purchase. As the cost of fuel cell micro-CHP is unlikely to ever fall below that of the much simpler gas boiler it replaces, the decision to purchase is akin to the decision to insulate your home or buy a more fuel efficient car; if the financial savings from reducing energy consumption outweigh the extra initial cost, it may become a desirable purchase. The following chapter therefore combines the data presented on PEMFC prices with the savings on energy bills estimated in the previous chapter, giving a holistic economic analysis.

Chapter 8:

HOLISTIC ANALYSIS AND ECONOMIC IMPLICATIONS

8.1. Summary

It has been shown that operating the current generation of fuel cell micro-CHP systems in the UK can result in substantial reductions to domestic energy bills with government support. While this benefit to householders is obviously appreciable, it does not account for the upfront cost of purchasing (and subsidising) the fuel cell, or other costs and savings incurred over its lifetime. All of these must be considered together in order to assess whether the fuel cell is a rational purchase to make.[119]

The following analysis presents several measures of the economic viability of fuel cell micro-CHP systems, focussing on financial payback periods and targets for sale prices that would give households in the UK a financial incentive to purchase. The conditions required for economic viability were investigated by varying several of the underlying assumptions, particularly the level of support offered by government and energy prices.

These economic metrics were combined with the simulated carbon emissions reductions that could be attained by operating a fuel cell in place of a condensing boiler, giving an estimate for the cost of abating carbon emissions with fuel cell micro-CHP. These appear to be the first estimates for the so-called 'carbon cost' of this technology, and provide a means of comparing the cost effectiveness of fuel cells with microgeneration, renewables, or demand reduction strategies, for example.

8.2. Methods

8.2.1. Review of Data and Assumptions

This analysis considers the industry-wide performance of 1kW micro-CHP systems, using the same central set of economic and environmental assumptions as in sections 6.3.2 and 6.4.2. Economic viability was assessed under a number of potential scenarios by varying the level of government support and the carbon intensity of displaced electricity.

Only PEMFC systems could be considered for the majority of the analysis, as information on the upfront price of other technologies is too scarce at present. Current and near-future prices for ENE-FARM systems were therefore used, relying on the assumption that the cost of systems

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[119] This assumes that householders would make the purchasing decision on purely economic grounds, ignoring any social influences such as a desire to be environmentally friendly or an interest in new technology which would drive some people to purchase even if there was no economic justification.[320]

from European, American and other manufacturers would be similar when they reached the same level of production, as was proposed in section 7.3.6. Price targets were calculated for the other three fuel cell technologies, against which capital costs can be compared when they become available.

The core data was drawn from the previous two chapters, and is summarised in Tables 8.1 to 8.4 below. To remain consistent with the annual savings estimated in the UK, the price of ENE-FARM systems were converted from Yen into Pounds, rather than Yen into Euros as in Chapter 7.[120] The stack lifetimes presented in Table 8.4 are generally lower than those used in other studies, with the 40,000 hour target lifetime for PEMFC systems equating to 5 rather than 10 years. With FC++, these fuel cells were simulated to operate for around 8,000 hours per year in UK houses due to high thermal demands, as opposed to the 4,000 hours per year that is often assumed. The lifetime in terms of years was therefore expected to be correspondingly lower.[88]

	Upfront price
2009	£15628 ± 488
2015	£8617 ± 2580
2020	£5895 ± 2473
2025	£4428 ± 2072

Table 8.1: Current and projected price of PEMFC systems, taken from the Average I and II experience curves and all deployment scenarios given in Figure 7.8.

FIT value (p/kWh)	Annual saving on fuel bills
0	£2 ± 58
5	£304 ± 90
10	£606 ± 131
15	£908 ± 175
20	£1210 ± 221

Table 8.2: Simulated annual savings on fuel bills, with varied levels of support from a feed-in tariff.

Displaced emissions (g/kWh)	Annual CO_2 savings (kg)
Grid average	1333 ± 292
250	-1072 ± 96
500	439 ± 156
750	1949 ± 388
1000	3459 ± 622

Table 8.3: Simulated annual CO_2 emissions reductions, with varied levels of displaced emissions.

	Lifetime (hours)	Lifetime (years)
PEMFC stack (current)	20,000	2.5 ± 0.9
PEMFC stack (near target)	40,000	5.0 ± 1.8
Auxiliary micro-CHP components		12.5 ± 2.5
Displaced condensing boiler		12.5 ± 2.5

Table 8.4: Current and target lifetimes assumed for PEMFC stacks and associated technologies.

8.2.2. Calculating the Total Cost of Ownership

Three economic metrics were calculated for PEMFC systems using the above data: the payback period, the Internal Rate of Return (IRR), and the cost per tonne of mitigating CO_2 emissions (the carbon cost).

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[120] As before, the average Interbank rate from 2004-08 was used, giving ¥215 per £, equivalent to €1.48 per £.

In order to calculate these metrics, the total cost of ownership had to be calculated. This was not a straightforward process of subtracting the annual savings from the upfront price, as multiple sources of expenditure and revenue must be considered, as in Figure 8.1:

- The initial (and significant) price paid for the fuel cell micro-CHP system, including all auxiliary components and installation costs;
- Additional periodic costs, such as the replacement of short-lived components (notably the stack), annual maintenance and repairs;
- Avoided costs from purchasing the fuel cell system, i.e. the purchase and maintenance of the reference heating system;
- Revenue in the form of savings on energy bills, which will change over the lifetime of the system due to changes in energy prices and the time-value of money.

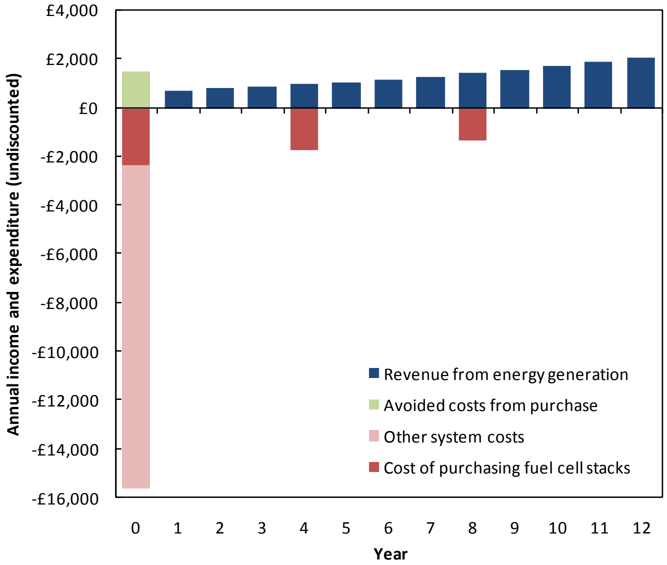

Figure 8.1: Example of the income and expenses from operating a fuel cell micro-CHP system over its total lifetime.

8.2.2.1. Economic Lifetime

The lifetimes of fuel cell stacks are currently lower than those of the other components of a micro-CHP system. Manufacturers are therefore expected to replace the stack (in addition to filters and other minor components) periodically during the 10-15 year lifetime of the system, as this is obviously more economical than retiring the entire system after just 5 years. The economic lifetime was taken to be that of the complete system, and so the cost of purchasing these replacement stacks had to be considered.

The stack was assumed to contribute 15% of the total installed system costs based on the manufacturers' cost estimate given in Figure 7.1.[121] Using the example given in Figure 8.1 of a 4 year stack life and 12 year system life, the overall cost to the customer would be 30% higher than the initial system price, assuming that two replacement stacks were initially purchased together with the main system.

A more realistic situation would be to consider that replacement stacks are bought at a later time than the initial purchase, as and when they are required. This complicates the calculation, as these future costs will be lower in real terms due to the additional experience gained by manufacturers, and then must be discounted to reflect the time-value of money.[122]

From the data presented in Section 7.4, overall system prices are projected to decrease by an average of 9-10% per year over the next decade. Assuming that stack prices fall at the same rate as was estimated for whole systems, the first stack replacement in year 4 would cost 65-70% of the initial stack price, and the second replacement in year 8 would cost 42-49%. Discounting at a 6% nominal rate would lower the amount of money initially required to fund these two replacements by a further 13% and 24% respectively; meaning that the present value of these stack replacements would be 14% that of the whole system – as opposed to 30% if they were purchased initially.

More generally, the cost of additional stacks was calculated as the present value of a growing annuity as in Equation 8.1.[321] The total investment could therefore be calculated by adding the present value *(PV)* of stack replacements to the initial price of the CHP system.

$$PV = R \cdot \frac{1 - \left(\frac{1+g}{1+i}\right)^n}{i - g} \tag{8.1}$$

Where:

R = the periodic payment to be made – the initial price of the fuel cell stack

i = discount rate over the period between stack replacements $= \left(\frac{1+6\%}{90.5\%}\right)^{L_{stack}} - 1$. The nominal discount rate was taken as 6%, and 90.5% was the relative cost of the stack after one year of experience gained.

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[121] This gave an estimated stack cost of €2,400, equal to 17% of the main generator costs. This share falls slightly when the cost of a boiler, tank and installation are included.

[122] The money for purchasing replacement stacks will not be needed immediately, and so interest (e.g. for a loan, or lost earnings on savings) will not have to be paid during the earlier years of operation.

n = number of stack replacements, calculated from the relative lifetimes of the fuel cell stack and the system as $\left(L_{system}/L_{stack}\right) - 1$. One is subtracted as the initial stack has already been paid for.

g = growth rate in prices between stack replacements $= (1 + 2.5\%)^{L_{stack}} - 1$, where 2.5% is the assumed annual rate of inflation.

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Sellers in Japan have recognised that current prices are out of the reach of most consumers, and the prospect of regular and expensive component replacements would further dissuade them from making a purchase. Tokyo Gas therefore offers ENE-FARM systems on a fixed price lease of ~£135 per month over a period of ten years.[80, 322] This price allows customers to "use the system without any limits on generation hours or cycles", and covers the cost of any maintenance and stack replacements required during the ten years.

It is not clear whether the upfront sale price also includes the cost of these replacements. The following analysis of PEMFC therefore considered this cost selectively, presenting results both with and without stack replacement costs. In both cases, it was assumed that the stack and system would have no salvage value at the end of their lifetime.[123]

8.2.2.2. Marginal Price

By purchasing a complete micro-CHP system with auxiliary boiler and heat store there would be no need for a traditional heating system, and so the cost of purchasing and installing the reference heating system (a condensing boiler) would be avoided. The value of this displaced purchase was therefore subtracted from the upfront price of the fuel cell system to give the marginal, or incremental price.

The installed cost of this boiler was assumed to be £1,500±250 for a new-build house.[19, 324] Regulations from both government and boiler manufacturers require that upgrades are made to the gas, electricity and heat distribution systems in older houses, increasing the fully installed cost by around £750. It is fair to assume that if these older properties fall short of the standards required by a condensing boiler, the same upgrades would have to be made when installing fuel

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[123] It could be argued that these systems will have a scrap value due to their precious metal content; however one can only speculate whether this would be paid to the owner on disposing of their fuel cell system.[323]

cell micro-CHP. It was assumed that this would increase the cost of installing a fuel cell by the same amount, leaving the marginal cost unchanged.

The lifetime of the condensing boiler was taken to be 10-15 years, the same as that of the non-stack components of the micro-CHP system.[19] Operation of the micro-CHP system over its economic lifetime was therefore assumed to displace the entire utility gained from the condensing boiler, and so depreciation over its lifetime did not need to be considered.

The marginal price of a PEMFC system is shown in Figure 8.2, calculated with the current and projected sale prices given in Table 8.1. The reference year given with the projected costs is purely indicative of when such prices can be expected, and the same reference system was considered in each case.

Figure 8.2: Marginal prices of a 1kW PEMFC micro-CHP system installed in place of a condensing boiler. The unmodified upfront cost of the fuel cell system was used in the left hand figure, while the present value of stack replacements (assuming current lifetimes of 2.5 years) were factored into the right hand figure.

The incremental cost of installing a fuel cell is currently very high; however this could halve over the next five years if no changes to the incumbent heating technology are realised in that time. Accounting for future stack replacements increases this incremental cost slightly, adding 10-20% to the overall price with 5 year lifetimes (as in the example given in the previous section), or by 20-40% with current lifetimes (as in Figure 8.2).

8.2.2.3. Factors Affecting the Revenue Stream

Revenue from operating the fuel cell was taken to be the savings made on energy bills relative to the reference scenario, including subsidies and payments for electricity generation and export.

There is the possibility that other costs incurred by the reference system could be avoided, particularly those for servicing and maintenance. ENE-FARM systems require servicing every two years,[81] and it was assumed that an annual gas safety check would also be recommended. This would give a maintenance regime similar to that for a condensing gas boiler in the UK, and as no firm estimates could be made for the cost of such maintenance on emerging fuel cell technologies, it was assumed that they would be equal to the cost of maintaining the reference heating system, giving no net change.

Changing energy prices and the effect of discounting would both impact on the value of the savings made over the fuel cell's operating life. The choices and assumptions made in these areas tend to dominate the results of economic assessments made over long time-scales. These impacts were not as decisive as in other studies of microgeneration due to the relatively short economic lifetime considered (10-15 years *cf.* 30+ years for solar PV).

A discount rate of 6% was used in the central analysis to reflect the cost of borrowing to social investors such as the government. Other potential investors such as energy supply companies (ESCOs) and individual households would assess the economic viability of fuel cells with higher discount rates due to their preference for higher returns and aversion to large capital expenditure.[25] It is too early to predict what business model will take hold in the UK and whether private, social or corporate investors will drive sales of microgeneration, so it is impossible to speculate on a specific discount rate that is appropriate for this type of analysis. The choice of 6% was a conservative one that would give the best-case scenario, as government are ideally placed to make long-term investment decisions because of their access to low cost capital. The impact of using higher discount rates was investigated as part of the IRR calculation in Section 8.3.2.

Energy prices were assumed to rise in line with inflation (2.5% per annum), and the feed-in tariff was assumed to remain constant over time. Energy prices in the UK have shown high volatility over the past decade, highlighting the difficulty in accurately projecting prices forwards over the next 10-15 years. Future projections by different organisations provide conflicting views of future prices (e.g. [325, 326]), and so no solid conclusions could be drawn. Growth rates in energy prices were varied by 10% around this central value to assess their impact, however for the majority of the analysis the value of the feed-in tariff was varied to show the impact that different levels of government support would have for fuel cell micro-CHP.

8.2.3. Calculating Payback Period

Payback times are often used to communicate the financial benefit of energy saving products, giving the number of years for which they must operate in order to recover the upfront cost of purchase.[327, 328] Shorter payback times are better, and 7-8 years is a desirable target for household investments due to how frequently people tend to move house.[30] Obviously, a payback time that is longer than the operational lifetime indicates that the initial cost of purchase is not recoverable, and will result in an overall loss being made by the owner.

The simple payback period is calculated as the marginal price *(MP)* divided by the annual revenue *(R)*, as in Equation 8.2. This does not account for annual growth (or decline) in revenue due to inflation or discounting, so the modified form in Equation 8.3 was used, where r is the annual growth rate of the revenue.[329] The different lifetime of the stack and other systems was accounted for in the marginal price.

$$n = \frac{MP}{R} \tag{8.2}$$

$$n = \frac{\log\left(\frac{R}{R + MP \cdot r}\right)}{\log(1 + r)} \tag{8.3}$$

To accommodate the spread in values for the marginal price and annual revenue, the payback period was calculated individually for each result from the FC++ simulations. The marginal price was calculated each time from the upfront fuel cell price, the displaced boiler price and individual component lifetimes; all of which were randomly varied as normal distributions over the ranges given previously.

An example of this calculation is worked through in Table 8.5 and Equations 8.4-8.8, using randomly generated parameters from one of the Monte Carlo trials. The calculated payback times can then be compared with the economic lifetime of the system (in this case, 12.9 years) to determine the economic viability.

Upfront fuel cell micro-CHP system price:	P_{CHP} = £15,639
Displaced boiler price:	P_{ref} = £1,728
Stack lifetime:	L_{stack} = 4.7 years
Non-stack components & boiler lifetime:	L_{BoP} = 12.9 years
Annual savings (with 10p/kWh FIT):	R = £558 per year
Discount rate:	i = 6%
Rate of energy price rise:	g = 2.5%

Table 8.5: Economic data used for calculating payback period in the following example.

Fuel cell stack price:

$$P_{stack} = 15\% \cdot P_{CHP} = £2{,}346 \tag{8.4}$$

Marginal price of the fuel cell system
(excluding stack replacements):

$$MP_{exc} = P_{CHP} - P_{ref} = £13{,}911 \tag{8.5}$$

(including stack replacements):

$$MP_{inc} = MP_{exc} + \mathrm{PV}(P_{stack}) = £15{,}509 \tag{8.6}$$

Discounted growth rate in prices:

$$r = \left(\frac{1+g}{1+i}\right) - 1 = -3.3\% \tag{8.7}$$

Payback period:
(with and without stack replacement)

$$n = \frac{\log\left(\frac{R}{R + MP \cdot r}\right)}{\log(1+r)} = \begin{array}{l} 51.6 \text{ years (exclusive)} \\ 74.2 \text{ years (inclusive)} \end{array} \tag{8.8}$$

Capital subsidies would reduce the payback time by lowering the marginal price of investment. These were not considered in this example or the subsequent analysis, as no such support is available in the UK at present.[320] However, a series of reduced prices for the fuel cell was considered (Table 8.1), which is equivalent to applying a capital subsidy to systems at today's prices.

8.2.4. Internal Rate of Return

An alternative means of assessing economic viability is calculating the Internal Rate of Return (IRR). If the homeowner took out a loan to purchase their fuel cell and paid it back using the savings made during its working lifetime, the IRR is the interest rate on that loan which would allow them to have paid it back in full.[124] Higher IRRs are preferable, and those above 6% would likely indicate an overall profit to the owner.

The IRR can be calculated as in Equations 8.10 and 8.11, using the same definitions as in Table 8.5 and the preceding equations. With the example used previously, the negative results confirm that the savings made from operation in this particular case would not be able to recover the initial cost of purchase – the owner would require a loan that paid (rather than charged) 7-8% of the outstanding balance each year in order to break even.

Present value of the lifetime
revenue from the fuel cell system:

$$PV = R \cdot \frac{1 - \left(\frac{1+g}{1+i}\right)^{n}}{i - g} = £1{,}380 \tag{8.10}$$

Modified internal rate of return:
(with and without stack replacement)

$$MIRR = \left(\frac{PV}{MP}\right)^{\frac{1}{n-1}} - 1 = \begin{array}{l} -7.3\% \text{ (exclusive)} \\ -8.1\% \text{ (inclusive)} \end{array} \tag{8.11}$$

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[124] In other words, the IRR gives the discount rate on the marginal price required to give an overall net present value (NPV) of zero for the investment.

8.2.5. Price to Beat Curve

In the absence of solid data on the capital cost of other fuel cell technologies, the estimated annual savings can be used to calculate a target price – or "price to beat" – which would give payback within the lifetime of the fuel cell. This definition is used in literature to suggest a price below which the fuel cell could compete with existing technologies, and is generally estimated in the range of £300-700 per kW for domestic micro-CHP.[124, 195, 286] These targets can then be compared with estimated or actual sale prices to draw conclusions on the likelihood of economic success, as in [43] for example.

This concept of a single price to beat for all fuel cell systems is over-simplified as there is no single price below which a particular fuel cell will become beneficial to all customers. The spread in fuel bill reductions seen in Figures 6.15 and 6.16 will result in range of target prices which can be represented as a probability distribution. Plotted as a price-to-beat curve, this shows the market size that could be rationally exploited for a given capital cost.

The target price was taken to be net present value of the lifetime earnings from the fuel cell, plus the avoided cost of purchasing a condensing boiler: $PVGA + P_{ref}$. Target prices were calculated from each of the 1,000 simulated results, and then ranked in descending order to generate the price to beat curve. This then shows the proportion of the modelled houses that would benefit financially from installing a fuel cell at a given price.

8.2.6. Calculating the Cost of Carbon Mitigation

The normalised cost of carbon mitigation, or simply the 'carbon cost', was defined as the additional financial investment required to install and operate the fuel cell system, divided by the total carbon savings made over its lifetime. This is a useful figure of merit for comparing low carbon technologies, policies and actions, giving a measure of the cost effectiveness of their emissions reductions.

The cost of carbon mitigation with fuel cell micro-CHP was calculated from two perspectives: the cost to government of providing the feed-in tariff, and the cost to society as a whole. Subsidies for low-carbon generation will ultimately be paid for by the public through taxation or levies, and so were included in the analysis.

The carbon cost of a feed-in tariff was calculated from the simulation results given in Sections 6.3 and 6.4: i.e. the annual revenue from the tariff and the carbon savings made in each property. Unlike energy prices, the value of the FIT will remain constant over the lifetime of the technology,[255] and likewise it was assumed that the carbon savings would remain static.[125]

The total carbon cost accounted for the additional investment required to purchase the fuel cell, and the additional savings (or costs) that would come from operation. This was calculated as the net present value of the revenues and payments (as in Figure 8.1 for example), divided by the total carbon reductions made over the 10-15 year system lifetime.

