FUEL CELL TECHNOLOGY FOR DOMESTIC BUILT ENVIRONMENT APPLICATIONS: STATE OF-THE-ART REVIEW

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ABSTRACT

Fuel cells produce heat when generating electricity, thus they are of particular interest for combined heat and power (CHP) and combined cooling heat and power (CCHP) applications, also known as tri-generation systems. CHP and tri-generation systems offer high energy conversion efficiency and hence the potential to reduce fuel costs and CO_2 emissions. This paper serves to provide a state-of-the-art review of fuel cell technology operating in the domestic built environment in CHP and tri-generation system applications. The review aims to carry out an assessment of the following topics: (1) the operational advantages fuel cells offer in CHP and tri-generation system configurations, specifically, compared to conventional combustion based technologies such as Stirling engines, (2) how decarbonisation, running cost and energy security in the domestic built environment may be addressed through the use of fuel cell technology, and (3) what has been done to date and what needs to be done in the future. The paper commences with a review of fuel cell technology, then moves on to examine fuel cell CHP systems operating in the domestic built environment, and finally explores fuel cell tri-generation systems in domestic built environment applications. The paper concludes with an assessment of the present development of, and future challenges for, domestic fuel cells operating in CHP and tri-generation systems. As fuel cells are an emergent technology the paper draws on a breadth of literature, data and experience, mostly from the United Kingdom, Germany, Japan, America and Australia.

Fuel cells are a technology of the future here today, providing a change in the way heat and power are supplied to end users. Fuel cells operating in CHP and tri-generation systems in domestic built environment applications could finally provide the means by which energy generation can transfer from centralised to decentralised locales in a sustainable and effective manner.

Keywords: fuel cell, combined heat and power, combined cooling heat and power, tri-generation, domestic

ABBREVIATIONS

CHP – Combined heat and power
CCHP – Combined cooling heat and power
CCP – Combined cooling and power
UK – United Kingdom
EU – European Union
JPN – Japan
US – United States of America
GER – Germany
AUS - Australia
SUI – Switzerland
DEN - Denmark
GHG – Greenhouse gases
PEMFC - Proton exchange membrane fuel cell
AFC - Alkaline fuel cell
DMFC - Direct methanol fuel cell
PAFC - Phosphoric acid fuel cell
MCFC - Molten carbonate fuel Cell
SOFC - Solid oxide fuel cell
CoP – Coefficient of performance
ICE – Internal combustion engine
SE – Stirling engine
CI – Compression ignition engine
PER – Primary energy ratio
NPV – Net present value
CFCL – Ceramic Fuel Cells Ltd.

1. INTRODUCTION

Humanity is currently facing a future of dwindling reserves of fossil fuels, rising energy demand and a greater understanding of the environmental impact by the use of fossil fuels. It is now of global importance that greenhouse gas (GHG) emissions associated with energy production are substantially reduced in order to limit the effects of climate change and environmental pollution. Agreements such as the 1997 Kyoto Protocol have been established in order to try and mitigate the effects of climate change by reducing the quantities of GHGs released into the atmosphere. More recently the United Kingdom (UK) set out in its 2007 Energy White Paper that it would commit to an 80% GHG emission reduction compared to 1990 levels by 2050 [1]. The European Union (EU) has committed to reduce CO_2 emissions by 20% by 2020 compared to 1990 levels [2]. Both the UK and EU targets are ambitious; however there is now a common trend amongst many nations towards aspirations of a low carbon future. In the 4th Inter-governmental Panel on Climate Change Assessment the built environment was identified as holding the largest economic potential for the reduction of CO_2 emissions [3]. Currently, in Europe, buildings account for over 40% of energy demand [4] and 50% of CO_2 emissions [5]. These figures illustrate the critical importance of decarbonising the built environment if substantial CO_2 emissions reductions are to be realised on a national and international scale across all emitting sectors.

Fuel cells have recently been identified as a key technological option on route to a future low carbon built environment. This is because of the ability of fuel cells, depending on hydrogen production technique, to produce electrical power with little or no emission of harmful pollutants such as CO_2 [3, 6]. Furthermore, fuel cells produce useful quantities of heat when generating electricity, thus they are of particular interest for combined heat and power (CHP) and combined cooling heat and power (CCHP) applications, also known as tri-generation systems [7, 8]. In CHP and tri-generation systems, the often wasted heat created in the electrical generation process is utilised in a useful process such as space heating or cooling, this offers the potential to bring about improved system efficiency and thus increased energy savings [9].

This paper serves to provide a state-of-the-art review of fuel cell technology operating in the domestic built environment in CHP and tri-generation system applications. The review aims to carry out an assessment of the following topics: (1) the operational advantages fuel cells offer in CHP and tri-generation system configurations, specifically, compared to conventional combustion based technologies such as Stirling engines, (2) how decarbonisation, running cost and energy security in the domestic built environment may be addressed through the use of fuel cell technology, and (3) what has been done to date and what needs to be done in the future. The paper is split into three sections. Section one provides a review of fuel cell technology, section two examines fuel cell CHP systems operating in the domestic built environment, whilst section three explores fuel cell tri-generation systems in domestic built environment applications. Fuel cells are an emergent technology, particularly in terms of real world application, thus there is a restricted research base. The review draws on data and experience from Japan, Europe, America and Australia. Next, an introduction to fuel cell technology, CHP and tri-generation systems for domestic built environment applications is provided.

1.1 Fuel cells

Fuel cells are electrochemical devices which combine hydrogen and oxygen to produce electricity, heat and water. Fuel cells are an attractive option for stationary building applications because of their; high electrical efficiency even at part load, low emissions, near silent operation and flexibility of fuel use. Because fuel cells produce heat when generating electricity, they are of specific interest for CHP and tri-generation systems, particularly in the domestic built environment. Owing to the variety of types of fuel cells and their modularity, fuel cells have the ability to cover a range of building applications from a single family home to an entire hospital [6]. Fuel cells are now recognised, across a variety of markets, most significantly the stationary, as a superior technological option compared to conventional combustion based generators [10]. As a result, the stationary sector is currently the largest user of fuel cell technology, showing year on year growth, demonstrated in Figure 1. In 2012 alone, 125MW of fuel cells for stationary applications were shipped, a 53% increase on 2011 figures, representing the rapid expansion of the sector. Furthermore, Ceramic Fuel Cells Ltd. (CFCL) reported that the domestic housing Solid oxide fuel cell (SOFC) market is around 17,000 kWe installed per annum, a large market potential. E.ON believes most UK homes are technically suitable for fuel cell micro-CHP, equal to a potential total installed capacity of 24GWe [11].

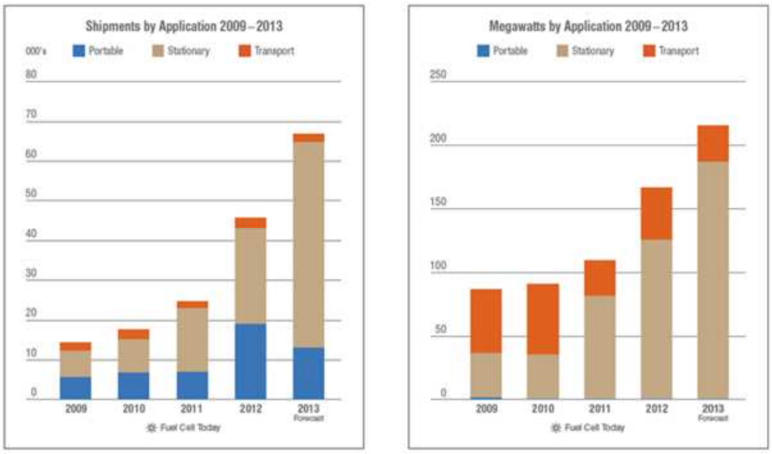

Figure 1 fuel cell use by application 2009 to 2013 [10]

Extensive literature searches have highlighted that successful work has been carried out on the application of fuel cells in the domestic built environment; most significantly EneFarm's field trials of a 1kWe Proton exchange membrane fuel cell (PEMFC) CHP system in Japanese households. The project has spear-headed the wider, global use of fuel cell CHP in the domestic built environment and the systems have confirmed annual CO_2 emission reductions in the order of 750-1250kg per annum are possible, illustrating the significant potential fuel cells have in assisting decarbonisation of the future domestic built environment [12].

1.2 Combined heat and power systems

CHP is defined as the generation of heat and power from a single fuel source, with the view to using both products. Figure 2 shows a typical domestic CHP system configuration. Fuel is supplied to the prime mover technology from the central network, to produce electrical power, and in the process creates heat. The electricity is used directly in the home, and if grid interactive; can be imported or exported as required. The heat produced in the electrical generation process is recovered and used in applications such as space heating or domestic hot water. By consuming this heat, system efficiency can be elevated from as low as 20% to over 90%, depending on the prime mover technology and the extent of waste heat utilisation [13]. In domestic built environment applications elevated system efficiency results in reduced primary energy demand, leading to decreased emissions and running cost for the consumer. However, as Beaussoleil-Morrison [14] states, if the thermal output of the CHP system cannot be fully utilised, then the system cannot expect to deliver a net benefit relative to grid electricity and a highly efficient condensing boiler. Therefore accurate building energy load assessments and sizing of the CHP unit is essential [15].