8.3. Results

8.3.1. Payback Times

The calculated payback times for PEMFC systems are plotted in Figures 8.3 and 8.4 with different levels of feed-in tariff. Payback times were not calculated with zero FIT as the majority of systems were simulated to increase the overall running costs, and so would not be able to pay back their marginal price in any length of time.

Figure 8.3 shows the payback times calculated using different assumptions for the upfront price of the fuel cell, neglecting additional costs due to stack replacements. Current ENE-FARM prices were used alongside the projected future prices to give an indication of how payback times would differ with lower priced systems. It should be remembered that these calculations ignore any future improvements in system performance (i.e. efficiency of the fuel cell and reference systems), and only consider reductions in purchase price.

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[125] While it is generally expected that the average carbon intensity of grid electricity will fall over time, the change in marginal emissions is uncertain.[20]

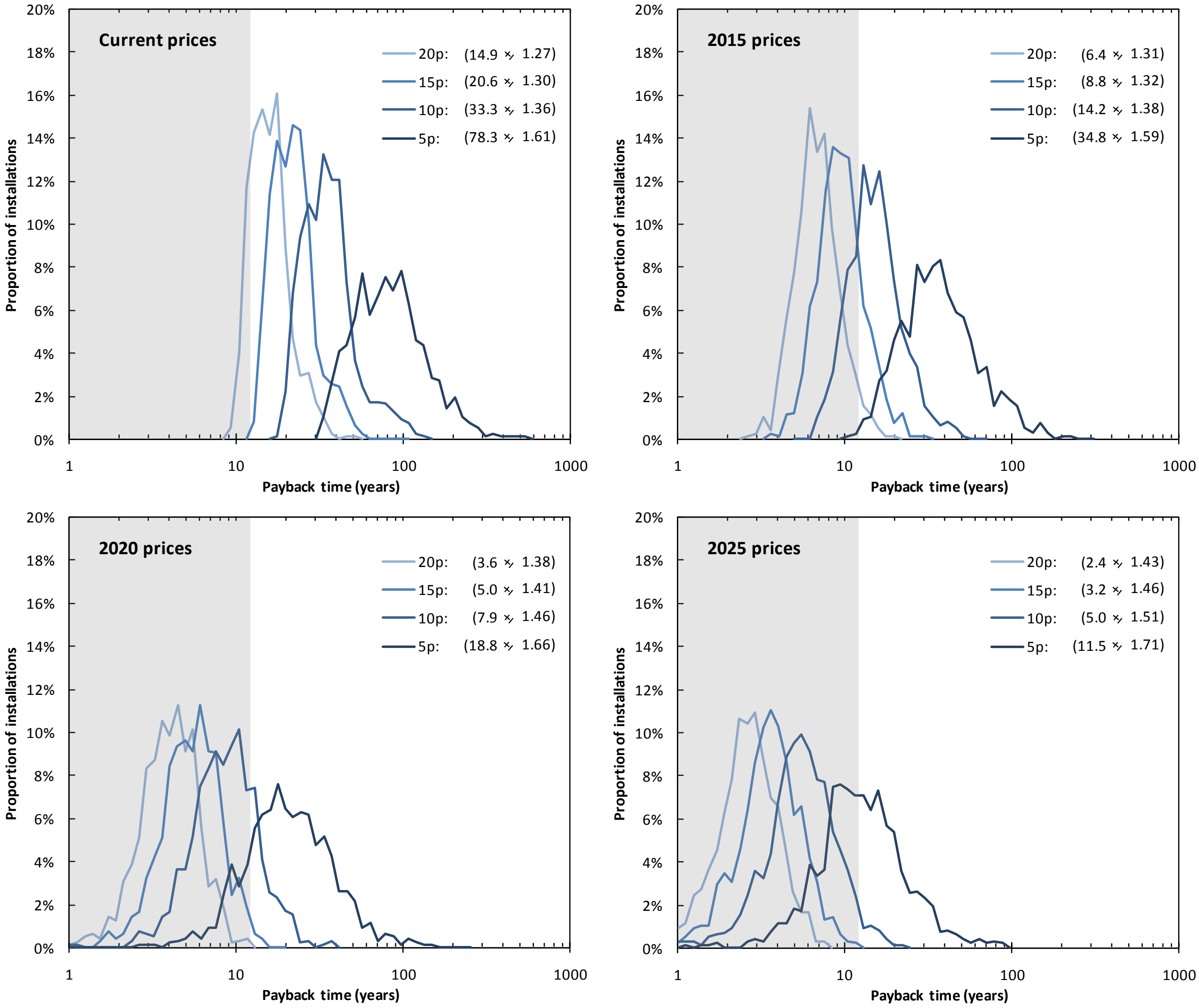

Figure 8.3: Histograms of the payback times calculated for PEMFC systems with different levels of FIT support and capital cost. The assumed economic lifetime of the system (average 12.5 years) is highlighted as a grey band towards the left of each plot. The mean and standard deviation of each log-normal distribution is given.[126]

The relative area under each curve that lies in the grey regions gives an indication of how likely – or in how many properties – the fuel cell would be able to pay back its marginal cost within its lifetime. From the top-left plot it is seen that a FIT above 20p/kWh is required with current prices. Around 23p/kWh is required for half of systems to break even, which is in the range of tariffs that are proposed for renewable microgeneration in the UK.[255] As system capital costs decrease to around £8,600 and then £5,900 (2015 and 2020 plots), a 15 and 10p/kWh FIT would enable the majority of installations to be economically viable.

Figure 8.4 repeats the calculations using the current upfront price of £15,628, and considers the impact of funding additional stack replacements based on current and target stack lifetimes. Payback times increase in line with the marginal price of the fuel cell system when stack

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[126] Because these are log-normal distributions, the standard deviation is given as "multiplied or divided by" rather than "plus or minus". For example, 14.9 ×/ 1.27 indicates a standard range of 11.7 to 18.9.

replacements are included, rising by 13-15% with target lifetimes and 35-45% with those currently demonstrated.

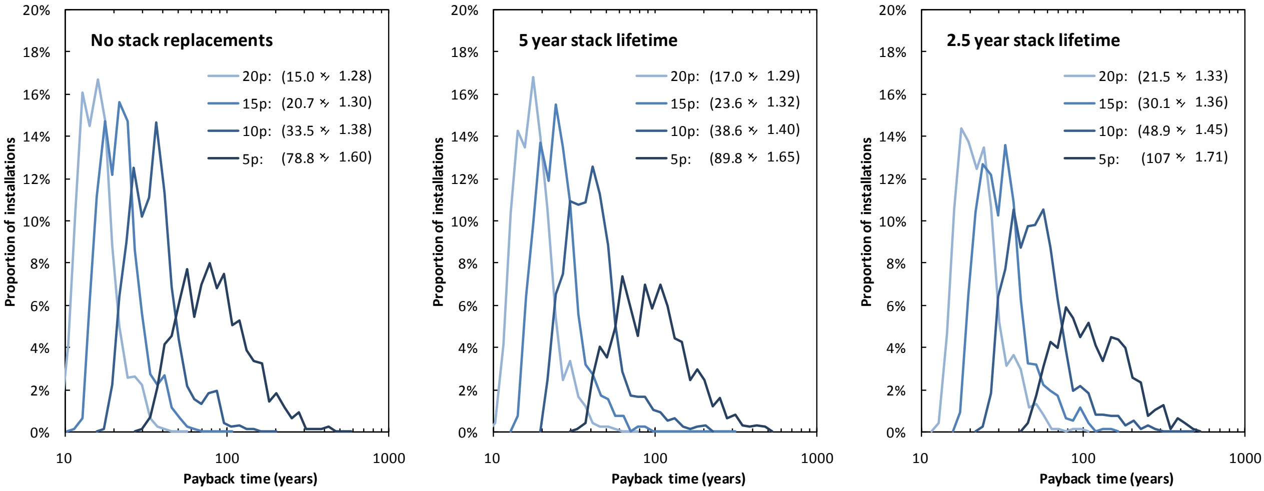

Figure 8.4: Histograms of the payback times calculated using current prices, with and without the additional investment required to fund future stack replacements. Note that the payback times with no stack replacements are slightly different to those given in Figure 8.3 due to the stochastic calculation methods.

Even with today's high fuel cell prices, payback times with a 10p/kWh feed-in tariff are similar to those of other microgeneration technologies (solar PV, solar thermal and micro-wind). Due to favourable energy tariffs and subsidies in Japan, Panasonic estimated a 16-17 year payback time for ENE-FARM systems operating in Japan, compared with over 20 years for solar PV.[307]

At present, payback times for Kyocera SOFC systems would be around three times higher than these projections, based on the tentative data on current prices given in Table 7.1. Similarly, the payback for PEMFC systems would take substantially longer (or become impossible) if higher discount rates were chosen, as the present value of the annual income would diminish more rapidly with time.

8.3.2. Internal Rate of Return

As an alternate way of assessing the payback times presented in Figure 8.3, the IRR was calculated for the four levels of upfront price and a feed-in tariff ranging from 0 to 20p/kWh. Figure 8.5 shows the range of IRRs that were seen across the set of houses, assuming that the cost of future stack replacements was included in the initial price.

The top-left plot in Figure 8.5 confirms that with current prices, fuel cells are not economically viable in the UK. The average IRR was -27±7% with no FIT support, and -7.5±2.3% with 10p/kWh.

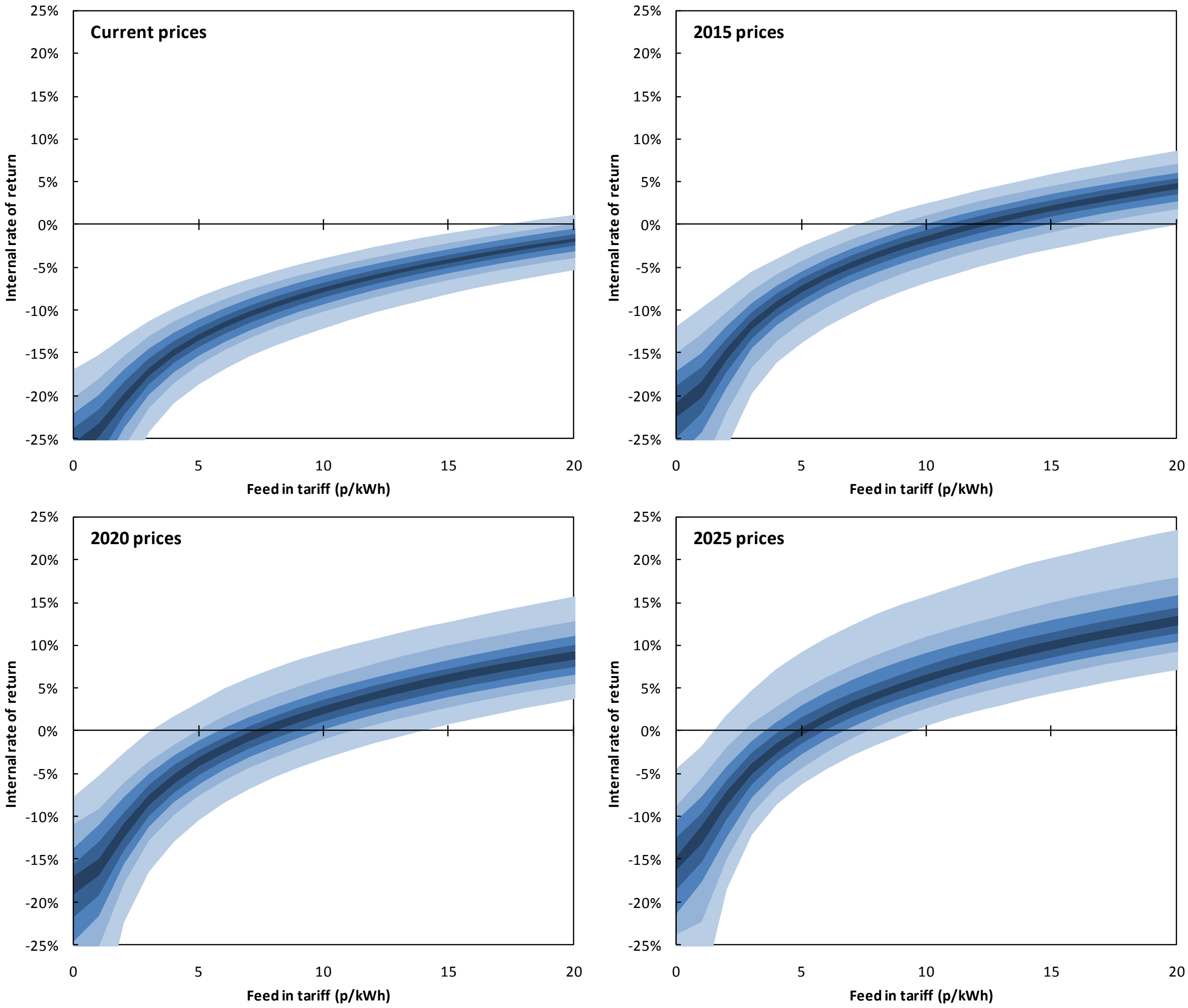

Figure 8.5: The range of IRR calculated for PEMFC systems with different levels of FIT support and upfront price.

Decreasing prices have little effect on the IRR when the feed-in tariff is below ~2.5p/kWh, as PEMFC systems would generate little or no revenue over their lifetime. However, with a 10p/kWh FIT, around 15% of systems would be able to recover their capital cost (excluding any interest accrued) if prices reduced to £8,600 (top-right plot) – or equally if a capital subsidy of around £7,000 per system was offered today. With a FIT of 12.5p/kWh or above, the majority of systems would be return a positive IRR in this situation.

As prices continue to fall below £6,000 as in the bottom two plots, then fuel cells become a rational investment for most households with a FIT of 10p or above. The IRR rises above the 6% chosen discount rate, and in some cases reaches the range of 10-15% that potential corporate investors would consider attractive.

8.3.3. Price to Beat Curve

Target prices were calculated for all four fuel cell technologies to work around the current uncertainty in sale prices. Three scenarios are plotted in Figure 8.6, considering feed-in tariffs of 0-20p/kWh. These targets relate to a system that will be fully operational over the 10-15 year lifetime of the CHP and boiler systems, and thus includes the cost of any stack replacements needed during this time.

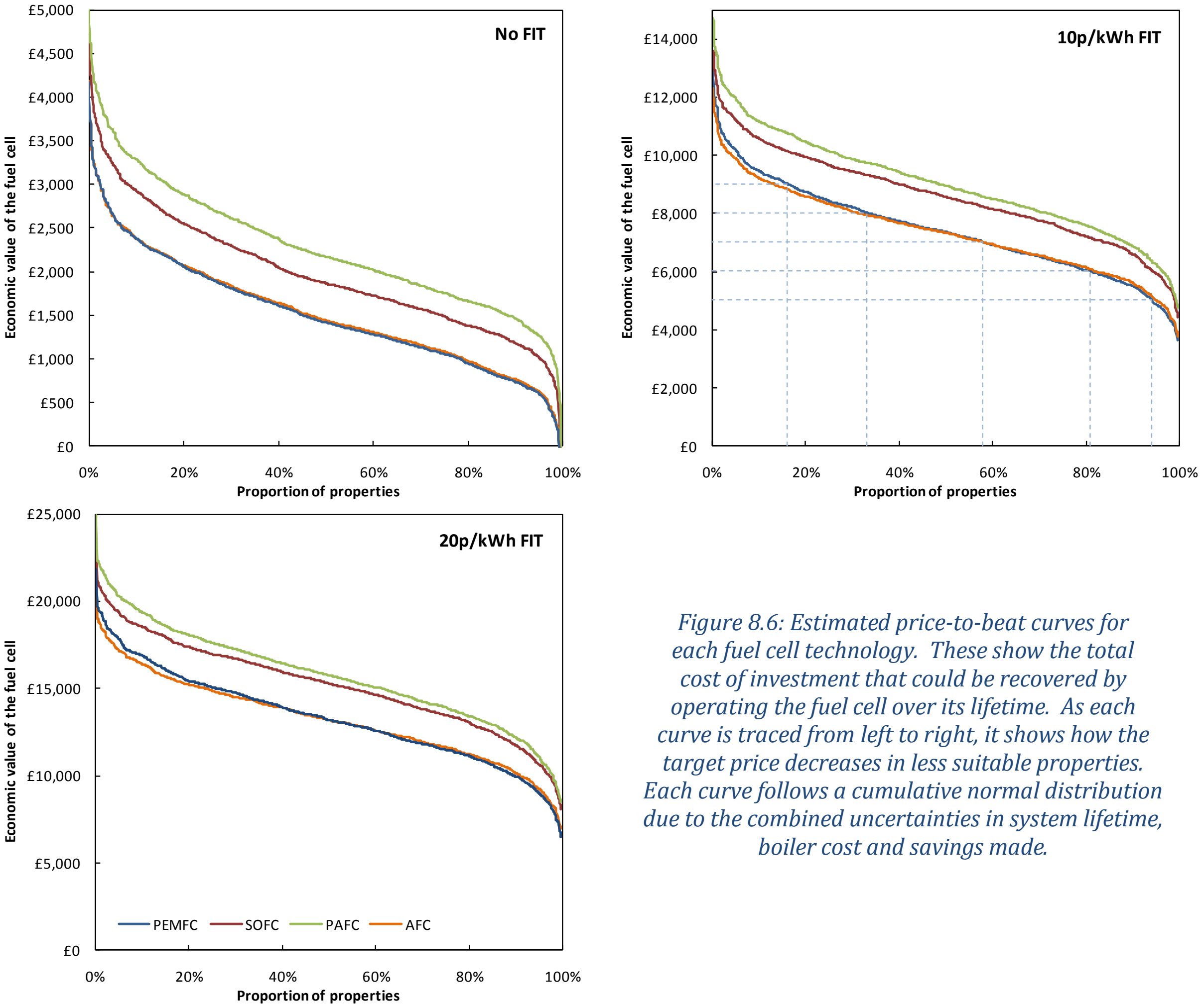

Figure 8.6: Estimated price-to-beat curves for each fuel cell technology. These show the total cost of investment that could be recovered by operating the fuel cell over its lifetime. As each curve is traced from left to right, it shows how the target price decreases in less suitable properties. Each curve follows a cumulative normal distribution due to the combined uncertainties in system lifetime, boiler cost and savings made.

With no feed-in tariff, the target price of PEMFC and AFC are seen to centre on the £1,500 avoided cost of the boiler, as the annual savings they provided were approximately zero. PAFC and SOFC targets are slightly higher as they are able to generate some revenue over their lifetimes. This gives manufacturers very little room to move unless capital subsidies are offered, as a complete system (including boiler, tank, etc.) is expected to cost a minimum of £2,300-2,900 to produce and install, based on the analysis presented in Section 7.4.

As seen previously, a FIT of 10p/kWh substantially improves the economics, raising the average target prices up to £7,000-10,000. Each curve in Figure 8.6 can be used to estimate the proportion of UK properties that would benefit from installing a fuel cell of a given price, as demonstrated in the top-right plot. A 1kW PEMFC system sold for £9,000 would provide a financial benefit in 16% of households (with a 10p/kWh FIT), and if prices fell to £7,000 then 58% of properties could benefit from installation.

It should be remembered that the given target prices relate to a system that is fully operational for ten years, including any stack and other component replacements. It was estimated that a stack lifetime of 5 years would add approximately 15% to the initial price of a PEMFC system over its lifetime, meaning that with the near-term target lifetimes the initial sale price of PEMFC systems would need to be $\left(\frac{1}{1+15\%}\right) = 87\%$ of those presented in Figure 8.7. The impact that stack replacements would have on other fuel cell technologies cannot be estimated in this way, as the breakdown of stack and other system costs is not known. It is however clear that the shorter lived technologies (AFC and SOFC) must either improve stack lifetimes or ensure that the price of replacing a stack is minimised in order to prevent this from having a major detrimental effect on the whole-lifetime economics.

8.3.3.1. Influence of Energy Prices and Feed-in Tariff

The spread in target prices for a PEMFC is shown in Figure 8.7, showing the strong dependence that target prices have on the energy prices and feed-in tariff. The average target price (that which would be viable in half of the simulated houses) could be as high as £10,000 if energy prices rise by 10% per year in real terms (12.5% nominal), or if a feed-in tariff of 20p/kWh was offered.

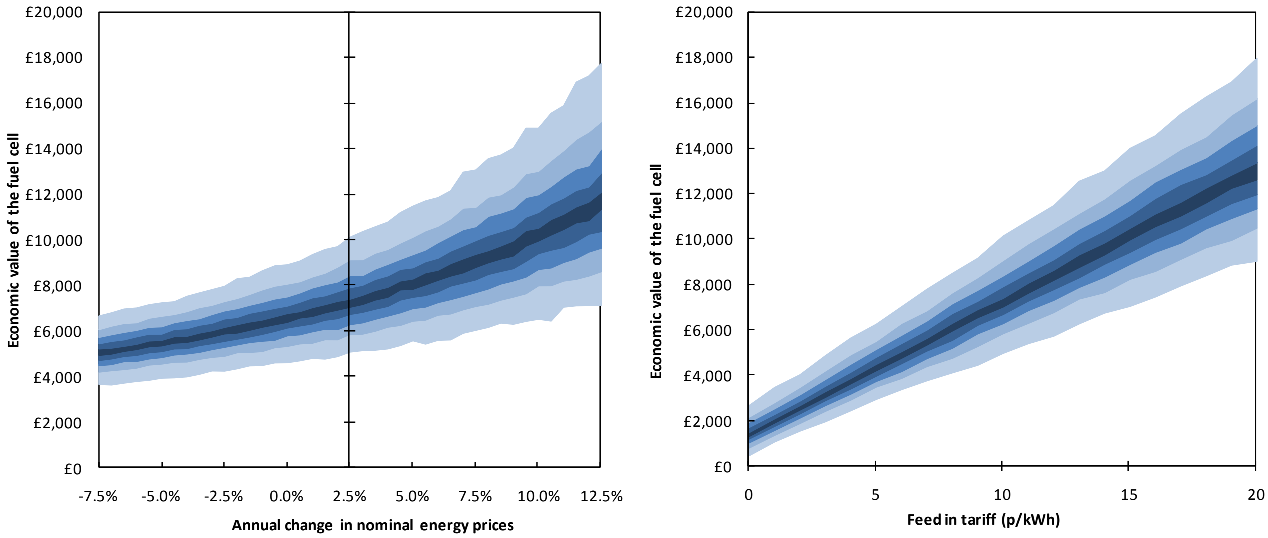

Figure 8.7: The spread in the target price for a 1kW PEMFC, calculated with a range of energy price escalators and FIT values. Left: the FIT was held constant at 10p/kW, and the annual growth in energy prices was varied by 10% around the central value. Right: default energy prices were used, and the FIT was varied between 0 and 20p/kWh.

8.3.3.2. Influence of Property

It was seen in Chapter 6 that larger properties (those with higher energy demands) generally gained the most from installing a fuel cell. It follows that these ideal properties will offer the best economic prospects, and the same trends are seen with the metrics calculated in this chapter. Figure 8.8 shows the influence of property on both the target costs, and the payback times of a PEMFC system. As seen before, it is houses which use more energy (having reference bills over £1,000 per year) that offer the best prospects for fuel cell systems, giving the highest target cost and lowest payback times.

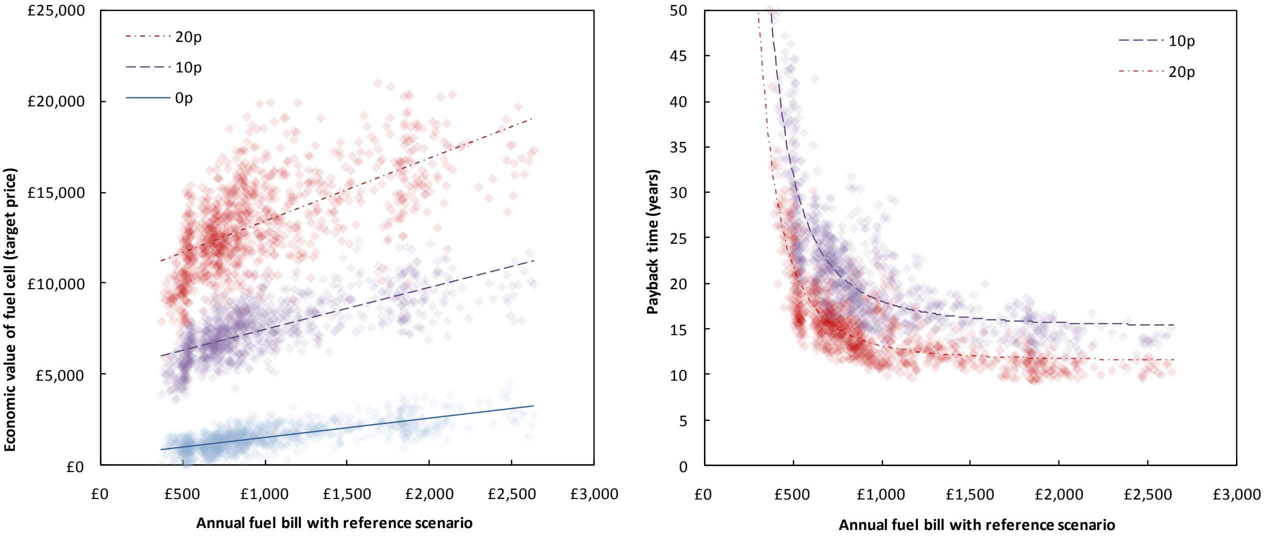

Figure 8.8: The variation in target price (left) and payback time (right) for PEMFC systems, plotted against the reference fuel bills of each property, and calculated with feed-in tariffs of 0, 10 and 20p/kWh. Payback times with no FIT were between 70 and ∞, and so were not shown.

8.3.3.3. Projected Dates for Economic Viability

As a means to put these findings into context, dates were mapped onto the target prices for PEMFC systems based on the expected rate of price reduction for the ENE-FARM systems. The timeline for price reductions is given in Figure 8.9, which was derived from the data presented in Section 7.4.

Figure 8.10 plots five price-to-beat curves for PEMFC systems with a FIT ranging from 0-20p/kWh. For each of these curves, the target prices that would be beneficial to 50% of the simulated houses were mapped onto a range of dates, which are given next to the points on each curve.

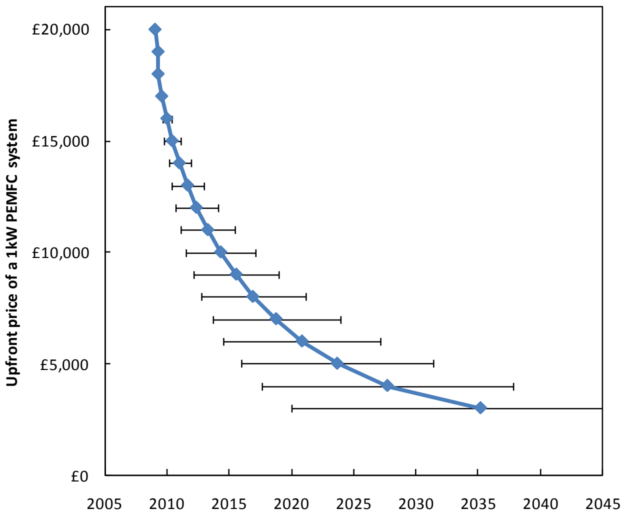

Figure 8.9: Expected timeline for price reduction of ENEFARM PEMFC systems. Rather than showing the variation in prices predicted for a given year, this shows the spread in the time required to achieve a given price, as predicted by the 'Average I' and 'Average II' experience curves, and the full range of deployment scenarios.

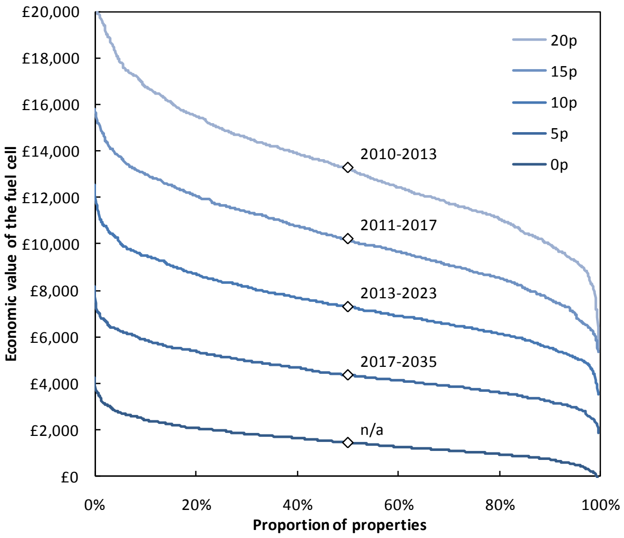

Figure 8.10: Price to beat curves for 1kW PEMFC systems with various levels of feed-in tariff. Estimated dates are given for when the purchase price of ENEFARM systems would reach the estimated target for 50% of UK households.

If the UK government were willing to support natural gas fired micro-CHP with a similar level of incentives that biomass and anaerobic digester CHP are expected to receive (9-11.5p/kWh)[255], then PEMFC systems could be economically viable in at least half of UK properties within 4 years. This assumes that there will be strong uptake (primarily in Japan) between now and 2013, enabling the price reductions at the optimistic end of the projected spectrum. Offering higher feed-in tariffs would obviously be beneficial; however it is more notable that if lower rates are offered, the range of dates for commercial viability slips back significantly. A FIT of 5p instead of 10p/kWh would double the time until break-even occurs, and offering no FIT would in all likelihood make it impossible for fuel cells to be competitive with current UK energy prices.

This preliminary analysis neglects any impact from future improvements in the performance of the fuel cell and reference system. The METI roadmap for ENE-FARM development aims for improvements to the electrical efficiency and lifetime of stacks over the coming decade, which will help to bring forwards the projected dates for commercial viability. Conversely, improving performance of condensing boilers or marginal electricity generation would detract from the financial or carbon benefits from micro-CHP and give the opposite effect.[277]

8.3.4. Carbon Costs

Results from the central simulations were used to give the annual reduction in carbon emissions from operating a fuel cell in place of the reference system, and the annual revenue generated from a 10p/kWh feed-in tariff. The carbon reductions were estimated with the whole life-cycle carbon intensity of natural gas (197 g/kWh HHV), and a range of values for electricity. These are plotted together in Figure 8.11 for a 1kW PEMFC system operating for one year.

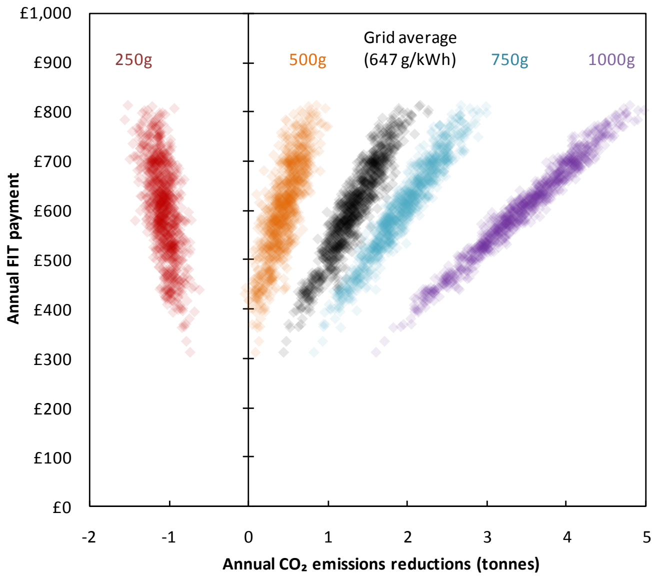

Figure 8.11: Relationship between the annual value of a 10p/kWh feed-in tariff and the carbon savings from a 1kW PEMFC system, when displacing electricity of different carbon intensities. Each data point represents the carbon savings and FIT payment from a single house used in the simulation.

In each case there is a strong correlation between carbon reductions and revenue from the FIT, as both were linked to the amount of electricity generated by the fuel cell. The gradient of each data set in Figure 8.11 indicates the cost of providing this FIT per tonne of carbon displaced – which is plotted in Figure 8.12.

The carbon costs of providing a 10p/kWh FIT were calculated using four of the scenarios given in Figure 8.11; no costs were calculated for the case of 250 g/kWh displaced emissions, as the fuel cell would increase rather than decrease emissions. The average cost of a 10p/kWh FIT to the government would be £466 per tonne of CO_2 for a PEMFC displacing average grid electricity. This cost scales linearly with the level of tariff offered, so for example a 2.15p/kWh FIT would be equivalent to a £100/T carbon cost in this situation.[127]

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[127] It could be argued that by offering a lower tariff, the less suitable (and thus higher-cost) households would not choose to invest in a fuel cell, lowering the average carbon cost further.

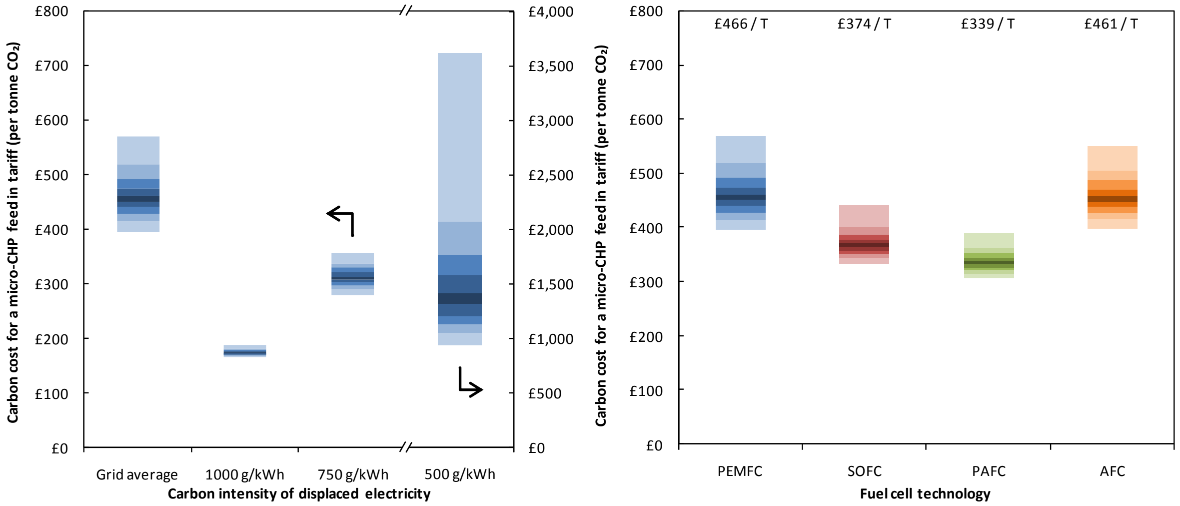

Figure 8.12: The cost to government of carbon mitigation with a 10p/kWh feed-in tariff for fuel cell micro-CHP systems. The left plot shows a PEMFC system displacing electricity of different carbon intensities, while the right plot shows the carbon costs for different technologies displacing grid average electricity.

Carbon costs are reduced if the fuel cell displaces higher carbon electricity generation – falling to an average of £177/T for a 10p/kWh FIT if coal fired plants at 1000 g/kWh were displaced. Costs however increase sharply as the carbon intensity of displaced electricity reduces towards that of the fuel cell (e.g. 410-450g/kWh for PEMFC). The higher efficiency of SOFC and PAFC systems means that they would offer lower carbon costs for a given level of FIT, as seen in the right hand plot of Figure 8.12.

As shown earlier, a 10p/kWh feed-in tariff alone would not provide sufficient revenue to make PEMFC systems economically viable with present prices, meaning that the household, industry or government would also have to contribute towards the cost of emissions reductions. When the total additional cost of the system is accounted for, carbon costs almost double to £911 per tonne as shown in Figure 8.13. This carbon cost will decrease rapidly in line with fuel cell prices, and so could be expected to halve within five years. These results show the same dependence on grid carbon intensity as in Figure 8.12, as the emissions reductions from the PEMFC were the same in both cases.

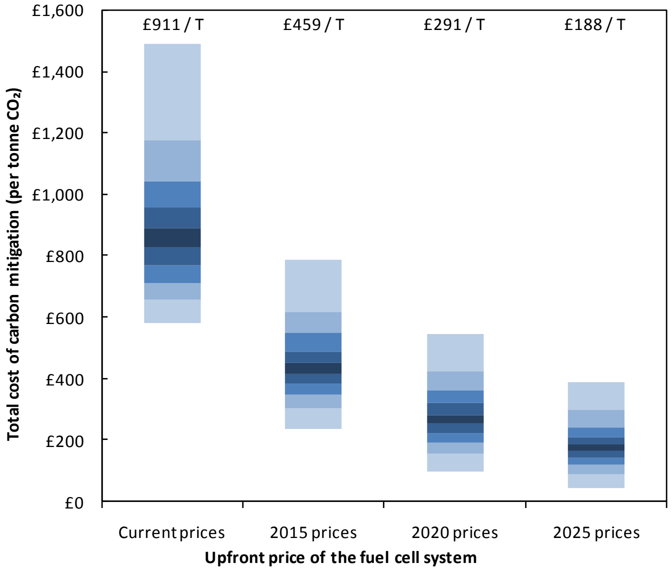

Figure 8.13: The total carbon cost for PEMFC displacing grid-average electricity, considering current and near-future prices for the fuel cell system. Average values are given for each upfront price, representing the combined cost to the household and to government.

8.4. Concluding Remarks

When the lifetime costs and savings from a fuel cell micro-CHP system are combined, they are dominated by the high upfront prices seen today. With the central assumption of a 10p/kWh feed-in tariff and current UK energy prices escalating at 2.5% per year, a 1kW PEMFC system is estimated to have a payback period of 25-45 years, compared to a working lifetime of 10-15 years.

This result is highly sensitive to reductions in upfront price, the level of support offered through a feed-in tariff, and the future development in the prices paid for energy. PEMFC systems could reach breakeven within 10 years if prices fall to the projected levels of around £6,000 per system. Similarly, the economic case for investing in fuel cells is greatly improved if historic rises in UK energy prices continue (~10% per year [330]), or if the level of FIT support offered by government is higher than expected here.

Even though fuel cells are the most expensive form of microgeneration at present, they are able to compete economically with much better established solar PV when given a level playing-field of incentives. A 20 p/kWh FIT could give financial payback within 12-19 years (possibly within the reach of current system lifetimes), reducing to 5-8 years by 2015 due to the expected decrease in capital costs. It is clear that the level of support that will be provided by the FIT, and future initiatives for renewable heat production will make or break the economic case for fuel cell micro-CHP.[128]

Over its economic lifetime of 10-15 years, a PEMFC is estimated to cost £14,100±1,100 more than the reference heating system and save 17±4 tonnes of CO_2 when displacing grid-average electricity. The estimated total carbon cost for the central case therefore lies between £750 and £950 per tonne of CO_2 avoided. These costs can be halved over the next decade with the expected price reductions, or immediately if it is valid to assume that coal fired plants will be displaced by fuel cell electricity generation.

Actions with a carbon cost below £25-50 are generally considered to be 'value for money' methods of combating climate change.[2, 7, 331, 332] The IPCC estimate that 20-40% of global CO_2 emissions could be avoided for under £50/T, which would be sufficient to stabilise the climate at 2-4°C above pre-industrial temperatures.[7] However, this would offer no guarantees against the most devastating effects of climate change, and so governments may have to accept higher costs of mitigation if they are to avoid catastrophe.[2]

Fuel cells are clearly not among the 'low hanging fruit' – measures such as improving building insulation and heating/cooling efficiency which could reduce CO_2 emissions with low or even negative costs.[129] As with renewables and other forms of microgeneration, current prices must be reduced substantially before fuel cells can become a mainstream and cost effective method of CO_2 mitigation. Today's carbon cost for PEMFC systems is in the same league as those estimated for domestic and large-scale solar PV and solar thermal installations, which range from £100-2,000 per tonne.[330, 333]

The motivation for industry and governments to invest in fuel cell technologies today is not to offer the benefits of CO_2 reduction and reduced fuel consumption in the short term, but rather to advance the technology to a point where it could be an economically attractive solution in the long term. Based on current understanding of prices and their rate of decrease, this could be expected within the next ten to twenty years with an international commitment to rapid deployment.

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[128] The Renewable Heat Initiative is intended to run alongside the proposed feed-in tariffs, rewarding low-carbon heating technologies such as micro-CHP by crediting heat output, much in the same way as the FIT credits electricity production.[255]

[129] A negative carbon cost implies that both carbon emissions and costs (from fuel purchase) could be reduced together.

Chapter 9:

CONCLUSIONS

9.1. Summary of the Contribution

Simulations of fuel cell operation and analysis of price data has given the first estimates of payback times and carbon costs for micro-CHP systems. This work can be divided into four main areas: characterising the performance and the sale prices of current systems, developing a techno-economic model for simulating these systems, and combining the results into a holistic economic analysis.

9.1.1. Fuel Cell Micro-CHP System Performance

The meta-review presented in Appendix A gives a better understanding of how fuel cell micro-CHP systems perform in houses by collating the aggregate performance of around fifty distinct academic and commercial systems. Several detrimental effects were seen when fuel cells are taken out of the laboratory and integrated into people's homes, and those relating to fuel processing, electrical conversion, voltage degradation, part-load operation, and start-stop behaviour were quantified.

Five areas were identified where the performance of fuel cell micro-CHP systems is often oversimplified or misunderstood:

- The extensive balance of plant required to make a fuel cell stack operate in a house sacrifices efficiency by up to a third;
- The efficiency of nearly every system (11 of 12) falls as power output decreases, so the widely held opinion that fuel cells benefit from high part-load efficiency is not applicable to domestic micro-CHP systems;
- Voltage degradation lowers electrical efficiency over time, but raises thermal efficiency;
- Lifetimes for SOFC systems have not shown marked improvement over the last ten years, unlike those of PEMFC and PAFC;
- The impact of dynamic operating patterns had not been widely reported, in particular the energy penalty of starting up the system, and so these were often overlooked.