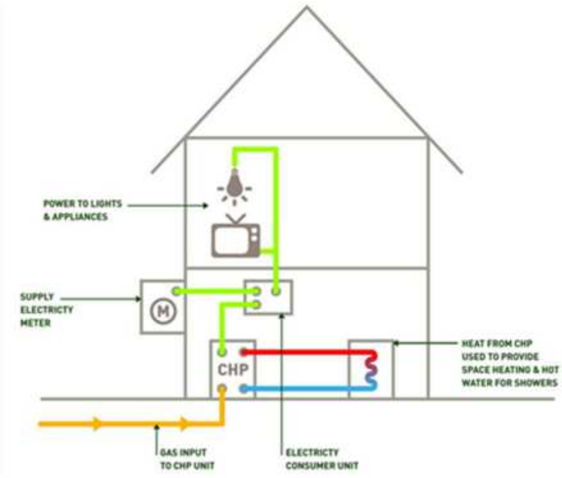

Figure 2 CHP in a domestic building [16]

1.3 Tri-generation systems

Tri-generation takes the concept of CHP one step further by utilising the recovered waste heat to produce a useful cooling output through a heat driven cooling technology. In small scale (<15kWe) tri-generation systems it has been estimated that over 80% of fuel energy is converted to usable energy, thereby increasing the cost and emission saving potential of adopting a CHP system [17]. In many domestic building applications the demand for cooling coincides with a reduction in heating demand, enabling tri-generation systems to operate for a greater period of time over the course of a year compared to conventional CHP systems. Tri-generation systems therefore have the potential to increase access to the benefits achievable from on-site electrical generation, primarily; reduced emissions and operating costs [17]. The application of tri-generation systems in the domestic built environment has been increasing, particularly in areas where the thermal demand during the cold season is balanced by an almost equal cooling demand during the hot season [18]. Furthermore, recent changes in climatic conditions means in many countries the demand for cooling in buildings is projected to increase. Several northern European cities such as London now report having higher summer cooling loads than winter heating loads. Kolokotroni, Zhang et al. [19] state that as a result of the urban heat island effect, cooling loads in cities is up to 25% higher than that of a rural location over the course of one year. Tri-generation systems are therefore a clear technological option to help address this change in demand, particularly in cities.

Because CHP and tri-generation systems produce electricity at point of use, they are often referred to as decentralised energy generators. Decentralised energy generation in the domestic built environment has many advantages associated with it compared to traditional centralised generation, including:

- Improved system efficiency, otherwise wasted heat is utilised (heating or cooling), therefore system efficiency can be elevated from as low as 30-50% in central power stations to around 70-90% [9]. Figure 3 illustrates the potential reductions in energy consumption when switching from centralised to decentralised energy generation with CHP. In a tri-generation system the CHP heat output is simply used to provide cooling in summer.
- Decentralised energy generation with CHP reduces significantly transmission losses, which account for 6 – 24% in the European transmission network [20].
- Improved system efficiency and greater fuel utilisation leads to reduced primary energy demands, resulting in cuts to CO_2 emissions and operating costs [21].
- Electricity is regarded as having an economic value of roughly three times that of gas. Therefore converting lower cost gas (common fuel in domestic CHP) to electricity allows households to recover cost and reduce energy bills. This is an important factor in the fight against fuel poverty [22].
- Centralised decarbonisation of electricity generation in many countries is problematic because of opposition to low carbon technologies such as renewables and nuclear. CHP in consumers' homes offers an option to assist in both decarbonising electricity production and providing energy saving benefits directly to the home owner [22].

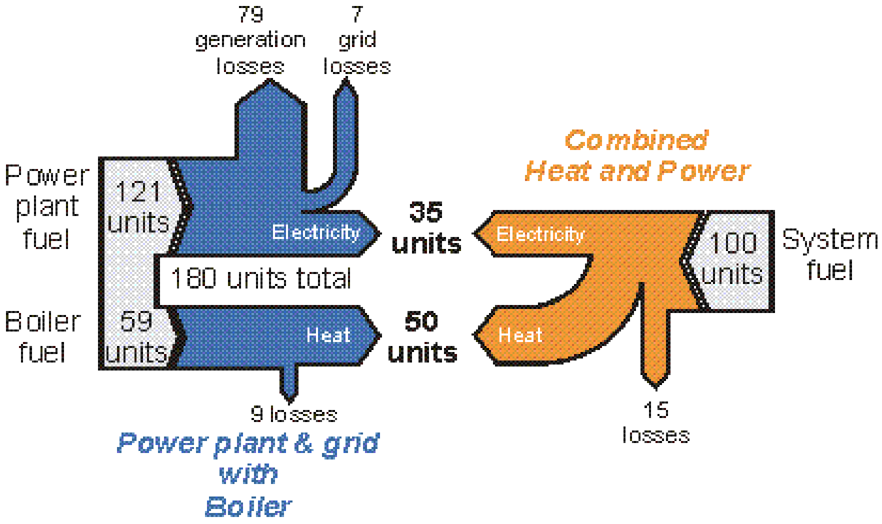

Figure 3 Sankey diagram of CHP vs. conventional energy generation [23]

Currently there are three key technologies used as prime movers in CHP and tri-generation systems in the domestic built environment. All are at varying levels of commercial and technological maturity; internal combustion engine, Stirling engine – both combustion based technologies, and fuel cells. The performance and operational characteristics of these three technologies are summarised in Table 1. It is evident that a fuel cell has some clear operational advantages, particularly when operating in the domestic built environment. Advantages include; higher electrical efficiencies, low heat to power ratio and near silent operation. However, the relative infancy of fuel cell technology has limited their extensive application and market involvement to date.