Using PEMFC as an example, these features of dynamic performance are seen to reduce average stack efficiencies of 37% HHV down to system efficiencies of 27% in the lab, leading to only 24% efficiency when operated in someone's home. Quoted stack efficiencies are therefore not a good indicator of the performance expected in a house, so the marketing tactics used by many companies (advertising up to 60% efficiency) will lead to customer confusion and dissatisfaction.[19]

9.1.2. Energy Demand from UK Houses

A similar attempt was made to define the broad spectrum of energy demands from UK houses, leading to a set of data being derived from measurements made in 259 houses. This was processed into 1,000 electricity and thermal demand profiles covering one year each, and was used to show that considering a large number of houses was as important as using high resolution data. Results from seemingly similar houses (in terms of size or total energy demand) could deviate by up to 40% due to the varied structure of heat and electricity demands.

A wide range of results was therefore produced from each technology simulation. This effectively provided the error bars that have been missing in previous studies, showing the context in which any observed trends and patterns must be viewed. Results such as annual energy output, operating efficiency, or financial and emissions savings all showed significant variation between properties, which cannot be captured when using a limited selection of profiles.

9.1.3. Techno-Economic Modelling

A model was developed to simulate the performance of fuel cell micro-CHP systems operating in a large number of homes. This relied on a computationally simple control method that used fuzzy logic, which demonstrated a 50% improvement in savings relative to simply following the maximum instantaneous demand. By incorporating the dynamic performance features found in the meta-review, this model was used to estimate the efficiency that fuel cell systems would obtain in the field.

From simulating the operation of industry-average fuel cell systems, the financial savings were shown to be negligible unless a feed-in tariff was provided or a higher rate was paid for exported electricity. Average annual savings of just £2-81 could rise to £600-750 with a 10p/kWh feed-in tariff, reducing the majority of customers’ total energy bills by 75% or more.

PEMFC were estimated to produce 431±19 grams of CO_2 per kWh of electricity generated, and 376±16 g/kWh were estimated for SOFC; giving 29-38% lower emissions than centralised generation in the UK. If the average grid mix was displaced, annual emissions reductions were estimated at 1.0-2.2 tonnes per household, but these could vary by a factor of three depending on which marginal plants were actually displaced by microgeneration.

In addition to the work presented in this thesis, the FC++ model was used to inform an Oxford MBA entrepreneurial report by providing estimated running costs for a proposed micro-tubular SOFC system.[334]

9.1.4. Fuel Cell Sale Prices

It is fair to say that little was known of sale prices at the start of this project due to the immaturity of the industry as a whole. Table 7.1 showed that 1kW systems currently sell for between €23,000 and €70,000, with much of the difference between manufacturers being attributable to the different levels of manufacturing experience gained so far.

The price of Japanese ENE-FARM systems was charted over the past five years, and was shown to have fallen by 19.1-21.4% for every doubling in installed capacity. Based on the projected deployment rates for the near future, prices are expected to halve over the next decade.

Tens of millions of systems would need to be produced before these experience curves project prices reaching the widely held €1,000/kW target. It was argued that this is an unobtainable goal for complete micro-CHP systems due to the costly auxiliary systems needed to provide satisfactory operation in UK houses.

9.1.5. Economic Analysis

The final economic analysis calculated payback periods and prices for manufacturers to beat, as well as carbon costs both for a feed-in tariff that supports fuel cell micro-CHP, and for the total investment required to purchase and operate a PEMFC based system.

With the central assumptions including a 10p/kWh feed-in tariff, payback times of 25-45 years were estimated for PEMFC, compared to a working lifetime of 10-15 years for the overall micro-CHP system. If the two or more stack replacements that would be required over this time are not included in the upfront price, these payback times would increase by approximately 15%. PEMFC systems could reach breakeven within 10 years if prices fall to the projected levels of around £6,000 per system, and a variety of other conditions such as increased energy prices or government support would also bring forward economic viability.

Target prices for all four fuel cell systems ranged from just £1,000-3,000 with no government support to £5.000-11,000 with a 10p feed-in tariff. Targets for SOFC and PAFC were slightly higher than those for PEMFC and AFC due to the lower operating costs, however these targets included the cost of all stack replacements required over the 10-15 year economic life, and so would likely end up being easiest for PAFC and PEMFC to attain, due to the low lifetime of current SOFC and AFC stacks.

The cost of carbon mitigation with PEMFC micro-CHP was estimated to be between £750 and £950 per tonne of CO_2 at present, when displacing grid average electricity. This cost could be halved over the next decade with the expected price reductions, or immediately if it is valid to assume that coal fired plants will be displaced by fuel cell electricity generation.

9.2. Critical Assessment

9.2.1. The FC++ Model

The main tool developed during this project was the FC++ model, and so it was subjected to extended testing and validation as documented in Chapter 5. The results from another model developed by Pawlik *et al.* and from field trials of Japanese systems were accurately replicated by using the appropriate input assumptions. Most notably, by providing the laboratory specifications of ENEFARM and Kyocera systems and an approximation of the energy demands of the Japanese homes they were installed into, FC++ was able to accurately simulate the generating efficiency that was experienced in the real world field trials.

The logical culmination of this was to validate the model by simulating the Baxi Beta system operating in the hydrogen house. Ideally, the energy demand of the house and the performance of the laboratory system would have been measured and fed into the model, giving a simulated operation and performance profile that could have been directly compared with the field trial system. Technical and contractual issues however prevented this, and so it remains as suggested work for future field trials.

The model lacks the finely tuned calibration of the Annex 42 simulations due to its broad and unspecific nature, and the ability of CODEGen to search for optimal control strategies as it was a simulation rather than optimisation routine. However, unlike these and other available models, it is able to simulate a wide array of fuel cell technologies operating in thousands of houses with thousands of Monte Carlo trials.

9.2.2. Modelling Results

The economic and environmental results from FC++ could only be directly compared with those studies used for validation, as none of the previous studies listed in Tables 3.1 and 3.2 modelled fuel cells operating under the same conditions. In the validations against Pawlik's model and ENEFARM systems, FC++ estimated financial and CO_2 savings that were statistically similar to the reference values. The savings from Kyocera systems were over-estimated due to the inability of FC++ to predict how much heat would be wasted in Japanese houses, which was in turn caused by the poor approximation to their energy demand profiles.

The financial savings predicted for the industry wide PEMFC and SOFC systems were lower than in previous studies focussed on the UK due to the different energy prices considered.[123, 124] Notably, the spark gap in these previous studies was 4.1 and 4.4, compared to an average of 3.3 considered in this work. Previous modelling work using FC++ considered a spark gap of 3.8, which resulted in higher annual savings of €200-300 for an SOFC [43]; compared to €211 in [123], and €250-325 in [124]. Savings with an SOFC for customers on the EDF tariff (with a 3.77 spark gap) were predicted to save €90-170 per year, which was also similar to these previous estimates.

Two of the emissions studies listed in Table 3.2 focussed on the UK and used displaced grid emissions of 420-430g/kWh. These estimated annual CO_2 savings of 900kg [123] and 1000-1400kg [20], which compares well to the 900-1600kg savings given by FC++ for PEMFC and SOFC, when using direct – rather than whole life-cycle emissions factors.

9.2.3. Learning Rates

The learning rates estimated for PEMFC micro-CHP systems in Chapter 7 cannot be compared with the values used in previous studies, as these have unanimously relied on authors' assumptions.[110, 155] The central estimates of 19.1-21.4% however lie centrally among the rates observed with other technologies (Figure 3.1), and the resulting experience curves project similar prices to those given by manufacturers and governing bodies (Figures 7.3 and 7.9). The most striking difference between this and previous studies was that current prices have been shown to be an order of magnitude higher than previous assumptions, starting at over €22,000 per system.

9.2.4. Economic Outcomes

As with the learning rates, the final calculations of payback periods and carbon costs have no peers for comparison.[130] These values built upon the preceding estimates and assumptions which could individually be reviewed and compared to previous literature, and were calculated using standard methods used with other technologies.

9.3. Further Work

9.3.1. Continued Meta-Research

Much of the underlying data that has been presented in this thesis can be continually updated as new information becomes available. The commercialisation of ENE-FARM will mean that new data points can be added to the experience curves as prices fall, refining the estimated learning and deployment rates. However, there still remains a void regarding the current prices of European and American systems, and those based on SOFC and other fuel cell technologies.

It is hoped that detailed technical and economic data will be provided by the ongoing demonstrations of PEMFC systems in South Korea, SOFC systems in Japan, and the German Callux programme. These could shed light on the closest rivals to the ENE-FARM: their current costs, durability, and performance in real world usage.

9.3.2. Extensions to FC++

Development of the FC++ model could be taken in several directions, for example:

- The addition of a front-end interface to guide users through the creation of configuration files;
- The addition of filters to accept other formats of energy demand data, enabling easier integration with building simulators;
- Incorporating the effects of device reliability, stochastically modelling downtime based on the Mean Time Between Failure (MTBF) and the time required for repairs and servicing;
- The development of learning or adaptive control algorithms, which record past demand and output from the fuel cell in order to determine optimal dispatch profiles;

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[130] The only other estimate for the payback period that could be found was made by Panasonic for their ENE-FARM system, and was 16-17 years in Japanese homes.[307] None of the underlying assumptions were published however.

- The development of a ubiquitous least-cost system controller that could optimally dispatch any combination of devices based on knowledge of their performance and operating costs.

In particular, the model could be given a wider scope by writing new scenario and device classes to describe other technologies, such as micro-CHP engines, heat pumps, micro-wind and solar based renewables. Stochastic models or externally generated data sets could be used to simulate the available energy yield and performance of these devices. A more generic microgeneration model could then be used to provide more direct comparisons between technologies, and to investigate potential technological conflicts, or synergies such as those proposed by Japanese gas companies with their “double generation” promotion (ENEFARM + solar PV).[335, 336]

Further uses of FC++ could inform the following investigations:[131]

- The relationship between operating strategy and fuel cell durability:

  Would minimising the time spent operating at low power affect degradation rates and operating lifetime, and thus increase lifetime energy output, along with economic and environmental benefits?
- The integration of hydrogen storage into micro-CHP:

  By delineating the production and consumption of hydrogen, could the limitations of inflexible fuel processors be overcome to improve the dynamic response of fuel cells operating on natural gas?
- The impact of fuel cell micro-CHP uptake on national electricity supply:

  What impacts would thousands (or millions) of microgeneration units have on the net national electricity demand which must be balanced by central generators? How would marginal plant, and the infrastructures for electricity and gas distribution be effected?
- Eliminating inefficient marginal generation with virtual fuel cell power plants:

  How many fuel cell micro-CHP systems would be required to balance national supply and demand? What would this virtual power plant cost per kW and per kWh, and what would the benefits to consumers be?

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[131] These were typical of the questions proposed by Professors Kevin Kendal and Richard Green during the course of this project, but were left unanswered at the time of writing.

9.3.3. Life Cycle Assessment

Figure 1.2 in the introduction showed that a life cycle assessment of the construction of fuel cell micro-CHP systems is an ongoing part of this project, and a forthcoming paper in this area is provided in Appendix C. The work underway in this area mirrors the contents of Chapter 7, assessing the environmental (rather than financial) costs of constructing fuel cells. This would allow some of the corresponding metrics to be calculated, such as the CO_2 emissions from construction and the energy payback periods.

Some major discrepancies and uncertainties in previous LCAs were highlighted in Section 3.4, indicating the need for further work in this area. Preliminary assessment of the previous LCAs given in Table 3.4 suggests that around 0.5-1 tonne of CO_2 is emitted in the production of a 1kW fuel cell micro-CHP system, which would have a small but appreciable impact on the lifetime carbon savings (5-20%) and thus the carbon cost of these systems.

9.3.4. Economic and Policy Implications

Finally, the implications of this research could be taken further, for example by factoring the empirically based cost projections into broader simulations of market uptake and technology policy such as [25, 33, 337, 338]. The widely differing assumptions used in these studies means that they arrive at polar-opposite conclusions, ranging from fuel cell micro-CHP playing a central role in future emissions reductions strategies to not being used at all over the next 40 years.

The initial sensitivity analyses performed on financial and carbon savings could be extended to establish the conditions required for fuel cells to provide the greatest carbon savings at the lowest cost. Comparisons could be made against other microgeneration technologies with consideration of alternative financial support mechanisms.

Other questions that will face policy makers could also benefit from the findings of this work:

- What would be the national impacts of large scale adoption of fuel cells? For example, on energy security, progress towards emissions targets, fuel poverty, urban air quality, industrial growth, etc.
- What would it cost to subsidise the commercialisation of fuel cell micro-CHP in the UK?
- Would this money be better spent on supporting other technologies and policies, such as building refurbishment, other microgeneration, or centralised grid decarbonisation with nuclear or renewables?

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APPENDICES

Appendix A

A REVIEW OF SMALL STATIONARY FUEL CELL PERFORMANCE

Abstract

The current technological status of four fuel cell technologies was reviewed, focusing on small (0.5-5kW$_e$) stationary units suitable for domestic CHP. These were polymer electrolyte membrane fuel cells (PEM, PEMFC, PEFC, SPFC), solid oxide fuel cells (SOFC), phosphoric acid fuel cells (PAFC), and alkaline fuel cells (AFC).

Seven categories of data were investigated that would impact on the performance of micro-CHP systems:

- Power density – power output per cm^2 of cell area, which determines the number of cells (or stack area) required;
- Efficiency of the complete natural gas fuelled CHP system, at full and part load;
- Durability – the operating lifetime and rate of degradation of the fuel cell stack;
- Reliability of the system, including ancillary components;
- Current prices and estimated high-volume manufacturing costs;
- Start-up time and other dynamic constraints on power output;
- Fuel tolerance of the stack, which impacts on the required fuel processing stages.

Performance figures were sought to represent the real-world capabilities of state of the art systems. Wherever possible, data was sourced directly from the field, giving the performance actually experienced by users, rather than quoted by the manufacturers. Both commercial and research systems were considered, so long as they could be suitable for a consumer product.

Due to the vast differences in research activity for each fuel cell technology, there was a wide range in the quality and age of available sources. Much of the PEMFC data came from the extensive field trials in Japan, which were highly regarded due to their relevance to this study. For SOFC, much of the data came from academic literature as commercial demonstrations are only just beginning. As domestic micro-CHP scale AFC and PAFC systems are only beginning to be developed, data had to come from similar, but not entirely relevant industrial CHP units, and from publications that are over a decade old.

The first revision of this review was published in 2007, and is available (for legacy) from http://wogone.com/iq/fuelcells. This review is an ongoing project, and it is expected that the final values presented will be updated as more information is collected and reviewed. The aim is to stay updated with the latest technological advances, and to continue broadening the overview of fuel cell technologies.

As the progress of technology marches on, the data presented in this revision will slide out of date. If readers could contact me at the above email address with any citable information (references to articles, web pages, etc.), I would gratefully acknowledge their efforts in improving this work.

PEMFC performance	**Mean**	**Standard deviation**	**Range (μ ± σ)**	**Number of references**
Operating cell voltage *(V)*	0.68	0.08	0.60-0.76	8
Operating cell current *(A/cm^2)*	0.51	0.30	0.20-0.81	
Power density *(W/cm^2)*	0.33	0.17	0.16-0.50	
Gross stack electrical efficiency *(HHV)*	37.1%	4.9%	32.3-42.0%	20
Net system electrical efficiency *(HHV)*	26.7%	3.5%	23.2-30.2%	
Net total efficiency *(HHV)*	66.9%	6.6%	60.3-73.6%	19
Operating lifetime *(kh)*	19.7	10.0	9.7-29.7	22
*(years)**	4.1	2.5	2.4-7.4	
Degradation rate *(μV/h)*	8.0	7.8	0.1-15.8	17
*(power loss per year)**	4.7%	4.6%	0.1-9.3%	
Current retail price	€20,000 to €50,000 for 1kW systems			2
Volume cost estimate	Anywhere from €100 to €10,000 per kW			4

SOFC performance	**Mean**	**Standard deviation**	**Range (μ ± σ)**	**Number of references**
Operating cell voltage *(V)*	0.71	0.05	0.66-0.76	11
Operating cell current *(A/cm^2)*	0.34	0.17	0.17-0.52	
Power density *(W/cm^2)*	0.27	0.14	0.13-0.41	
Gross stack electrical efficiency *(HHV)*	44.2%	5.7%	38.5-50.0%	10
Net system electrical efficiency *(HHV)*	34.7%	4.5%	30.2-39.2%	
Net total efficiency *(HHV)*	72.4%	4.4%	68.0-76.8%	6
Operating lifetime *(kh)*	11.3	7.1	4.2-18.4	12
*(years)**	2.8	1.8	1.0-4.6	
Degradation rate *(μV/h)*	12	16	0-28	16
*(power loss per year)**	6.9%	9.2%	0-16%	
Current retail price	Over €50,000 for 1kW systems			2
Volume cost estimate	Between €300 and €900 per kW			5

PAFC performance	**Mean**	**Standard deviation**	**Range (μ ± σ)**	**Number of references**
Operating cell voltage *(V)*	0.66	0.03	0.63-0.70	9
Operating cell current *(A/cm^2)*	0.24	0.04	0.20-0.28	
Power density *(W/cm^2)*	0.16	0.02	0.14-0.18	
Gross stack electrical efficiency *(HHV)*	44.3%	4.6%	39.8-48.9%	7
Net system electrical efficiency *(HHV)*	32.5%	3.3%	29.1-35.8%	
Net total efficiency *(HHV)*	76%	-	69-78%	2
Operating lifetime *(kh)*	58	15	43-72	7
*(years)**	14.5	3.7	10.9-18.2	
Degradation rate *(μV/h)*	2.6	1.3	1.3-3.9	7
*(power loss per year)**	1.6%	0.8%	0.8-2.4%	
Current retail price	Around €3000-5000 per kW for industrial CHP			5
Volume cost estimate	*Unknown*			-

AFC performance	**Mean**	**Standard deviation**	**Range (μ ± σ)**	**Number of references**
Operating cell voltage *(V)*	0.68	0.03	0.65-0.71	4
Operating cell current *(A/cm^2)*	0.14	0.03	0.11-0.17	
Power density *(W/cm^2)*	0.10	0.03	0.07-0.12	
Gross stack electrical efficiency *(HHV)*	41.3%	3.6%	37.7-44.8%	4
Net system electrical efficiency *(HHV)*	29.7%	2.6%	27.1-32.2%	
Net total efficiency *(HHV)*	66.6%	-	-	1
Operating lifetime *(kh)*	6.7	1.9	4.8-8.6	7
*(years)**	1.7	0.5	1.2-2.1	
Degradation rate *(μV/h)*	19.5	9.4	9.1-28.0	8
*(power loss per year)**	10.9%	5.5%	5.4-16.5%	
Current retail price	*Unknown*			-
Volume cost estimate	Between €150 and €600 per kW			6

Table 1: The following tables summarise the performance of each fuel cell technology, giving the weighted mean and standard deviation for each data category. Ranges that should cover two-thirds of systems are given for each value.

** Intermittent operation was assumed for calculating lifetimes and voltage losses, with 4,000 operating hours per year.*

Methodology

Information was mostly sourced from open literature, for example from journal publications, field trial reports and commercial data sheets. Due to the commercial nature of the industry, some information must however remain confidential.

Data was reviewed and modified where necessary to give a standardised view of each technology and to avoid biased comparisons. In compiling technology wide averages, a semi-quantitative weighting was given to each source of data based on its perceived relevance.

Tables of data are presented in the following sections, giving the original and modified information, along with the date and a brief description of the report. The weighting factor (w) is also given for each result, so that the relative contribution towards the averages presented in Table 1 can be seen.

Weighting method

Not all data sources are equal. In trying to collect a broad overview of the field, some reports are cutting edge, some are from over a decade ago. Similarly, some are from extensive field trials and report the performance experienced in people's houses, others are from promotional material. A weighting method was devised in order to reconcile these differences, and prevent the less representative (but still beneficial) sources from dominating the overall averages presented in the abstract.

A weighting factor (w) for each datum was defined as follows; from the number of measurements or units that are represented (N), the age of the data source in years (A), and two qualitative multiplication factors based on the source quality (SQ), and data quality (DQ):

$$w = \big(1 + \ln(N)\big) \;\cdot\; \exp\left(-A \cdot \left(\frac{\ln(2)}{3}\right)\right) \;\cdot\; SQ \;\cdot\; DQ$$

- The quantity term $\big(1 + \ln(N)\big)$ accounted for the greater representation offered when more units are tested. A single value arising from three units would be given approximately double the weighting, data from a group of 10 would be given a weighting of 3.3, and data from 100 would be given 5.6.
- The time constant of $(-\ln(2)/3)$ accounted for the decreasing relevance of older data due to the continual march of technological improvement. Data that is three years old was given half the weighting, six year old data was given quarter the weighting, etc.
- The source quality (SQ) reflected differences between the ideal source of information, and was given the following values:
    - 4 for data arising from field trials
    - 2 for data arising from independent (preferably peer reviewed) experiments
    - 1 for manufacturer's specifications, promotional material and other sources
- The data quality (SQ) reflected differences between the ideal domestic CHP system and what was actually tested. It was given the following values:
    - 1 for complete systems running on natural gas
    - 0.9 for the fuel cell stack only (full or short stack)
    - 0.5 for single cells only
    - 0.7 for operation on hydrogen
    - 0.5 for pressurised operation

The weighted mean and standard deviation (μ *and* σ) for each data set was calculated as follows; where each data value x_i has a weighting factor of w_i, and n is the number of non-zero weights:[1]

$$\mu = \frac{\sum(w_i \cdot x_i)}{\sum w_i} \qquad \sigma = \frac{n}{n-1} \cdot \frac{\sum(w_i \cdot (x_i - \mu)^2)}{\sum w_i}$$

Power Density

The electrochemical performance of each fuel cell type is presented: the operating voltage, current density, and resulting power density, per unit area of cell. Ideally, pressurised systems were excluded as they demonstrate significantly higher performance, but require significantly more expensive auxiliary systems which precludes them from use in commercially viable systems.

Commercial examples of every technology show similar operating voltages around 0.65-0.7V. Voltages are not significantly higher than average for AFC systems which operate with limited current density, or significantly lower than average for PAFC due to their electrolyte. Power density is one of the clear dividing lines between the technologies, as highlighted in Figure 5. The power density of PEMFC and SOFC cells continues to advance, with the highest reported values being in excess of 500mW/cm^2.

In Figures 1-4, the voltage and current density of each system are plotted together, to give industry-wide VI curves. Lines are included on each graph to indicate the average current density (plus one standard deviation), and a weighted linear fit of voltage against current density. Please note the different scales for current density in the first and second sets of figures.

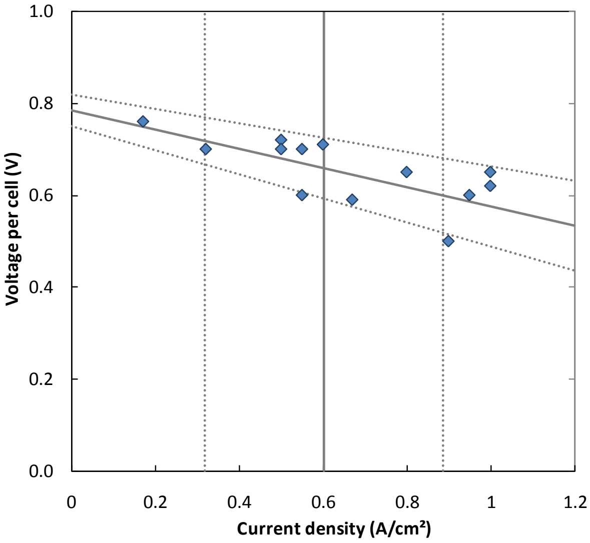

Figure 1: PEMFC electrochemical performance

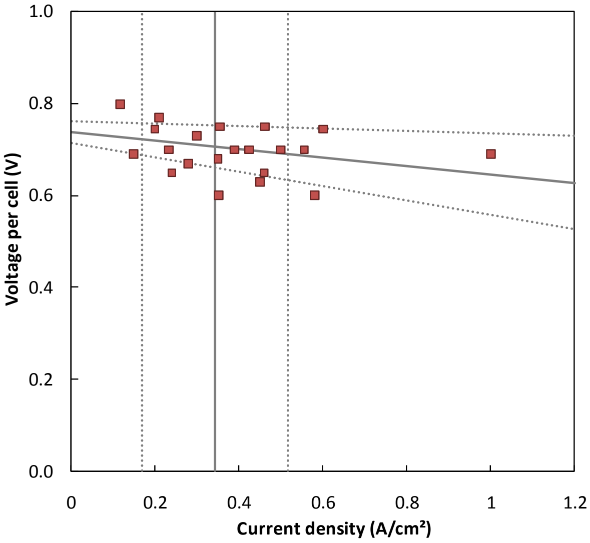

Figure 2: SOFC electrochemical performance

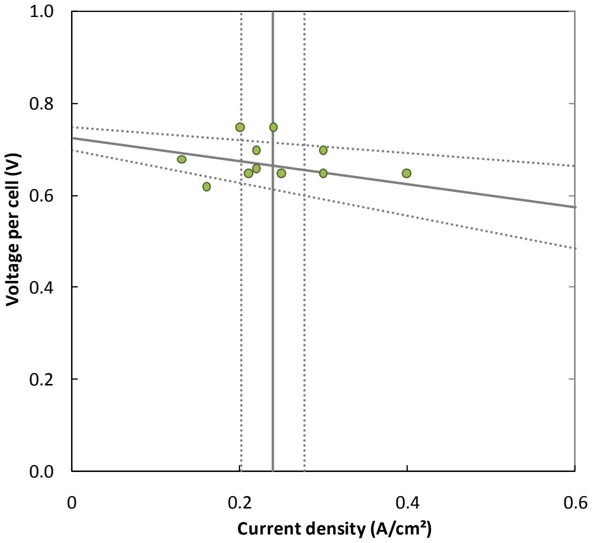

Figure 3: PAFC electrochemical performance

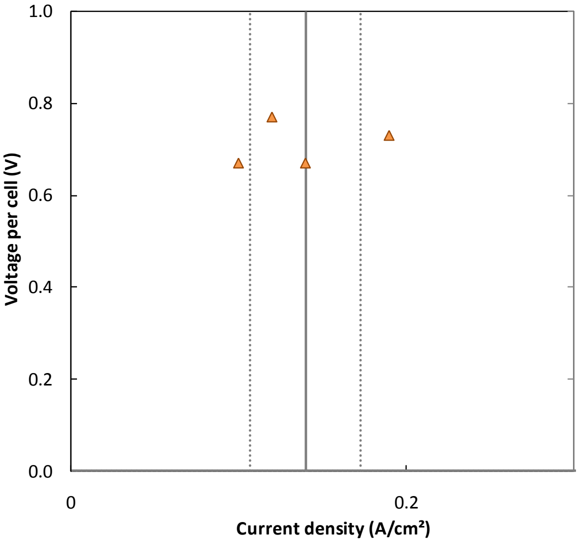

Figure 4: AFC electrochemical performance

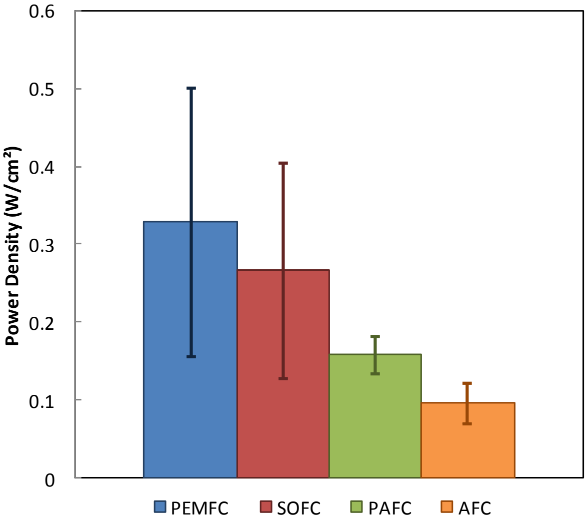

Figure 5: Average power density of each fuel cell technology.

Operating Point (V/cell x A/cm^2)	**Power Density** (W/cm^2)	**Catalyst Loading** (mg/cm^2)	**Year**	**Description**	***w***	**Ref.**
0.72 x 0.5	0.36	*?*	*2007*	Results from operating a single small-scale Ballard cell.	*1.69*	[2]
0.62 x 1.0	0.62					
0.59 x 0.67	0.40	0.2 + 0.2	*2007*	Results from single cells produced by the CCM method operating on unhumidified hydrogen & air.	*1.20*	[3]
0.5 x 0.9	0.45					
0.7 x 0.5	0.35	0.45_{PtRu} + 0.6	*2006*	Results from a single Gore 56 cell at start of operating life.	*1.34*	[4]
0.65 x 0.8	0.52					
0.71 x 0.6	0.43	0.05 + 0.4	*2004*	Results from single cells optimised with a low catalyst loading. Operated on 150kPa hydrogen.	*0.30*	[5]
0.65 x 1.0	0.65					
0.7 x 0.55	0.39	*?*	*2003*	The performance of 55-series cells running on natural gas, as claimed by Gore.	*0.34*	[6]
0.6 x 0.95	0.57					
0.7 x 0.32	0.22	0.4 + 0.7	*2002*	Results from an in-house stack built with E-Tek catalysts.	*1.07*	[7]
0.6 x 0.55	0.33					
0.76 x 0.17	0.13	*?*	*2002*	Results from operating Gore 56 cells in a 36-cell stack.	*1.07*	[8]

Table 2: PEMFC electrochemical performance

Operating Point (V/cell x A/cm^2)	**Power Density** (W/cm^2)	**Cell Type**	**Year**	**Description**	***w***	**Ref.**
0.77 x 0.21	0.16	Planar 750°C	*2007*	Performance of a 10kW KEPCO/Mitsubishi module *(top)*, and a 1kW system *(bottom)* in long term tests.	*2.32*	[9]
0.73 x 0.3	0.22					
	0.50	Flat Tube, 750°C	*2007*	Reported by Osaka Gas for 1kW domestic units from Kyocera, operating on internally reformed natural gas.	*1.16*	[10]
0.75 x 0.35	0.27	Planar 850°C	*2007*	Performance of 1cm^2 demonstration cells for the Hexis Galileo model, demonstrating a new cathode formulation. Using an excess of hydrogen and air.	*0.82*	[11]
0.7 x 0.43	0.30					
0.75 x 0.46	0.35	Planar 900°C				
0.7 x 0.56	0.39					
0.65 x 0.46	0.30	Flat Tube	*2007*	Performance of modified tubular cells from Siemens; Delta9 cells *(top)* and HPD-5 cells *(bottom)* were operated on hydrogen, at an unknown temperature.	*0.82*	[10]
0.6 x 0.58	0.35					
0.68 x 0.35	0.24	Flat Tube				
0.63 x 0.45	0.28					
0.7 x 0.39	0.27	Tubular 800°C	*2006*	Performance of single cells from Acumentrics *(top)*, and a short-stack operating on reformed natural gas *(bottom)*.	*0.69*	[12]
0.65 x 0.24	0.16					
0.7 x 0.5	0.35	Planar 750°C	*2006*	Testing of a prototype Fuel Cells Scotland 1.3kW stack, using InDEC cells operating on hydrogen.	*1.30*	[13]
0.80 x 0.20	0.16	Planar 800°C	*2004*	Performance of 1.2kW stacks using Topsøe cells when operated on reformed natural gas.	*1.16*	[14, 15]
0.79 x 0.2	0.12	Planar 750°C				
0.7-0.79 x 0.6	0.49-0.55	Planar 850°C	*2002*	Average performance of anode supported FZJ cells operating on hydrogen in internally manifolded short stacks produced by ALSTROM.	*0.52*	[16]
0.61-0.77 x 1.0	0.34-0.42	Planar 800°C				
0.67 x 0.28	0.19	Planar 950°C	*2000*	Results from a single 1kW Sulzer Hexis unit in a European field trial, fed by steam reformed natural gas.	*0.92*	[17]
Confidential data collected from a short stack running on hydrogen					*1.30*	-

Table 3: SOFC electrochemical performance

Operating Point (V/cell x A/cm^2)	**Power Density** (W/cm^2)	**Year**	**Description**	***w***	**Ref.**
0.65 x 0.25	0.16	*2001*	The operating voltage and current density of UTC PC25C plants at start of life.	*5.80*	[18, 19]
0.7 x 0.3	0.21	*1999*	Performance of single cells made by LG-Caltex using Pt anode and Pt-Fe-Co cathode.	*0.32*	[20]
0.65 x 0.4	0.26				
0.66 x 0.22	0.15	*1999*	The performance of a 50kW stack of LG-Caltex cells operating on hydrogen *(top)*, and the subsequent performance of a 10kW stack operating on natural gas *(bottom)*.	*1.56*	[20]
0.7 x 0.22	0.15				
0.68 x 0.13	0.09	*1998*	Average cell performance in a 1kW stack built at the ERI, in South Africa.	*0.51*	[21]
0.62 x 0.16	0.10				
0.75 x 0.2	0.15	*1991 - 1997*	Performance of 11MW power plant assembled by Toshiba using UTC PC-23 cells, operated at 7.3 bar with 0.1 + 0.5mg/cm^2 Pt loading.	*0.58*	[22, 23]
0.65 x 0.21	0.14	*1993*	Separate measurements of the performance from single cells of a UTC PC25A.	*0.16*	[22, 24]
0.75 x 0.24	0.18				
0.65 x 0.3	0.20	*1992*	Performance of Mitsubishi atmospheric single cells.	*0.06*	[22]

Table 4: PAFC electrochemical performance

Operating Point (V/cell x A/cm^2)	**Power Density** (W/cm^2)	**Cell Type**	***Year***	**Description**	***w***	**Ref.**
0.67 x 0.14	0.09	Platinum	*2003*	Performance of a 0.8kW Eident stack using 0.52mg/cm^2 total Pt loading.	*2.34*	[25]
0.67 x 0.1	0.07	Platinum	*1999*	Performance of a 0.4kW Zevco Mark II module.	*0.93*	[26]
0.73 ± 0.10 0.19 ± 0.08	0.14	*Multiple*	*1998*	Average of 6 operating points from 5 different sources, which are not listed separately here.	*0.74*	[27]
0.77 x 0.12	0.09	*?*	*1960*	Tests by Karl Kordesch on a 6kW fuel cell stack used for transport.	*0.00*	[28]

Table 5: AFC electrochemical performance

Efficiency

Methods

The following four tables present the information gathered on fuel cell micro-CHP system efficiencies, split by the cell technology used. Each table gives the estimated electrical efficiencies of the fuel cell stack and the whole system, and the total CHP efficiency – all against the Higher Heating Value of the fuel input. A description of the source is given, along with the original efficiencies given in the source, and the key markers denoting what the measurement relates to. The following abbreviations for the key markers were used in the following tables:

- **Heating value of fuel input:** *(LHV, HHV)*
- **Fuel used:** natural gas *(NG)*, hydrogen *(H)*, or pressurised hydrogen *(PH)*;
- **Electricity output:** *(AC/DC)* to indicate whether losses from the inverter are included;
- **Ancillary loads:** Whether the energy output is measured gross *(G)* excluding parasitic losses, or net *(N)* and includes the electricity and heat consumed by pumps, fans, controllers, the reformer, etc.

These markers were used to estimate the three standard definitions of efficiency which are included in the following tables. The following definitions of efficiency are used to give a more standardised means of comparing the efficiencies found in each report:

$$Stack\ efficiency = \frac{DC\ electricity\ output}{HHV\ of\ hydrogen\ energy\ input}$$

$$System\ efficiency = \frac{AC\ electricity\ output - electricity\ consumption}{HHV\ of\ natural\ gas\ input}$$

$$\begin{aligned} Total\ efficiency &= System\ efficiency + Thermal\ efficiency \\ &= System\ efficiency + \frac{Useful\ heat\ output\ recovered\ in\ coolant\ water}{HHV\ of\ natural\ gas\ input\ to\ reformer\ \&\ aux.burners} \end{aligned}$$

In order to calculate these standardised efficiencies, the original reported values were modified to account for the four points listed above. In doing so, the following table of component efficiencies was used to estimate the losses in converting natural gas to hydrogen, DC to AC power, and in powering the auxiliary systems needed to operate a fuel cell system:

Component	Efficiency
AFC fuel processor:	81.5 ± 4%
PAFC fuel processor:	83 ± 4%
PEMFC fuel processor:	81.5 ± 4%
SOFC fuel processor:	89 ± 4%
Inverter & power conditioning:	89 ± 5%
Parasitic loads (pumps, controller):	96 ± 3%

Table 6: The assumed efficiency of other system components.
The results used to produce these values are given in the following sections.

To summarise, the following rules were applied to each source:

- If the source used lower heating values, electrical and thermal efficiency were converted to HHV:
    - × 0.9008 if using natural gas;
    - × 0.8454 if using hydrogen.[29, 30]
- If the fuel cell ran on hydrogen, the efficiency of the fuel processor was accounted for:
    - Stack efficiency was unchanged, and system electrical efficiency was multiplied by the fuel processor efficiency given in Table 6;
    - Thermal efficiency by the square root of this value, for lack of a more precise estimate;[132]
- If DC electrical output was measured, system efficiency was multiplied by the efficiency of the inverter and transformer;
- If parasitic losses were not included (gross efficiency given), the estimated system efficiency was reduced further.

Validation

In a small number of instances, the performance of a system running in realistic conditions (natural gas fuelled, AC output, net of parasitic losses) was presented alongside the laboratory results (hydrogen fuelled, gross DC output). Five examples of this are seen in the following tables, which are useful for checking the validity of the auxiliary component efficiencies given the previous sections. In all the cases where joint information is given, the estimated system efficiency deviates by less than 2% from the actual values, and the two appear to be evenly balanced. The spread in differences can be explained by some manufacturers having above or below average performance for their auxiliary systems, while the near-zero mean implies there is little bias (systematic error) in the process – even though the auxiliary efficiencies were taken from a separate set of sources, rather than tailored to fit this subset of data.

	Given for a natural gas fuelled system	Estimated value, based on a hydrogen system, stack or cells
Toshiba TM-1 (PEMFC) [34]	32.0%	30.2%
Plug Power (PEMFC) [35]	19.7%	21.4%
Prototype (SOFC) [36]	38.1%	36.5%
Kyocera & Osaka Gas (SOFC) [37-39]	37.3%	37.2%
UTC PC25A (PAFC) [24]	30.3%	30.1%

Table 7: Estimated system efficiency for models where a comparison could be made.

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[132] The logic for this was that thermal efficiency of a natural gas fuelled system will be lower than that of one running on hydrogen, as some of the useful chemical energy in the fuel is lost ($CH_4 \rightarrow H_2$ conversion rates are ~80% in steam reformers).[31, 32] However, thermal efficiency will not suffer as strongly as electrical efficiency, as some useful heat can be recovered from the fuel processor. In the case of a poorly optimised H-Power PEMFC system, this accounted for around 1/3 of the thermal energy output.[33]

Reported Values			Estimated HHV Efficiency			*Year*	Description	*WF*	Ref
Elec.	Total	Test conditions	Stack	System	Total				
27.7%	64.8%	HHV, NG, AC, N	38.5%	27.7%	64.8%	*2009*	Average performance of 1kW ENEFARM systems from all manufacturers, installed into Japanese houses. *Bottom:* 175 systems installed in 2005, operated during 2006; *Middle:* 777 installed in 2006, operated during 2007; *Top:* 930 systems installed in 2007, operated during 2008.	*3.58*	[40]
26.4%	63.2%	HHV, NG, AC, N	36.7%	26.4%	63.2%	*2008*		*2.78*	[41]
26.0%	63.1%	HHV, NG, AC, N	36.2%	26.0%	63.1%	*2007*		*1.84*	[42]
20%	57%	HHV, NG, AC, N	27.7%	19.9%	57.0%	*2009*	Results from a 12 month field trial of a single fuel cell system. Average results from the whole trial (top), and results from a single month when the fuel cell was allowed to operate uninterrupted (bottom)	*2.71*	-
22%	62%	HHV, NG, AC, N	30.0%	21.6%	61.5%				
32%	85%	LHV, NG, AC, G	37.7%	27.1%	74.8%	*2009*	Rated specifications for the Baxi Gamma 1.0	*0.88*	[43]
38.0%	93.0%	LHV, NG, AC, ?	46.2%	33.2%	82.7%	*2008*	Rated specifications for the latest generation of Panasonic ENEFARM units at full power.	*0.54*	[44]
35.5%	84.1%	LHV, NG, AC, ?	43.1%	31.0%	74.8%	*2008*	Achieved during a trial of three 1kW systems from Fuji Electric.	*0.79*	[45]
27%	80%	LHV, NG, AC, G	31.3%	22.5%	70.6%	*2007*	Rated specifications for the Baxi Beta 1.5 Plus.	*0.43*	[46]
	74.9%	HHV, NG, -, -			74.9%	*2006*	Measured performance of Ballard 1030 v3 stacks, installed in LIFUEL systems in Japan.	*0.68*	[47, 48]
37%	87%	LHV, NG, AC, G	43.6%	31.3%	76.4%	*2006*	A comparison between the manufacturers specifications and the achieved efficiencies, of LIFUEL systems.	*0.17*	[49]
30%	75%	LHV, NG, AC, N	37.6%	27.0%	67.6%			*0.68*	
32%	71%	HHV, NG, AC, N	44.5%	32.0%	71.0%	*2005*	Specifications of the FY2005 model Toshiba unit: the TM1-A. Top - running on natural gas (as used in the Japanese field trials). Bottom - a pure hydrogen model.	*0.36*	[34]
37%	77%	HHV, H, AC, N	42.0%	30.2%	74.5%				
33%	83%	LHV, NG, AC, ?	40.1%	28.8%	73.9%	*2005*	Measured from 2 sets of 700W Toshiba LPG fuel cells installed in Japanese homes in 2005. The average generating efficiency to June 2008 was reported.	*1.40*	[50]
31%	76%	HHV, NG, AC, ?	41.8%	30.1%	75.1%	*2004*	Efficiency from a 2nd stage trial by Fuji Electric of their 1kW natural gas reforming PEMFC system.	*0.28*	[51]
34%	83%	HHV, NG, AC, ?	45.8%	33.0%	82.0%	*2004*	Reported as the highest achievement by a 1kWe Mitsubishi stack.	*0.21*	[52]
26.5%	63.5%	LHV, NG, DC, G	27.5%	19.7%	53.1%	*2003*	Performance of a 4kW Plug Power beta unit installed in France. System efficiency *(top)* was measured, while stack efficiency *(bottom)* was calculated theoretically.	*0.34*	[35]
36%		LHV, H, DC, N	30.4%	21.4%				*0.34*	
43%	80%	HHV, PH, DC, N	43.0%	30.9%	71.8%	*2003*	A 5kW Ballard stack (MK5-E), operated on 3 bar H_2.	*0.34*	[53]

Reported Values			**Estimated HHV Efficiency**			***Year***	Description	*WF*	Ref
Elec.	**Total**	**Test conditions**	**Stack**	**System**	**Total**				
44%	80%	HHV, PH, DC, N	44.0%	31.6%	71.5%	*2003*	An unnamed commercial 1kW stack, operating on 2 bar H_2.	*0.34*	[54]
30%	68%	HHV, NG, AC, G	39.2%	28.2%	66.2%	*2002*	Reported for a 10kW demonstration stack.	*0.13*	[55, 56]
34%	72%	LHV, NG, AC, G	40.0%	28.8%	63.0%	*2002*	A 250kW Ballard unit during a 1 year field trial.	*0.27*	[57]
36%		LHV, NG, DC, N	39.7%	28.5%		*2001*	A prototype 1kW Proton Motor stack “suitable for reformant gas operation"	*0.21*	[58]
41%	80%	HHV, PH, DC, N	41.0%	29.5%	72.6%	*2001*	An 1kW R&D stack containing 0.9mg/cm^2 Pt catalyst and operated on 2 bar H_2.	*0.21*	[54]

Table 8: Efficiency of PEMFC systems, as reported originally (left) and when modified to give the consistent definitions of efficiency (middle). The conditions used in each measurement are given with the reported values: heating value, fuel, electricity output and inclusion of ancillary loads.