Table 1 Domestic CHP technologies [3, 7, 22, 24, 25]

	Internal combustion engine (ICE)	Stirling engine (SE)	Fuel cell (FC)
Capacity (electrical)	1kW+	1kW+	0.7 kW+
Electrical efficiency (%)	22	11	PEMFC - 35 SOFC up to 60
Overall efficiency	90	90	up to 90
Heat to Power ratio	3 : 1	8-10 : 1	1 : 1
Able to vary output	No	No	PEMFC – Yes SOFC - No
Fuel used	Gas, Biogas, Liquid fuels	Gas, Biogas, Butane	Hydrocarbon, Hydrogen
Noise	Loud	Fair	Quiet
Maturity	High	Fair	Low
Companies	Vaillant ecoPower	EHE Wispergen	Baxi, CFCL

Because of the low electrical efficiency and correspondingly high thermal output of the internal combustion and Stirling engine, they should only operate when their thermal output can be fully utilised, otherwise the CHP system cannot expect to deliver a net benefit relative to grid electricity and a highly efficient condensing boiler [14]. Fuel cells, however, with their higher electrical efficiency have much lower heat to power ratios; therefore their operation can be largely independent of thermal demand, making them a well suited technology for domestic CHP applications [3]. As a result, the fuel cell can be operated in an electrically led manner, thus providing increased net benefit to the user. Figure 4 shows that according to a report by Delta-ee energy consultants, fuel cell CHP systems for domestic applications outsold conventional combustion based systems for the first time in 2012, accounting for 64% of global sales, illustrating a major shift in the domestic CHP market on account of fuel cells clear operational advantages [10]. Growth is being driven by Japan and to a lesser extent Germany, which together account for more than 90% of yearly sales [26]. However as Steinberger-Wilckens [25] states, for fuel cells to produce a marked effect on the stationary market they need to match and surpass the performance of current CHP technologies such as SEs and ICEs. Steinberger-Wilckens proposes that meaningful performance indicators include; amount of CO_2 / fossil fuel avoided through the use of fuel cell technology or the total and electrical efficiency of the fuel cell system.

Figure 4 global micro-CHP sales by technology [26]

This section has provided an introduction to the operating concept and justification of; fuel cell, CHP and tri-generation system technology in domestic built environment applications.

2. FUEL CELL TECHNOLOGY

By combining hydrogen and oxygen in electrochemical reactions as shown in Figure 5, fuel cells have the potential to produce electrical power without the emission of environmentally damaging pollutants such as CO_2. Furthermore the exothermic nature of the electrochemical reaction makes fuel cells ideal candidates for CHP applications. Invented in 1839, fuel cell technology is by no means new, however, in the past, fuel cells have struggled to flourish particularly in terms of commercialisation and market application. This stalled start has occurred for a variety of reasons; technological reliability, lack of interest, lack of supporting infrastructure but mainly cost [27].

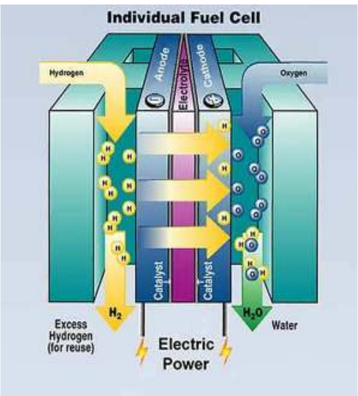

Figure 5 fuel cell operating concept [28]

Fuel cells are often categorised by the type of electrolyte. This is determined by the type and purity of the fuel and oxidant used and the operating temperature. There are currently six types of established fuel cells on the market [29]:

(1) Proton Exchange Membrane Fuel Cell (PEMFC)
(2) Alkaline Fuel Cell (AFC)
(3) Direct Methanol Fuel Cell (DMFC)
(4) Phosphoric Acid Fuel Cell (PAFC)
(5) Molten Carbonate Fuel Cell (MCFC)
(6) Solid Oxide Fuel Cell (SOFC)

The first three fuel cells are classified as low temperature (80 – 250°C), whilst the remaining three are medium to high temperature (250 – 1000°C). The operating temperature is often a significant factor when determining which type of fuel cell should be used in a particular application. This is due to a number of factors including; heat usability, start-up time and ability to vary output. Of the six fuel cell variants listed above, the low temperature PEMFC and the high temperature SOFC demonstrate the greatest promise for early market application, attracting the most attention and investment in building application projects [6, 27, 30]. The discussions in this review will therefore focus on these two variants. PEMFC and SOFC characteristics are summarised in Table 2.

Table 2 Summary of PEMFC and SOFC characteristics [3, 24, 27, 31]

	PEMFC	SOFC
Operating Temp. (°C)	30 -100	500 – 1000
Electrical Efficiency (%)	35 – 45	45 – 60
Electrolyte	Solid polymeric membrane	Solid, stabilised zirconia ceramic matrix with free oxide ions
Charge carrier	H^+ ions	$O^=$ ions
Construction	Plastic, metal or carbon	Ceramic, high temperature metals
Fuels	Hydrocarbons or methanol	Natural gas or propane
Contaminants	CO, Sulphur, NH_3	Sulphur
Cell Configurations	Flat plate	Tubular, Flat plate, Planar
Applications	Automotive, stationery	Stationery
Companies	Baxi, Panasonic	CFCL, Ceres
Advantages	Quick start up time, can vary output quickly, compact, no corrosive fluid used	High temperature enables internal reforming, no liquid electrolyte used, useful high temperature heat output can be used in another cycle
Disadvantages	Expensive platinum catalysts required, high purity H_2 required	Long start up time, expensive heat resistant materials needed

Recent advances in low temperature SOFC technology using ceria-carbonate two or multi-phase nanocomposite has illustrated that high electrochemical performance (1.2 W/cm^2) can still be achieved at reduced temperatures

(500°C). This is a clear advantage for the domestic sector where high temperature operation results in technical complexity and consequent costs that inhibit commercialisation. Furthermore these developments mean SOFC stacks can be manufactured for prices below 400 €/kWe compared to 1000 €/kWe for conventional SOFC systems [32, 33]. Currently it is estimated SOFC developments are around five years behind PEMFC, however many commercial developers believe the future of fuel cell technology in the domestic built environment lies with SOFC systems. This is due to lower capital cost as they do not need to use expensive platinum catalysts like PEMFCs and can be fuelled directly by natural gas, with fuel reformation occurring directly on the anode [34, 35]. Furthermore SOFCs are often cited as a more attractive fuel cell option for tri-generation system applications because of their high quality exhaust heat [36].

2.1 Fuel cell CHP systems

A fuel cell in principle is very simple, requiring few parts (even less moving), resulting in near silent operation and little maintenance required. However, in order to operate a fuel cell system i.e. a load supplied by a fuel cell, many auxiliary devices and interconnections are needed for both the correct operation of the fuel cell and the delivery of heat and power to the load. Some of these auxiliary devices have a power demand, thus they are a parasitic load on the system. The electrical efficiency of the entire system can be between a fifth and third less than the quoted stack efficiency due to these parasitic loads [3]. Auxiliary equipment also contributes to increased noise, vibrations and maintenance. However, in comparison a fuel cell CHP system can expect to produce 0-55dB, whereas an internal combustion engine is around 95 dB [3]. Figure 6 shows a schematic of a fuel cell CHP system, with the main auxiliary equipment.

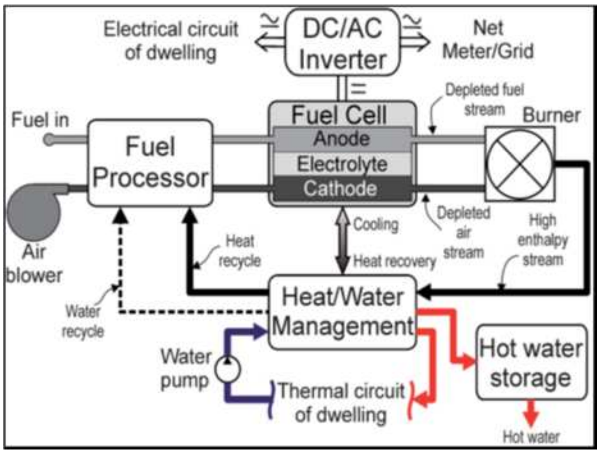

Figure 6 a fuel cell CHP system [3]

The following provides a list of the components found in a domestic fuel CHP system illustrated in Figure 6.

Fuel cell system

- **Fuel cell stack**, where hydrogen and oxygen are combined to produce electricity, heat and water.
- **Fuel processor**, converts a hydrocarbon fuel such as natural gas into hydrogen and CO_2
- **Inverter, grid tie and power electronics;** converts the DC electrical output of the fuel cell stack into AC electrical power to either serve the buildings energy demands or to be fed back to the grid.
- **Heat recovery system**; used to recover heat from the fuel cell in order to improve; (a) the performance of the fuel cell stack and (b) the environmental performance i.e. makes it a CHP system.
- **Balance of plant;** includes pumps, fans, valves sensors, piping and control system, used to ensure the whole system functions in a safe, efficient manner for long term stable operation.