Reported Values			Estimated HHV Efficiency						
Elec.	**Total**	**Test conditions**	**Stack**	**System**	**Total**	**Year**	**Description**	***w***	**Ref.**
36.1%	74.0%	HHV, NG, AC, N	46.0%	36.1%	74.0%	*2008*	Average performance of 0.7-1kW SOFC systems installed in Japanese houses, mostly from Kyocera. Top: 35 systems installed in 2008, measured from Aug-Nov 2008 Bottom: 27 systems installed in 2007, measured Jan-Dec 2008	*3.00*	[59]
34.1%	71.3%	HHV, NG, AC, N	43.4%	34.1%	71.3%			*2.27*	
41%	82%	HHV, NG, AC, ?	50.6%	39.8%	80.8%	*2007*	Performance of a 10kW module from KEPCO / Mitsubishi.	*0.43*	[9]
35.5% - 41%		LHV, NG, ?, ?	37.6% - 43.4%	29.1% - 33.6%		*2007*	Given as the average performance of 6 recent small SOFC systems from American companies.	*0.77*	[10]
29%		HHV, NG, DC, G	30.6%	24.0%		*2006*	Estimated full-power efficiency of a 6kW Acumentrics stack, based on a measured peak efficiency of 36% at 33% power.	*0.34*	[60]
56%		LHV, NG, DC, N	56.6%	44.4%		*2006*	Results from 2.5kW domestic units from Tokyo Gas, Kyocera, Rinnai & Gastar.	*0.34*	[61]
36%		HHV, H, AC, N	40.9%	32.1%		*2006*	Testing of a prototype Fuel Cells Scotland 1.3kW stack, using InDEC cells operating on hydrogen.	*0.69*	[13]
45%	75%	LHV, NG, AC, G	48.5%	38.1%	65.1%	*2005*	Performance of a prototype stack *(top)* and system *(bottom)*.	*0.14*	[36]
55%		LHV, H, DC, N	46.5%	36.5%				*0.14*	
44%	78%	LHV, NG, AC, G	47.5%	37.3%	67.9%	*2004*	Results from 1kW domestic units from Osaka Gas & Kyocera. Field trials of a system running on natural gas are given *(top)* and experiments on a hydrogen fuelled stack *(bottom)*.	*0.43*	[37-39]
56%		LHV, H, DC, N	47.3%	37.2%				*0.11*	
28%	70%	LHV, NG, DC, N	28.1%	22.0%	59.9%	*2000*	Mean efficiency of the best performing 1kW Sulzer Hexis field trial unit in Europe. The average over all 6 units was ~30% lower. A 20% increase in thermal efficiency was envisioned with better insulation.	*0.34*	[17]

Table 9: Efficiency of SOFC systems, as reported originally (right) and when modified to use consistent definitions (left).

Reported Values			Estimated HHV Efficiency			*Year*	Description	*w*	Ref.
Elec.	Total	Test conditions	Stack	System	Total				
38.0%	83-87%	LHV, NG, AC, N	46.7%	34.2%	74.8% - 78.4%	*2004*	Widely verified performance of UTC PC25 units: Efficiency starts at 40% and drops to 38% after infancy; this falls further to 35% at the end of life, giving a lifetime average of 37% over 40,000 hours. (vs. methane LHV)	*4.49*	[22, 55, 56, 62, 63]
40.0%		LHV, H, DC, ?	32.8%	24.0%		*1999*	Measured from a 50kW LG-Caltex stack.	*0.52*	[20]
37.0 ± 0.75%		LHV, NG, DC, G	36.6% - 38.1%	26.8% - 27.9%		*1998*	Performance of an ERI 1kW stack, corrected for the varied cell construction. Efficiency was lowered by poor fuel utilisation temperature control.	*0.56*	[21]
42%	74%	HHV, PH, AC, N	47.5%	34.8%	70.5%	*1991 - 1997*	11MW Toshiba plant.	*0.22*	[64]
31.6 ± 1.2%		HHV, NG, AC, N	43.1%	31.6%		*1997*	Efficiency of 30 PC25B and C systems installed in military bases between 1994-1997 and operated until 2000-2003.	*1.10*	[65]
52%		LHV, H, DC, G	41.3%	30.3%		*1993*	The measured performance of individual cells from a UTC PC25A stack *(top)*, and the overall system *(bottom)*.	*0.09*	[24]
38%		LHV, NG, DC, N	41.1%	30.1%					
37%		HHV, H, AC, ?	40.4%	29.6%		*1985*	Performance of 4.5MW power plant made for Tokyo Electric, operated at 2.5 bar.	*0.01*	[23]

Table 10: Efficiency of PAFC systems, as reported originally (left) and when modified to give the consistent definitions of efficiency (middle).

Reported Values			Estimated HHV Efficiency			*Year*	Description	*w*	Ref.
Elec.	Total	Test conditions	Stack	System	Total				
45.0%	87.0%	LHV, PH, DC, N	38.0%	27.4%	66.6%	*2006*	Independent Power's Pulsar-6, 6kW stack operating on 4-6 bar hydrogen and pressurised air.	*1.32*	[66]
55%		LHV, PH, DC, N	46.5%	33.5%		*2004*	Astris-E8 2.4kW stack, operating on 6-200 bar hydrogen and pressurised air.	*0.83*	[67]
51%		LHV, H, DC, ?	41.8%	30.1%		*2003*	Performance of a 0.8kW Eident stack using 0.52mg/cm^2 total Pt loading.	*1.32*	[25]
47%		LHV, H, DC, N	39.7%	28.6%		*1999*	Performance of a 0.4kW Zevco Mark II module.	*0.52*	[26]

Table 11: Efficiency of AFC systems, as reported originally (left) and when modified to give the consistent definitions of efficiency (middle).

Discussion

Figure 6 plots the electrical and thermal efficiency of different CHP systems. Lines connect the efficiency of competing systems in the UK, with the average being gas central heating and the UK average grid efficiency, and the best being a top-rated condensing boiler and a CCGT power station. It is seen that most fuel cell systems are 10-40% above the best available alternative in the UK; or 30-60% above the average systems currently in place.

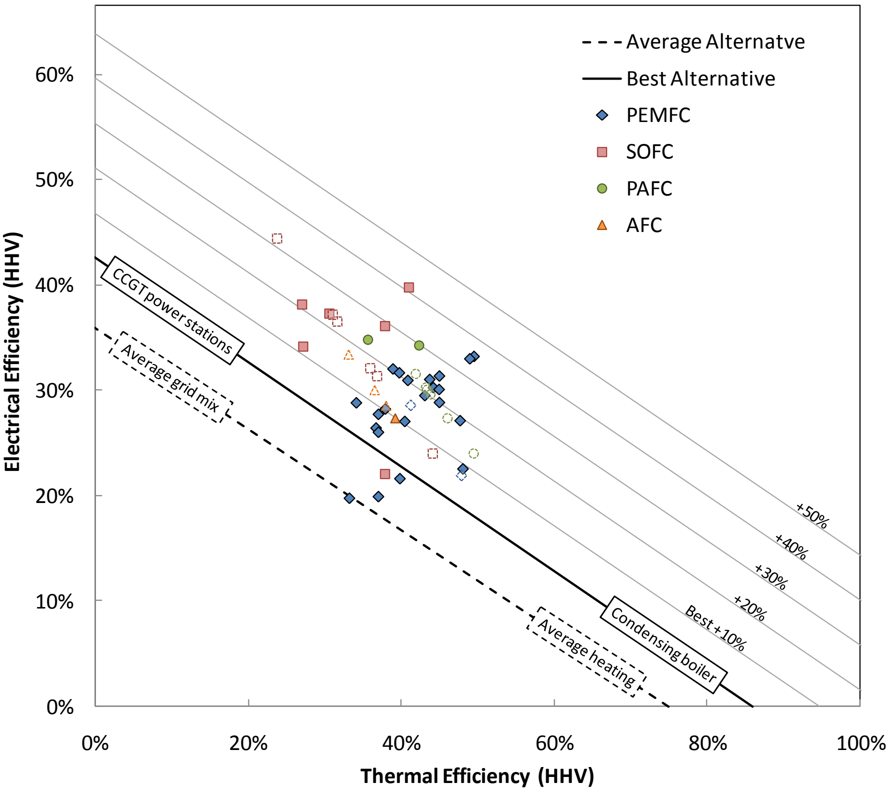

Figure 6: Thermal and electrical efficiency of fuel cell CHP systems, plotted against lines that connect the electrical and thermal efficiency of traditional alternatives. Filled data points indicate that both thermal and electrical efficiency of the fuel cell was known. Hollow data points indicate that only electrical efficiency was recorded, and thermal efficiencies were estimated based on the average total efficiency for that type of system.

Part Load Efficiency

One of the widely reported benefits of fuel cells is their high efficiency at part load. This is an inherent characteristic of the fuel cell stack itself as individual cell voltages rise towards Open Circuit Voltage (~1V) when less current is drawn from them, giving the highest efficiency at low loads. Twelve sources were found which had measured the efficiency of complete fuel cell systems (as opposed to only the stack) at different levels of power output. The part-load efficiency of each system is plotted in Figure 7 relative to its efficiency at full power. It is clear that across nearly all products electrical efficiency falls as power output decreases, and the thermal efficiency of domestic-scale systems is either constant or falls.

The part-load efficiency can be broken down into the different components:

- Efficiency of the fuel cell stack is higher at lower load factors, as cell voltage rises at lower current densities – see Figure 8 for a comparison.
- Reformer efficiency drops slightly: at half load, the efficiency is 90-95% of full power efficiency.[33, 68]
- Fuel utilisation however falls more sharply, by 10-30% at half power.[9, 33, 35]
- Inverter and transformer efficiency stays constant over much of the power range, falling only at very low load-factors – and thus does not have a significant impact.[12, 69, 70]

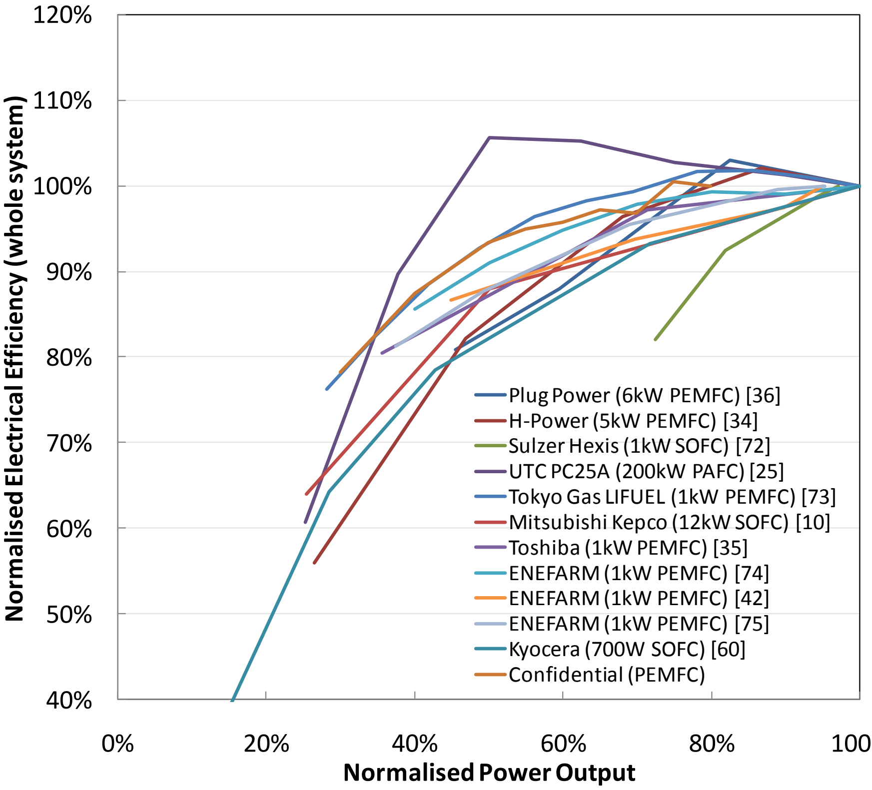

Figure 7: Whole system electrical efficiency (including fuel processing, inverters and parasitic loads) from different fuel cell CHP systems, measured against power output. The efficiency of each system is presented relative to full power.

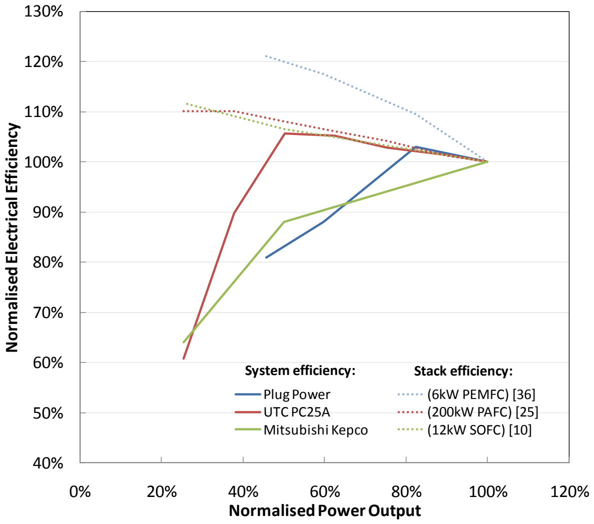

Figure 8: A comparison of the part-load electrical efficiency of the fuel cell stack and whole system for three fuel cell CHP products.

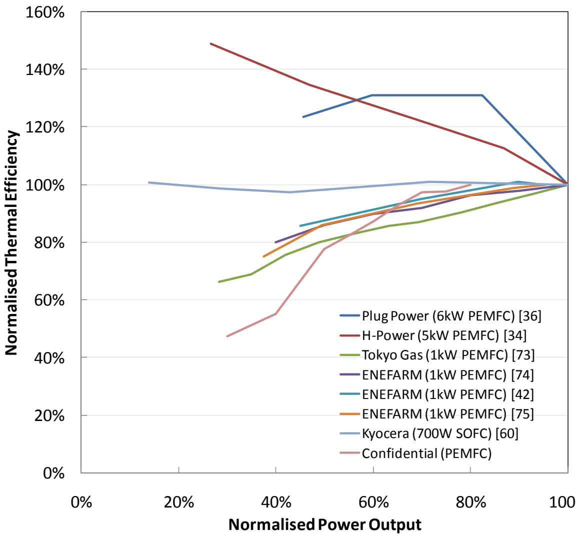

Figure 9: Thermal efficiency of different models of fuel cell CHP system measured against power output. As in Figure 8, the efficiency is given relative to full power.

Fuel Processor Efficiency

Processing natural gas into useable hydrogen is one of the major energy consuming stages in a domestic CHP system, and lowers the overall efficiency significantly. Steam reforming of natural gas was the only method considered, as it offers higher efficiency than can be achieved with Auto-Thermal Reformers (ATR) or Partial Oxidation (POX) reactors. For example, the efficiency of an H-Power ATR was 62.5% when operating at maximum power, or 60% at the rated 4kW.[33] The increased difficulty of reforming higher hydrocarbon fuels will also result in lower efficiency. As another example, auto-thermal reforming of LPG (a mixture of propane and butane) yielded 50% HHV efficiency.[71]

To remain consistent with the rest of this report, fuel conversion efficiency was considered relative to HHV energy contents. It is worth noting that most publications report LHV efficiencies for fuel processors, so the values presented here for converting natural gas to hydrogen are a factor of 1.066 higher than in most sources.[133]

Most authors gave the efficiency for the entire integrated processor that was used in their particular system, and did not separate their analysis into individual components. It was therefore difficult to give a breakdown of the efficiency of individual components. It was also notable that most of the studied fuel processors were for PEMFC systems, with notably none found for SOFC systems.

Table 12 presents data on the efficiency of different fuel processing systems, making use of the following acronyms for each stage that is included:

- DeS – Desulphuriser
- SR – Steam Reformer
- WGS – Water Gas Shift
- PROX – Preferential Oxidation
- CO – Unspecified carbon monoxide removal stage
- FP – Complete fuel processor

Component	Efficiency (HHV)	Year	Source	Ref.
SR + ?	81.4%	2008	Reported for a novel town gas reformer developed by Tokyo Gas and Mitsubishi, which produces 99.999% pure hydrogen.	[73]
FP	85-87%*	2005	Measured over 1800 stop-start cycles for a Tokyo Gas fuel processor.	[74, 75]
SR + WGS	81.5-82.1%*	2005	Measured from a steam reformer when coupled with a 1kW PEMFC stack from Proton Motor. Was tested with and without PROX stage, and with anode off-gas recycling.[134]	[58]
SR + WGS + PROX	80-80.5%*			
DeS + SR + WGS + PROX	83%	2004	Measured from a compact natural gas reformer developed by Osaka Gas. Tests used simulated off-gas recycling to mimic operation when coupled with a fuel cell..	[72]
SR + WGS + PROX	76.1-79.3%*	2003	Measured for a steam reformer operating with a 4kW Plug Power PEMFC installed in a French town hall.[135]	[35]
SR + WGS + CO	81%	2003	Reported for the fuel processor developed by Fuji Electric.	[76]
SR + ?	88.5%*	2003	Reported for a multi-fuel reformer developed by the Hiroshima Research Centre, for use with a 1kW PEMFC system. Results based on either city gas or LPG.	[76]
SR + WGS + CO	82%*	2000	Two reported values for an early version of the fuel processor developed by Tokyo Gas for use in LIFUEL PEMFC systems.	[68, 77]
	81.7%*	2001		
DeS + SR + WGS	85.3%*	1993	Measured from a 200kW industrial PAFC (PC25A). The efficiency showed little change over 18,000 operating hours.	[24]

*Table 12: Efficiency of fuel processing systems. Efficiencies noted with * were converted from LHV.*

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[133] This value is calculated from the ratio of HHV to LHV energy content for hydrogen and natural gas (1.183 / 1.110).[72]

[134] Over 100% reformer efficiency was reported with off-gas recycling, as this was assumed to increase reformer output rather than the fuel utilisation in the stack. Those results are therefore not considered here.

[135] Reformer efficiency was calculated from the fuel processing efficiency and hydrogen utilisation rates given.