Additional items for housing CHP applications

- **Boiler**, to provide peak thermal loads alongside the fuel cell.
- **Thermal energy storage** i.e. hot water tank, to store the thermal output of the fuel cell.
- **Smart meters** to measure and record energy production and consumption.
- **Internet connection;** to facilitate remote monitoring and data acquisition.

To summarise, this section has provided an introduction to the fundamentals of fuel cell technology, the operational advantages fuel cells offer compared to conventional domestic scale CHP technology such as SEs and the components required in a complete domestic fuel cell CHP system. Next fuel cell CHP systems operating in domestic built environment applications are discussed.

3. FUEL CELL CHP IN THE DOMESTIC BUILT ENVIRONMENT

This section examines fuel cell CHP systems operating in the domestic built environment. Maintenance, durability, cost, emission reductions, global state of the industry, commercially available fuel cell CHP products and optimised domestic housing integration will all be discussed. Because tri-generation systems can be deemed a subset of CHP, particularly when the same prime mover technology, in this case fuel cell, is used, much of the discussions pertaining to maintenance, durability and cost discussed here apply also to the tri-generation systems discussed in Section 4.

It is envisaged that the first generation of fuel cells for the domestic built environment will run on hydrocarbon fuels such as methane and propane. Following this, the second generation of fuel cells will run on pure hydrogen [27]. There are two reasons for the first and second generational stages of fuel use. One, the infrastructure to store, transport and deliver natural gas to individual homes is already present in both the UK and most developed countries. Two, currently, the production of hydrogen is expensive and, depending on the production method, needs careful consideration to ascertain whether greenhouse gas emissions would actually be reduced due to the substitution of hydrogen for other energy sources [37]. Braun, Klein et al. [38] developed a system model to evaluate the performance of different residential scale SOFC CHP systems. One of the main findings was that hydrogen fuelled SOFCs did not offer any efficiency advantages over methane for both internal and external reforming, and in some cases the magnitude of efficiency advantage of methane can be as high as 6%. This result demonstrates a positive outlook for the current use of hydrocarbons in fuel cells. However, the transition from the first generational stage of fuel use (hydrocarbon) to the second generation (hydrogen) will offer additional benefits, including; CO_2 emission reductions onsite and the ability to operate a range of fuel cells without localised reformation. However, if a significant increase in the use fuel cell technology in domestic homes does occur in the next 10 years, an increasing shift in gas demand and with it an increase in cost can be expected, a potential shortcoming to the extensive use of the technology as it is today in the domestic built environment, and something that will require further consideration.

In the next four sections: maintenance, durability, cost and emission savings associated with fuel cell CHP systems are discussed. It is essential these topics are covered as they will directly impact the future, wider viability of the use of the technology. Earlier reviews related to the topic have however, failed to effectively cover this, mainly due to a previous lack of information, and the fast moving nature of the field.

3.1 Maintenance

As a result of the lack of moving parts in a fuel cell, regular maintenance work to the fuel cell stack itself is hoped to be less in comparison to conventional combustion based CHP technologies. However, due to the size and complexity of the auxiliary equipment in a fuel cell system this will be the source of the majority of maintenance work. For systems using hydrocarbon fuels, the fuel processor will need to be changed periodically [3]. CFCL predicts the SOFC stack in their 1.5kWe BlueGEN CHP unit, discussed in Section 3.6, will need to be changed once every five years [39].

3.2 Durability

Lifetime, reliability and durability of fuel cells are currently one of their largest limiting factors. Fuel cells need to meet both lifetime and stop-start operating targets in order for them to become viable as CHP technologies in the domestic built environment, competing with both current centralised and decentralised generation technologies. It is estimated that both PEMFC and SOFC stacks lose power at a rate of 0-5% per 1000 operating hours [3]. Currently the industry holds a target of 40,000 hours for stationery applications. This gives around 10 years of operation if the unit is operated at regular intervals instead of continuously, which is a more likely scenario for the lower temperature PEMFC. CFCL state that their SOFC CHP unit will operate continuously due to the long start up and shutdown times required of the high temperature operation of SOFC systems. The CFCL unit has a target lifetime of 15 years, although this includes stack replacement every 5 years [39]. Laboratory tests of both PEMFC and SOFCs have shown the 40,000 hour target is possible, nonetheless limited data is available regarding actual field results, and even more so for domestic CHP systems. In 2008 as part of the EneFarm Project, Panasonic's home use PEMFC demonstrated durability of 40,000 hours with 4,000 start-stop cycles [40]. The latest Panasonic model, launched in April 2011 has a quoted system lifetime of 50,000 hours [41], showing great promise for the stationary market. SOFC systems have not been tested on such a large scale as PEMFCs. Limited data beyond 10,000 operational hours has been reported in the literature reviewed.

In summary, the development of fuel cell technology has now matured to a point where stack technology is at a level commensurate with operational targets. It is the other relatively untried components of the fuel cell CHP system that are causing reliability issues and require developmental work. However, with the introduction of more fuel cell CHP units to the market and increased volumes of both field tests and commercial applications, it is hoped these problems will soon be dealt with.

3.3 Cost

All cost figures in this section have been given in American dollars to assist in comparison. Currently there is a lack of standard industry prices for fuel cell CHP systems; however, they can be expected to be higher than those of conventional CHP systems due to the maturity of the technology. Many cost targets have been set, most significantly those by the US Department of Energy which aims for $1,200/kW by 2015 and $1,000/kW by 2020 for a complete 2kW natural gas fuelled PEMFC CHP system [42, 43]. However as Staffell and Green [44] state these future targets are currently unrealistic even with a large industry effort, and the price of a domestic fuel cell CHP system will generally be 25-50% higher, even though mass production began three years ago. Staffell and Green [44] therefore propose a long term cost target of $3,000-5,000 for a 1-2kW system as being a more feasible figure, attainable by 2020.

For demonstration projects, a quoted price in 2009 ranged from $16,000 to $160,000 for a 1kWe PEMFC unit [3]. Panasonic's EneFarm branded 1kWe PEMFC CHP unit had a retail price of $42,464 in 2009, then in 2011 with the launch of the new model the price dropped to $33,650 [41]. In 2013 the price was reduced to $21,000 before subsidies, which can further reduce the price by up to 25% [10]. By 2015 Panasonic believe they can offer the unit at a price of $5,608 to energy companies [34]. An interesting development in the EneFarm project is the planned phasing out of its subsidies. During the EneFarm demonstration phase the subsidy reduced the cost of the unit for the consumer from $73,609 to $26,990. However as of 2010 the subsidy has been capped at $15,949, with plans to eliminate subsidies all together once production volumes are such that the units are cost effective and affordable on their own. Subsidy removal will mark a significant milestone in the deployment of fuel cell technology for domestic built environment applications as it will prove their worth without external assistance [42].

Data regarding SOFC system cost is limited in comparison to PEMFCs. This is due to SOFCs less substantial commercial development. Staffell and Green [44] estimate that currently a domestic SOFC CHP system will sell for $25,000 per kW, a figure in reasonable agreement with the SOFCs presented in Table 3, for example CFCL are currently charging $31,968 for their 1.5kWe SOFC CHP unit (~$21,312/kW). However once in mass production CFCL forecast the cost to drop to around $8012 [39]. Many commercial developers believe the future of cheaper fuel cell technology lies with SOFC systems. This is because they do not need to use expensive platinum catalysts like PEMFCs [34].

To summarise, as time progresses and the volume of fuel cell CHP units produced increases, it is anticipated that their price will decrease, encouraging their wider uptake. Currently the Japanese EneFarm project is spearheading this drive for economies of scale.

3.4 Emission savings achievable with fuel cell combined heat and power

The likely contribution domestic fuel cell CHP systems will provide regarding CO_2 emissions reduction is explored. Currently, natural gas fed fuel cell CHP poses a potential challenge in terms of a transition to a zero or even low carbon domestic built environment [11]. Currently, it is estimated that the achievable reduction in CO_2 emissions for a fuel cell CHP system running on natural gas is around 30% compared to grid electricity and gas boiler [45]. However, the aforementioned generational stage of fuel use is an essential component in optimising the resource present today and ensuring the arrival at a zero carbon economy in the future when pure hydrogen becomes more widely available. As previously discussed, there is currently a limited bank of available data regarding the benefits of fuel cell technologies operating in the domestic built environment; this is a result of the still premature level of implementation of the technology.

The Annex 42 project [14] has carried out extensive real world and simulation based performance assessment studies for both SOFC and PEMFC technologies operating as CHP units in single and multifamily homes, comparing them to a reference system. Beausoleil-Morrison [14] states four key findings from the Annex 42 project, supported by similar research found in the literature. (1) Individual buildings employing fuel cell CHP systems could reduce non-renewable primary energy (NRPE) demand compared to a reference system using a gas boiler and grid electricity. However the magnitude of reduction is highly dependent upon the reference systems grid electricity generation mix i.e. the kg/CO_2/kWh. A finding backed up by the work of Pade, Schröder et al. [46], Dorer, Weber et al. [47] and Steinberger-Wilckens [25] who all state that the impact of fuel cells on primary energy reduction, and thus emission savings, is highly dependent upon the energy system they are placed in. For example, Pade, Schröder et al. [46] demonstrate that in Denmark, the use of SOFC CHP would reduce NRPE demand and create a corresponding cut in CO_2 emissions in the Danish energy system, however in

France, fuel cell power generation would primarily replace nuclear, thus creating an increase in natural gas consumption and CO_2 emissions. (2) When the reference system utilised centralised electricity generation from a combined cycle gas turbine and an individual home heat pump, the operational electrical efficiency of the fuel cell had to be greater than 40% in order for it to be competitive both on a cost and CO_2 emission level basis. (3) In order to obtain maximum system efficiency and CO_2 emission reduction at least 80-90% of the homes annual heat demands needed to be met by the fuel cell. (4) The way in which the fuel cell CHP unit was operated had a large impact on the benefits gained. When in heat led mode, the system showed the best energy efficiency. However, when in electrical led mode, it created the greatest cost savings. In general, base load sizing offered better energy savings than peak load sizing.