Power Conversion Efficiency

Information was harder to find on power converters, so many are from larger industrial CHP systems. These may not be representative for those used in domestic CHP systems, as low voltage single-phase inverters have different characteristics to 400V three-phase systems. Table 13 gives the data, using the following acronyms:

- Inv – Inverter
- Tr – Transformer

Component	Efficiency	Year	Source	Ref.
Inv + ?	92%	2009	Rated performance of the inverter in a TOTO 2kW class fuel cell (210W lost in converting 2.85kW DC output)	[59]
Inv + Tr	81.4%	2007	Measured difference between AC and DC efficiency of a 10kW KEPCO / Mitsubishi stack.	[9]
Inv	96.7-97.5%	2006	Measured from the Acumentrics power inverter developed for the SECA project, over the range of 2-5kW output.	[12]
Tr	97.0-97.4%			
Inv + Tr	86%	2006	*Confidential information from a custom 1.5kW, 3-phase inverter.*	-
Inv + Tr	92-94%	2004	Modelled efficiency of 6 products in the range of 0.5-5kW, based on product specifications.	[69]
Tr	97.5-98%	2004	Reported for a custom designed Ballard transformer.	[69]
Inv	96.5-97%	2004	Reported for a 30kW Ballard Ecostar Power Converter.	[78]
Inv + Tr	89%	2004	Measured from a H-Power RCU 4500 v2.	[33]
Inv + Tr	92%	2002	Estimated as the realistic maximum efficiency of a simplified electrical subsystem for a fuel cell CHP unit.	[79]
Inv	90%	2001	Target for the1kW PEMFC developed with Tokyo Gas, which was expected to be met by market entry.	[80]
Inv + Tr	80.5%	2001	Measured from a H-Power system tested by Gaz de France.	[70]
Inv + Tr	83-87%	1999	Reported for a 50kW PAFC stack that produced 16V at 700A.	[20]
Inv	97%	1993	Measured from a PC25A PAFC, converting 220V DC to 400V AC.	[24]

Table 13: Efficiency of power conversion systems.

9.4. Parasitic Loads

The net power output of a fuel cell system is further degraded by parasitic loads: the electrical requirements of the system controller, pumps and blowers. These loads are often excluded from the reported efficiencies of domestic fuel cell systems, all the way up to centralised power stations. For comparison, CCGT, coal and nuclear power stations in the UK respectively consume 2.0%, 5.3% and 9.4% of the power they generate.[81] Note that the parasitic loads presented in Table 14 can be thought of as *(1 – efficiency)*.

Component	Parasitic Draw	Year	Source	Ref.
All	12%	2009	Supplemental equipment in a TOTO 2kW class fuel cell consumed 340W (relative to 2.85kW DC output)	[59]
All	3.9%	2004	Reported for a 2.4kW AFC system at full load.	[82]
All	4.8%	2004	Reported 300W power consumption from a 6.3kW AFC system at full load.	[83]
All	22%	2004	Measured from a H-Power RCU 4500 v2. Parasitic loads were equivalent to 6% of the gross natural gas consumed, and were magnified by the low efficiency of the stack.	[33]
All	9%	2001	Estimated power consumption of the 1kW PEMFC developed with Tokyo Gas, all full power.	[80]
Con	5.6%	2001	Measured power consumption of the system controller a 5kW Ballard stack, which was equivalent to 2.5% of the gross hydrogen consumed when operating at 45% electrical efficiency.	[53]
All	4.1%	1991	Measured difference between the gross and net AC efficiency of the 11MW PAFC power station operated in Goi.	[64]

Table 14: Power drawn by fuel cell systems, relative to their power output.

Thermal Loop Temperature

It is known that with other microgeneration systems, thermal efficiency falls as the inlet temperature of coolant water rises.[84] When this rises above the dew point of the flue gasses (50-57°C) condensation of water vapour in the heat exchangers is inhibited. This is not a particular effect for fuel cell systems, and has been observed in condensing boilers, IC engines and Stirling engines.[85-87]

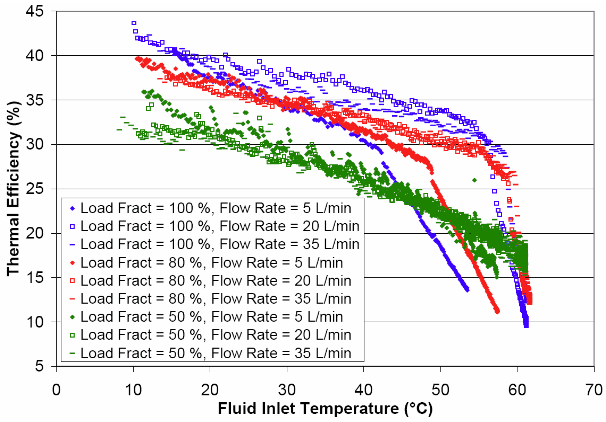

Figure 10: Thermal efficiency of a PEMFC CHP system against coolant inlet temperature. Taken from [88]

An unnamed 5kW PEMFC system was installed and tested at NIST in 2005.[88] The fuel cell was used to heat 1000L of fluid at different temperatures and thermal efficiency was measured. During normal operation, efficiency decreased at 2.2-3.1% HHV per 10°C temperature rise. A sharp knee was seen in some of the tests when the outlet temperature reached the maximum rated 63°C, and efficiency fell off rapidly. Due to this, a separate real-world test for providing hot water was found to give thermal efficiencies of just 7-14% HHV.

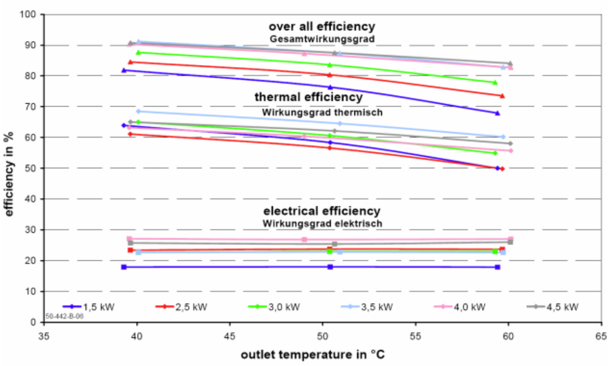

Figure 11: Thermal efficiency of a PEMFC system against coolant outlet temperature. Taken from [89]

A prototype Vaillant "Euro 2" 4.6kW PEMFC system was tested at the Technical University of Munich, also in 2005.[89] The fuel cell was operated at steady state for between 5 and 20 hours at a series of power outputs and inlet/outlet temperatures. The electrical efficiency was seen to be constant with output temperature, and the thermal efficiency fell by 3.5-7.0% LHV per 10°C – over the range of 26-54°C inlet temperatures (30-60°C outlet).

External Temperature

There is limited evidence to suggest that the ambient temperature around the fuel cell system has an impact on its efficiency. From analysis of SOFC systems in the northern region of Japan, average electrical efficiency fell from ~36.5% at 5°C to ~35.5% at -5°C. Correlation in the data set was poor ($R^2 = 0.24$) so more evidence is needed. This would obviously only affect fuel cells that are installed outdoors – as they are in Japan at present.[59]

Start-up Energy Requirements

A substantial amount of energy is required to pre-heat microgeneration systems to operating temperature – as seen with condensing boilers and Stirling engines in field trials by the Carbon Trust.[85] Despite this, the amount of energy required to start fuel cell micro-CHP systems has not been widely studied, and only one prior experimental investigation has been found.

The Vaillant "Euro 2" (4.6kW PEMFC system) was started up from cold, with detailed monitoring of the energy consumed and produced.[89] During the 2.5 hour cold-start of the fuel cell, 29.0kWh of natural gas was consumed (LHV), producing 18.3kWh of heat and 1.4kWh of electricity. The natural gas consumption equated to 6.3kWh per kW of electrical output, however the useful energy outputs must be accounted for:[136]

- The efficiency of the system at steady state was 25.7% electrical + 65.0% thermal (LHV) - so the amount of gas that would have been consumed in producing the 1.4kWh of electricity (and some heat) could be calculated, and subtracted from the total start-up consumption.
- Similarly, the remaining heat production could be credited with avoided production from a condensing boiler (with 95% LHV efficiency). Additional production from the fuel cell could not be used, as the electricity by-product of CHP generation would not be credited.
- The following table shows these steps towards arriving at the additional gas consumption:

	Electricity produced (kWh)	**Heat produced (kWh)**	**Gas consumed (kWh LHV)**
Entire start-up sequence of the fuel cell from cold:	1.4	18.3	29.0
Credit for electricity production by the fuel cell:	1.4	3.55	5.45
Subtracted amount:		14.75	23.55
Credit for heat production by a condensing boiler:		14.75	15.5
Subtracted amount:			8.05

Data from [89]

It is therefore estimated that an additional 8.05kWh of natural gas (8.95kWh HHV) was required to heat the fuel cell from cold. If this scales linearly with capacity, a 1kW fuel cell would require 1.95kWh of gas consumption to start from cold.

It should be noted that this method of crediting avoided production is one possibility, and that without detailed thermodynamic modelling it would be impossible to separate the amount of gas used solely to raise the generator temperature from that used in producing useful energy.[90]

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[136] I wish to thank Thomas Badenhop (Vaillant) for discussing this calculation and result.

Lifetime and Degradation Rates

The functional lifetime is a crucial and contentious issue for the commercialisation and economic viability of fuel cell micro-CHP systems, and is one of the characteristics which varies most between designs. The de-facto target of 40,000 hours continuous operation has hung over the industry for nearly a decade,[91, 92] only being attained in the field by industrial PAFC systems from UTC and Fuji. Figure 12 shows that the demonstrable lifetime of PEMFC systems is gradually moving towards this target, but SOFC and AFC appear to have stagnated with stack tests not lasting for more than 10,000-20,000 hours for SOFC, or 5,000-10,000 hours for AFC.

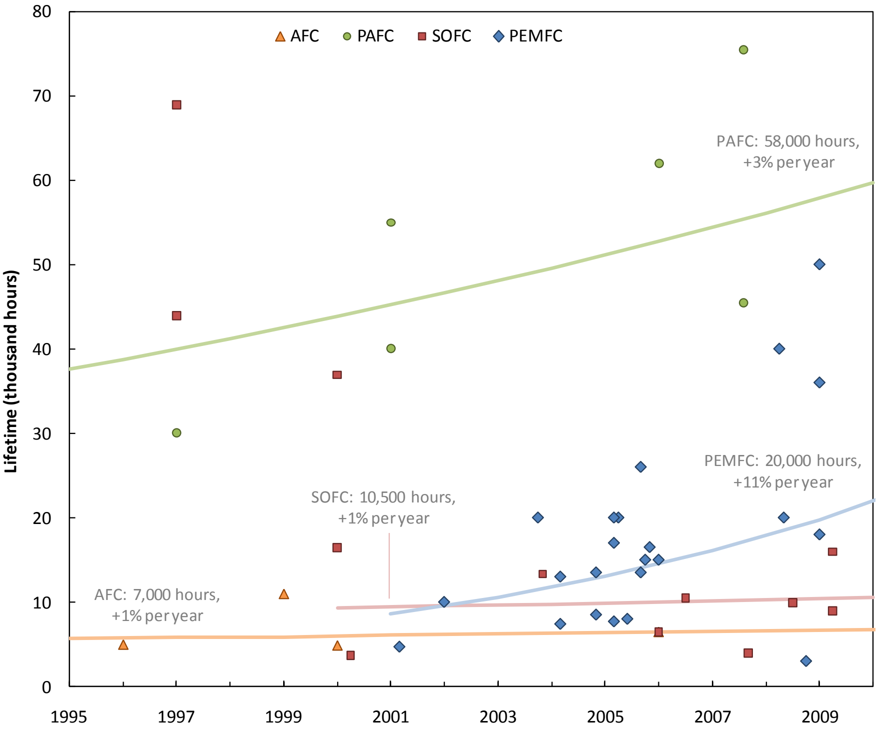

Figure 12: The improvement in demonstrated stack and system lifetimes of different fuel cell technologies over the past 15 years. A weighted exponential fit is shown for each technology, with a label giving the rate of improvement, and estimated average lifetime as of 2009.

Lifetime (kh)	**Degradation** (μV/h)	***Year***	**Description**	***w***	**Ref.**
50	3.7	*2009*	Single cell tests at Osaka Gas, ran on H_2, CO_2 (20%) and CO (10ppm). The cell was fabricated in 2001, and has not yet failed. Degradation without CO appears to be 0.6μV/hr.	*1.14*	[93, 94]
36	35				
18		*2009*	Full 0.75kW cogeneration unit operated at Osaka Gas. It is not known whether the unit failed.	*2.27*	[93]
3.0 ± 0.7	16 ± 6	*2008*	12 demonstrations of 50kW Nedstack units for chlor-alkali plants, using "type A" cells	*1.87*	[95]
20		*2008*	Achieved by two JOMO ECOCUBEs, installed in the Japanese Large Scale Fuel Cell Demonstration Project. The 700W stacks were produced by Toshiba Fuel Cells, and installed in 2005.	*4.69*	[96]
40		*2008*	The estimated lifetime of new generation Matsushita LIFUEL systems, based on accelerated aging experiments. These systems are also expected to perform 4,000 stop/start cycles before failing.	*0.90*	[44]
8	2 - 4	*2005*	Tests on a 40 cell Nuvera stack, operating on steam reformate.	*0.90*	[97]
10 - 17	0.5 - 5	*2005*	Reports of cells and stacks in a variety of tests and conditions.	*0.45*	[4]
26	6.4 (plus 40-140 temporary)	*2005*	A single cell (Gore 56) running on hydrogen. The temporary decay was observed throughout the test. Failure of the cell was due to experiment definition, rather than inability to operate.	*0.45*	[4]
13-20		*2005*	Durability of FY2005 LIFUEL units from Matsushita & Ebara	*0.90*	[74, 98]
15		*2005*	Claimed as the current durability of a Ballard 1030 v3.	*0.45*	[99]
20		*2005*	2 sets of a 700W Toshiba FC installed in Japanese homes in 2005 - fuelled by LPG. Ran continuously for 20,000 hours.	*2.34*	[50]
7.7	7.3	*2005*	Results from the FY2005 model Toshiba unit: the TM1-A. Top: field trial units (no failure reported) Middle: stack in the lab running on reformate (believed to have failed) Bottom: short-stack running in the lab on reformate (unsure)	*1.11*	[34]
17	5.6				
20	4.6				
	1.5	*2004*	Long term tests (5000 hours) for a 20 cell stack from Mitsubishi on low humidity steam reformate (25% CO2, 10ppm CO)	*0.36*	[100]
4 - 13	3.5	*2004*	Results from trials of 300 PlugPower units, which may include such radical repairs as complete stack replacement.	*2.49*	[101]
7.4		*2004*	Early 250kW Ballard trial units achieved 2.5-5kh, a later revision averaged 7.4kh without failing	*1.43*	[102]
	2 - 10	*2004*	Quoted as the commonly reported range of values.	*0.36*	[102]
13	0.5	*2004*	Lab trial of a Ballard short stack operating on natural gas.	*0.72*	[102]
15 - 25	1 - 5	*2003*	Single cells with Gore 56 membranes, running at 0.6A/cm^2.	*0.14*	[22, 103]
10		*2002*	A single cell using a 3M membrane operating on reformate.	*0.11*	[22]
	8 (plus 424 temporary)	*2002*	A 36 cell stack running at 0.2A/cm^2. The 0.4mV/hr degradation was seen during constant operation, but could be recovered by stopping power output and starting the stack again.	*0.45*	[8]
4.7 ± 2.3		*2001*	The average life-span of 4-5kW systems from Plug Power, Nuvera, ReliOn and IdaTech - installed as part of the US DoD Residential PEM Fuel Cell Demonstration Project in 2001-02.	*0.93*	[104]
			Plus 2 confidential values from anonymous sources.	*1.54*	-

Table 15: PEMFC lifetime and degradation rates

Lifetime (kh)	**Degradation** (μV/h)	**Cell Type**	**Year**	**Description**	***WF***	**Ref**
10.0	7 *	Planar, 850°C	*2008*	Testing of a 30 cell (350W) Staxera stack, on hydrogen at 0.75V/cell x 0.125A/cm^2.	*1.78*	[105]
	14 *	*Multiple Planar*	*2007*	Given as the average degradation of 6 recent small SOFC systems from American companies.	*1.77*	[10]
4.0	56-126 *	Planar, 950°C	*2007*	Demonstration of Sulzer Hexis systems, which "required replacement in as little as six months" due to leakage of fuel.	*1.00*	[106]
	9 + 13 mV/cycle	Planar, 950°C	*2006*	Degradation of a 5-cell Hexis short stack over 3500h with nickel coating on the anode side of the interconnect.	*1.58*	[11]
	2-5	Planar, 850°C	*2006*	Degradation of single Topsoe cells tested on syngas, at current densities of 0.25-1A/cm^2 over 1500h.	*0.79*	[14]
10.5		Tubular	*2006*	Demonstration of a 5kW Acumentrics SOFC system for stationary, auxiliary & backup power running in their lab.	*1.26*	[107]
6.5	37 *	Planar, 950°C	*2006*	Degradation of a 1kW Hexis Galileo 1000 N stack during 6000 hours of operation.	*1.58*	[11]
	0	Tubular 800°C	*2006*	Degradation of an Acumentrics short stack running on reformed natural gas, measured over 1000h.	*0.79*	[60]
13.4	13	Planar, 800°C	*2003*	Long term experiment with a 5-cell Topsoe short stack running on hydrogen and nitrogen, including 9 thermal cycles. Average voltage dropped from 0.77V to 0.62V during the test, predominantly because of two cells.	*0.79*	[15]
	1.8 * + 3.5 mV/cycle	Planar, 750°C	*2005*	Degradation of a KEPCO / Mitsubishi 10kW module, with heating and cooling times of 7 and 10 hours during over 20 daily thermal cycles.	*1.26*	[9]
	25 + 2-4 mV/cycle	Planar, 800°C	*2002*	Data from a 2-cell short stack of the FZJ 'E-Design', using stainless steel interconnects with a ceramic contact layer. Voltage degradation was measured over 4000h of running on hydrogen at 0.3A/cm^2 to be 2-3%/1000h. A similar stack was thermally cylced 40 times to 220°C at 2°C/min, increasing degradation rates to 5-8%/kh (140-220mV over 2900h)	*0.44*	[108]
2.1-4.8	24 *	Planar, 950°C	*2000*	Degradation of a single Sulzer Hexis stack during a 3000 of steady state operation. Additional voltage loss was caused by shutdowns. Average lifespan taken from 10 stacks that were run during the field trial.	*0.79*	[106]
37	~0	Tubular	*2000*	Lifetimes of 100kW Siemens-Westinghouse stacks demonstrated in field trials in the Netherlands and USA	*0.91*	[10, 22, 109]
16-17	~0					
69	0.7-3.5 * + 0 μV/cycle	Tubular	*1997*	The best results from laboratory tests of Siemens-Westinghouse large tubular single cells.	*0.05*	[22, 23, 110]
44	1.4 *	Tubular	*1997*	The best results from laboratory tests of Siemens-Westinghouse air-electrode supported (AES) single cells.	*0.05*	[22, 23]
		Plus 3 confidential values from anonymous sources.			*4.15*	-

Table 16: SOFC lifetime and degradation rates

Lifetime (kh)	**Degradation** (μV/h)	***Year***	**Description**	***WF***	**Ref**
75.6		*1998 - 2007*	From the installed fleet of Fuji Electric FP100E and F models, 4 of 22 units have failed after 42-49,000 operating hours, and another 5 units have already exceeded this *(bottom)*. The longest lived unit was installed in 1999, and had operated for 72,500 hours as of August 2007.	*4.76*	[111]
45.4					
62		*1999 - 2006*	Longest reported lifetime for a UTC PC25C - in Central Park Police Station. At least 7 other units have operated for longer than 50,000 hours.	*2.56*	[112]
	4.9 *	*1994 - 2001*	The operating voltage of 14 UTC PC25B plants decreased by 7.6% per 10,000 hours *(top)*, and the voltage of 15 PC25Cs fell by 5.04% per 10,000 hours *(bottom)*.	*1.74*	[19]
	3.3 *				
40		*1992 - 2001*	After 40,000 of operating a fleet of UTC PC25B plants: 2 were still operating at full power, 8 at a reduced maximum power (to preserve cell voltage), and 1 stack had failed.	*1.64*	[19]
55		*1992 - 2001*	Longest reported lifetime for a UTC PC25A operated by Tokyo Gas - as of 2001.	*0.80*	[18, 63]
	1.3 - 2.0 *	*1992 - 2001*	The operating voltage of 5 UTC PC25A plants had decreased by 4-10% after 20k operating hours, and 8-12% after 40k hours *(top)*. The voltage of six late-model PC25C had fallen by 4% after 20kh, and were expected to be at 6% after 30kh *(bottom)*.	*1.43*	[18]
	1.1 - 1.5 *				
	2 - 5	*1999*	Degradation rate of Mitsubishi single cells, tested over 6000 hours at 0.2-0.25A/cm^2.	*0.13*	[20, 22]
30 ± 6		*1994 - 1997*	The lifetime of UTC PC25B and C installations at 30 US military bases, installed between 1994-1997 and operated until 2000-2003.	*0.79*	[65]
	4	*1992*	Test of UTCs 'advanced atmospheric water cooled' short stack over 4500h at 0.2A/cm^2.	*0.05*	[22]
	3	*1992*	Degradation of 'previous state of the art' systems from CNR/TAE (Italy), Westinghouse/DOE, & Electric Utilities (Japan).	*0.03*	[22]
23		*1991 - 1997*	Lifetime of the 11MW Toshiba power plant in Goi.	*0.08*	[64]

Table 17: PAFC lifetime and degradation rates

Lifetime (kh)	**Degradation** (μV/h)	**Cell Type**	**Year**	**Description**	***WF***	**Ref**
5 - 8		Ni / Ag	*2006*	Internal tests at Astris Energi "consistently see 5,000 hours" with new carbon materials.	*3.93*	[113, 114]
	27 *	Pt	*2003*	An Eident Energy V1.1 module is expected to lose 10% of its initial power over 2500 hours.	*1.97*	[25]
	5 - 10	Pt	*2003*	Single Eident Energy V1.1 cells were operated at 0.67V x $0.15A/cm^2$ during a 2800 hour test, with electrolyte replacement. Voltage loss at $0.1A/cm^2$ *(top)* was half that at $0.2A/cm^2$ *(bottom)*.	*1.97*	[25]
	20					
4.9 ± 1.1		*Multiple*	*1986 - 2000*	The average of six lifetime studies that are not repeated here.	*1.75*	[27]
	24	Ni	*2000*	Half cell test at KTH. Cell was operated at $0.1A/cm^2$ over 1500 hours. Unoptimised electrode hydrophobicity was thought to cause the rapid decay.	*0.98*	[115]
11	3.4	Pt/Pd	*1999*	Half cell test at KTH. Cell was operated at $0.1A/cm^2$, with intermittent polarisation at high current density and electrolyte changes.	*0.78*	[116]
5	17	Ag	*1996*	Half cell tests at DLR. Cells were operated at 0.1-$0.15A/cm^2$. 15,000 hour lifetime was predicted for a full module with a changeable circulating electrolyte, however this was never built.	*0.39*	[117, 118]
6		Pt	*1987*	Tests by Elenco into CO_2 poisoning.	*0.05*	[27]
5	13	Pt	*1987*	Elenco and Zevco tests showed minimum cell lifetime to be 5,000 hours.	*0.10*	[26, 27]
8		Ni / Ag	*1986*	The average lifetime achieved by approximately 20 Siemens units. 15,000 hours was mentioned as the maximum seen.	*0.09*	[22, 119]
	25	Pt	*c. 1970*	Degradation of UTC stacks running on H_2/O_2 during space missions.	*0.00*	[22]

Table 18: AFC lifetime and degradation rates

Ancillary Component Lifetimes

Fuel processor

- The Osaka Gas fuel processor used in 50-100kW PAFC systems had demonstrated 40,000 hour lifetimes in 2001. The components used in it were identical (except in scale) to those used in their 1kW PEMFC fuel processor (with the additional of a further CO cleanup stage).[120]
- The Tokyo Gas fuel processing system for 1kW PEMFC systems has been demonstrated for at least 20,000 hours and 4,000 stop-start cycles with no loss of efficiency. They were confident that 10 year operation (40,000 hours) will be achieved as demonstrations continue.[77]

Power conversion

- Data on inverter lifetimes is relatively scarce, however warranties of 10-15 years are now offered by leading manufacturers.[121, 122]

Reliability

PEMFC

Only the Japanese manufacturers of ENEFARM systems have been willing to release information on the durability of their demonstration systems, which spans the past 6 years of development. From the data presented by the NEF,[40] fleet-wide values for the MTBF were estimated[137] to rise from 2,300-5,500 hours in 2005-06 to 5,100-9,800 hours in 2007. Based on the first data point for revised 2008 models, a tentative MTBF of over 30,000 hours was seen – however this will need to be confirmed once more recent data is released.

Year	Results	Ref.
2002-03	• Average of 4 failures per system experienced across a fleet of 33 in a 1 year period. • 1/2 of all failures occur during 4 months • The three least reliable components: fuel processor (30% of all failures), fuel cell stack (25%) and water treatment (24%).	[123]
2005 (1st stage)	• Average of 3 failures per system experienced across a fleet of 175 in a 1 year period. • 1/3 of systems experienced 1 or less failures, but some experienced up to 8. • The three least reliable components: water treatment (37% of all failures), fuel processing system (18%) and system controller (17%). • The fuel cell stack itself only accounted for 3% of failures.	[124]
2005 (1st)	• MTBF was reported to be over 3,300 hours for the 40 installed Toshiba systems.	[34]
	Average number of failures per system per year across the entire demonstration fleet, split by the year of installation:	[40, 125]
2005 (1st)	> 2.5, from the first 2 years of operation	
2005 (2nd)	> 2.3, from the first 2 years of operation	
2006	> 2.4, from the first 2 years of operation	
2007	> 1.2, based on the first 12 months of operation	
2008	> 0.3, based on the first 3 months of operation	

Table 19: Key results about the reliability of Japanese PEMFC systems during the research and demonstration project.

SOFC

The reliability of the SOFC systems installed in the Japanese field trials has been reported by the NEF.[59](p. 85) It is thought that 21 faults developed in the 28 systems operating in 2006; which reduced to 6 faults during 2007. The following values for MTBF were given:

2006: 1626 hours
2007: 5654 hours
2008: 7926 hours (projected)

PAFC

11 commercial PAFC systems were operated by Tokyo Gas (UTC PC25A and PC25C, Fuji Electric FP50 and FP100).[18] The MTBF over their lifetime was 4593 ± 2626 hours, and during the 2000 fiscal year was 4688 hours. Plant availability was 91.3 ± 10.3% over their lifetime, and 96.6% during 2000. The failure occurrence rate over 5 years was between 0.2 and 0.8 forced shutdowns per 1,000 hours of operation.

Reliability of the US Department of Defense's fleet of UTC PAFC systems was not as good, as they were earlier models than used in Japan.[19] MTBF was 1594 hours for the fleet of 14 PC25B units, and 1766 hours for the 15 PC25C units. During 2000-01, the MTBF for PC25C models had improved to 2621 hours. The average outage time was 899 hours for the PC25Bs, and 317 hours for the PC25Cs. Plant availability was 56% (30-75% range) for PC25Bs and 77% (62-82% range) for PC25Cs. Availability of the PC25B series was low, as they were discontinued during the trial, and so replacement parts became hard to source.

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[137] These estimates were simply based on 8,760 operating hours per year. MTBF values would have been lower if the actual number of operating hours (3-6,000 hours per year) were used.

Other mentioned values:

- 2,500 hour MTBF for the PC25.[62]
- 6,750 hour MTBF for the 400kW 'advanced PAFC'.[62]

Operating Constraints

Fuel cell system	Turndown ratio	Ref.
Ebara-Ballard & Panasonic LIFUEL models (1kW PEMFC)	30%	[74, 98, 126]
Baxi Gamma (1kW PEMFC)	30%	[43]
Viessmann Fuel Cell Energy Center (2kW PEMFC)	20%	[127]
Kyocera (0.7kW SOFC)	7-14% (50-100W minimum)	[59](p. 47)
ENEFARM (1kW PEMFC)	40% was the minimum load factor typically seen during demonstrations	[41, 98, 126]
Toshiba & Eneos ENEFARM models (1kW PEMFC)	36% (250W minimum)	[128]

Table 20: Turndown ratio for fuel cell micro-CHP systems.

Fuel cell system	Start up time	Ref.
H-Power: 4.3kW PEMFC	'Over an hour'	[70]
Toshiba ENEFARM (PEMFC)	1 hour	[129]
Vaillant NextGenCell, based on a high temperature PEMFC membrane.	Less than one hour	[90]
Unnamed PEMFC[138]	0.75-1.25 hours until full power	-
CFCL GenNex module (1kW SOFC)	13 hours (preliminary specifications)	[130]
GS Fuel Cell, Fuel Cell Power & Hyosung (1kW PEMFC)	'About 1 hour'	[131]

Table 21: Start up time for fuel cell micro-CHP systems.

Maximum ramp rate: It is thought that SOFC systems in particular will not be capable of changing power output rapidly, however the Kyocera system appears to tolerate load changes of 300W per minute (0.7% per second).[59](p. 48)

Estimated High-Volume Manufacturing Cost

Literature estimating the cost of mass produced fuel cell CHP systems was sought to give a basis for estimating the retail price when the technology has is fully commercialised and in widespread use. These costs are intended to reflect the current state-of-the-art design, manufactured with present day methods at high volume (i.e. >10^5 systems per year).

The assumptions used in each cost estimate differed widely as they were concerned with different scenarios – e.g. current or future performance of the fuel cell; residential or industrial CHP units. When sufficient detail was given in the estimate, these assumptions were altered to conform with the other information presented in this report. Typical examples were lowering the power density of the fuel cells to the industry-wide average (thus increasing the number of cells required); or increasing the price of platinum to reflect current prices. The individual modifications are given as footnotes to each table of data.

All costs have been converted to 2007 Euros for consistency, based on a constant global inflation rate of 2.5% per annum (0% in Japan), and exchange rates of 150¥ = \$1.30 = £0.70 = €1. The cost is split into the following categories:

- The fuel cell stack, which is typically quoted per kW of electrical capacity;
- The balance of plant (BoP), which consists of all ancillary equipment;

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[138] This is the mean time until full power output (± one standard deviation) taken from an analysis of 181 operation periods of a field-trial system.

- Operation and maintenance, which includes all ongoing costs incurred during the operating lifetime.

System Price	Year	Description	Ref.
€22,000 - €24,000	2009	Initial sale price of ENE·FARM models from Toshiba and Eneos were ¥3,255,000 through Osaka Gas, and ¥3,465,000 for Panasonic models sold through Tokyo Gas.	[128, 132]
~€56,000	2008	80M Won was the expected price for Korean systems from GS Fuel Cell, Fuel Cell Power & Hyosung in 2008; down from 100M in 2007 and 130M in 2006.	[131, 133]
€20,000 - €200,000	2005-2009	An indicative range of quotes received by the University of Birmingham's Fuel Cells Group for micro-CHP systems	-

Stack Cost	BoP Cost	O & M Cost (/MWh)	Year	Description	Ref.
€600/kW (materials)	€190 + €175/kW		2005	Estimated materials cost for the stack and balance of plant, using empirical formulae to relating to capacity.[139]	[134]
€2450	€11,900		2004	Manufacturing costs for 1kW ENEFARM systems estimated by the system manufacturers in 2004, considering a production volume of 10,000 units per year.	[135, 136]
€180-5500/kW	€230		2000	Costs for a 1kW domestic system were extrapolated from a 50kW pressurised stack, with a separate assessment for the BoP.	[27]
€85 + €160/kW			1999	Estimate for a 3kW stack (3-50kW were considered) using commercial cost estimation software and information from the US Department of Energy. BoP costs were considered, but were unfeasibly high.[140]	[137]

Table 22: Current and expected retail prices for PEMFC micro-CHP systems (top); and estimates for the mass-production costs of stacks and systems (bottom).

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[139] Some unexpected conclusions were drawn from this report, such as an almost constant cost of $400 for heat exchangers of any size.

- The cost of heat exchangers, pumps and misc. components were reduced by a factor of 5, to be in line with other reports.
- The compressor was replaced with a $15 blower, to remove the additional expense of pressurisation.
- Overall BOP costs were assumed to scale proportional to capacity$^{0.7}$, which was roughly the mid-point of the individual components.
- The stack power density was reduced by 33%

[140] The analysis of BOP costs was omitted due to misgivings in component costs, which were typically 5x higher than expected.

- The number of bipolar plates was reduced by 33%, as 1 cooling channel every 3 cells was considered instead of 1 for every cell.
- The stack power density was reduced by 30%
- Platinum cost was raised by 240% to €32/g
- The area of individual cells was held at 100cm^2, rather than scaling down to 10cm^2 for a 1kW stack (giving an unrealistic 3x3x160cm dimensions). This removed the benefit of larger stacks using larger die stamps, etc..

System Price	Year	Description	Ref.
€47,500	2000-2005	Mentioned as the cost of 1kW CHP systems demonstrated by Hexis. The newer Galileo model was described as “less costly”, but no price was given.	[10]
~€70,000	2007	The METI technology roadmap described Japanese 1kW-class models as costing “tens of millions of yen” at the end of FY2007.	[138]

Stack Cost	BoP Cost	O & M Cost (/MWh)	Cell Type	Year	Description	Ref.
€3,500-4,100/kW			Flat tubular 750°C	2007	The expected retail price of a 0.7kW domestic unit (including hot water tank) from Kyocera & Osaka Gas when mass produced (estimated to be 2008 onwards).	[139]
€575/kW			Tubular, 800°C	2006	Materials costs for a 6kW Acumentrics Phase I Generator, estimated as part of the SECA project.	[12]
€350/kW	€625 (1.3kW)		Planar, 850°C	2006	Estimated materials costs for a 1.3kW system based on the Fuel Cells Scotland stack.	[140]
€150-450/kW			Planar	2004	The range of estimated costs given for a 5kW residential unit, from a sensitivity analysis performed by Tiax.[141]	[141]
€550-600/kW			*Multiple Planar*	2007	Given as the range of costs for 6 recent small SOFC systems.	[10]
€50-225/kW					Estimated cost of manufacturing individual cells, based on assumed mass-production process.	[142]

Table 23: Current and expected retail prices for SOFC systems; and estimated costs for mass produced stacks and systems.

Stack Cost	BoP Cost	O & M Cost (/MWh)	Year	Description	Ref.
€4666/kW			2008	The retail price of a 100kW Fuji system, including installation.	[143]
€1600/kW	€240/kW	€13	2006	Unsubstantiated theoretical estimates for a 200kW system.[142]	[144]
€2700/kW		€51	2002	The retail price of a UTC PC25 system.	[63]
€5700/kW			2002	The retail price of a 200kW system as of Jan 2002, which could be reduced to €4700/kW with government subsidies.	[23]
€3000-3900/kW		€25	<2002	The retail price of a 2004kW ONSI system during production.	[56]
€2500-3750/kW			2001	The retail price of a 2nd generation Fuji 100kW system.	[145]

Table 24: Retail prices for PAFC based industrial CHP systems. Note, no estimates were found for domestic CHP systems.

Stack Cost	BOP Cost	O & M Cost (/MWh)	Year	Description	Ref.
€220/kW			2006	Claimed materials cost for the Astris Powerstack M-250.	[146]
€600/kW			2003	The actual bill for materials required to produce an Elenco V1.1 module, approximately €220 of which would be for platinum. Assembly costs were not included.[143]	[25]
€130-560/kW	€225	€2-26	2001	Estimates for high-volume manufacture of a domestic AFC system, including the ongoing costs of soda lime consumption for a CO_2 scrubber.	[27]
€400-500/kW			1992-1994	Based on a review of reports from DLR, LBST, ZSW, Hoechst & The Royal Institute of Technology in Stockholm.	[117]
€75-240/kW			1986, 1993, 1999	Projections and estimates for stack or material costs, taken from three separate sources.	[27]
€200/kW			1998	Projected mass-production cost of a Zevco module, which was sold for €1600/kW at the time.	[27]

Table 25: Estimated costs of mass produced AFC fuel cell systems

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[141] Assumptions used in the cost estimate:

- Power density was reduced by 29% to the average presented here of 340mWcm^{-2}, with the relationship between cost and power density fitted to: $C = 33.13/PD^{1.3566}$.
- The portion of defective cells from the firing process was chosen to be 0-1%.
- A production rate of 100MW annually.

[142] The breakdown of estimated cost was: €1600/kW for the 200kW PAFC stack; €11750 for a fuel reformer; €10250 for heat exchangers; €26000 for electrical transformer; and €205000/yr for maintenance. Constant operation at full power was assumed with 90% availability (1578MWh/yr).

[143] Calculated from a specific power of 160W per gram of platinum (as given), and an updated platinum price of €32/g.

Fuel Tolerance

A summary of the tolerance to impurities of each fuel cell stack is given in Table , while more detailed information from the first revision of this report is given on the following page.

	PEMFC [22, 31, 91, 147]	**SOFC** [23, 31, 36]	**PAFC** [22, 23, 31, 62, 91, 148]	**AFC** [31, 116-118, 149-152]
Sulphur (as S, H_2S)	< 0.1 ppm	< 1 ppm	< 50 ppm	?
CO	< 10-100ppm[144]	*Fuel*	< 0.5-1%	< 0.2%
CO_2	*Diluent*	*Diluent*	*Diluent*	< 100-400ppm or < 0.5-5%[145]
CH_4	*Diluent*	*Fuel / Diluent*[146]	*Diluent*	*Diluent*
NH_3	Poison	< 0.5%	< 4%	?

Table 26: Fuel tolerance of different systems.

PEMFC

Substance	**Quantity**	**Effect**	**Description**
CO	10ppm	Poison	Platinum catalyst poisoning.[54, 91]
CO	10ppm	Poison	Caused a reduction of 0.1-0.2V during operation, unsure if this is permanent degradation.[147]
CO	100ppm	None	100ppm CO + 2% O_2 at the anode gives the same performance as no CO, resulting in a 4% loss of fuel[22]
S, NH_3, HCl, Si	*?*	Poison	Mentioned as poisons.[23]

SOFC

Substance	**Quantity**	**Effect**	**Description**
CO	1400ppm	?	Kyocera SOFC system[59]
CO	-	Fuel	[23]
CO_2	-	Diluent	[23]
H_2S	1ppm	Poison	[23, 36]
NH_3	0.5%	Diluent	Described as “Relatively harmless”.[23, 36]
HCl	0.1ppm	Poison	[23, 36]
Si	*?*	Poison	[23]

PAFC

Substance	**Quantity**	**Effect**	**Description**
CO	0.5-1%	Reversible	Performance loss reversible at 190°C[22, 91]
CO	0.7%	Reversible	Performance loss due to increased cell resistance above 0.7%.[148]
CO	1%	Poison	Catalyst poisoning.[22, 23]
CO_2	10%	Diluent	No effect other than to dilute the fuel.[22, 23]
NH_3	4%	Poison	Molecular nitrogen content of 4% reduces the electrolyte.[22, 62]
S	-	Poison	Tolerance is greater than that of the reformers.[62]
S	50ppm	Reversible	Acceptable as <20ppm H_2S and <30ppm COS. Performance loss is reversible by polarisation at high potential.[22, 91]

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[144] CO_2 tolerance is highly dependent on the cell design. Strongly bonded nickel and silver electrodes with a circulating electrolyte can be highly tolerant, while platinum and carbon with an immobilised electrolyte are highly sensitive.

[145] Standard Pt anode catalysts can only withstand CO concentrations up to 10 ppm, and PtRu alloys up to 30 ppm.[31] These limits can be extended by bleeding air into the anode and using alternative bi-layer catalysts.[153, 154]

[146] Internal reforming is possible with SOFC anodes, making desulphurised natural gas a viable fuel. Extended lifetimes required for domestic CHP operation have not yet been demonstrated however.

AFC

Substance	Quantity	Effect	Cell Type	Description
CO_2	~400ppm	None		Hydrocell employs an amine based regenerative filter. Regenerated by periodic heating to release CO_2.[155]
CO_2	0.1%	50h life	Pt + fixed electrolyte	Rapid decay and cell death was seen in experiments with platinum anodes and a non-circulating electrolyte.[116]
	5%	5h life		
CO_2	<100ppm	None	Standard Pt	Experiments showed that CO_2 causes electrode pores to be blocked or mechanically damaged. Strongly bonded electrodes can support un-scrubbed air for many thousands of hours.[151]
	~400ppm	None	Strongly bonded	
CO_2	0.3-0.4%	<1% voltage loss	*?*	Reversible loss of performance seen in experiments.[150]
CO_2	1%	None	Ag	No significant effect on performance in experiments at 72°C.[152]
CO_2	4%	9% voltage loss	Ni/Ag	Reversible loss of performance seen in experiments.[152]
CO_2	5%	No degradation	DLR (Ni/Ag)	CO_2 found to have no influence in degradation rate on strongly bonded, non-noble electrodes over several thousand hours.[117, 118]
CO	0.2%	V loss	Ni/PTFE	Reversible loss of performance – 10% current – at 72°C.[149]

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Appendix B

ANALYSIS OF THE BAXI BETA 1.5 PLUS FIELD TRIAL

Access to this chapter is restricted due to commercial confidentiality.

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Appendix C

PUBLICATIONS

Electronic copies are available from the respective publishers:

I. Staffell, R. Green, and K. Kendall, *Cost targets for domestic fuel cell CHP.* Journal of Power Sources, 2008. **181**(2): p. 339-349. doi:10.1016/j.jpowsour.2007.11.068

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A. Hawkes, I. Staffell, D. Brett, and N. Brandon, *Fuel Cells for Micro-Combined Heat and Power Generation.* Energy & Environmental Science, 2009. **2**: p. 729-744. doi:10.1039/b902222h

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