Field trials of 1kWe PEMFC CHP units in Japanese homes has indicated a reduction of a 750 – 1250 kg CO_2 per household per annum when switching from a gas boiler and grid electricity to a fuel cell CHP system. Simulations by Hawkes, Staffell et al. [3] based upon the UK illustrate fuel cell CHP has the potential to reduce CO_2 emissions by 1.5 tonnes per annum for a high demand home, a figure which is consistent with previous simulations that predict around 1 tonne per annum are achievable for an average sized family home [48].

E.ON estimates that the 1.5kWe SOFC CHP unit produced by CFCL can achieve CO_2 emission reductions of up to 4.5 tonnes/house/year [11]. Ceres Power, a manufacturer of an intermediate temperature 1kWe SOFC, anticipate savings of up to 2.5 tonnes of CO_2 per year and £250 in energy bills are attainable for a UK residence when switching from gas boiler and grid electricity to their fuel cell unit [49]. Clearly these estimates are much larger than the data presented above. It is clear that emission and energy savings are highly dependent upon the specific case. There is a danger of manufactures overselling the benefits of fuel cell CHP systems to consumers; this needs to be restricted until a sufficient bank of reliable, real time operational data can be acquired in order to accurately verify the possible benefits.

Steinberger-Wilckens [25] states that currently, in the EU, there are no clear indications for the desired minimum performance stationary fuel cells are to meet in order to satisfy the EU goals of energy efficiency and greenhouse gas emission reduction. As a result Steinberger-Wilckens has been working on a methodology to accurately assess the environmental advantage delivered by fuel cells operating in current electricity markets across Europe. Currently a benchmarking approach has been adopted, which considers; a reference dwelling, key performance merits - CO_2 / fossil fuel avoided and the total and electrical efficiency, different CHP technologies (PEMFC, SOFC, SE, ICE) and different operating strategies (electrical or heat led and economic optimisation). Initial simulations for s single family home show an increasing electrical efficiency of a domestic CHP system creates greater CO_2 emission reductions. For a SOFC using internal steam reforming operating at an electrical efficiency of 55% emission savings in the order of 2. 4 tonnes per annum are predicted. For a PEMFC system with electrical efficiency of 35% this figure drops to around 1.5 tonnes per annum, a figure in good agreement with Hawkes et al. [3] and the work at EneFarm. A SE with an electrical efficiency of around 12% shows emission savings in the order of only 0.5 tonnes per annum are achievable - a much lower potential compared to the fuel cells simulated. It is intended that the methodology will be reported back to the US and Japan to try and gain global standardisation with regards to the performance assessment of stationary fuel cells. This represents a significant opportunity for the benefits of fuel cell CHP to be verified and disseminated.

In summary, from the literature presented in this section, it is clear that currently there is no conclusive set of figures concerning the CO_2 emission savings achievable from fuel cell CHP operating in the domestic built environment. Sizeable reductions are achievable, but are largely dependent upon a range of factors including; central electricity mix, the home's annual energy demand and electrical / total efficiency of the fuel cell system. It can be anticipated that CO_2 emission savings in the future will only improve with the introduction of renewable biogas / hydrogen and improved fuel cell efficiencies. In this case fuel cell CHP could potentially reach zero carbon status.

3.5 Current state of the industry: fuel cell combined heat and power in the domestic built environment

In terms of commercialisation, fuel cell CHP in the domestic built environment is still in its infancy. It is predicted SOFC demonstration projects are around 5 years behind those of PEMFC, with around 80% of projects employing PEMFC technology and 20% SOFC [3]. Japan is currently the leader in terms of fuel cell CHP technology in the domestic sector. In 2008 there was an estimated 3,300 PEMFC units under demonstration in residential buildings in Japan (Nishizaki 2008), and as of 2012 that figure is closer to 40,000 [10]. Real world applications of fuel cell systems are essential in the development of an efficient, effective and usable technology. Currently Asia followed by Europe lead the world in terms of fuel cell CHP for domestic applications. The state of the industry in these two regions is discussed below.

(i) Asia

EneFarm is a fuel cell research, development and demonstration (RDD) project based in Japan, and is the largest and most successful of its kind in Asia and the rest of the world to date. The project started in the 1990s and involves many companies including Panasonic, Tokyo Gas Co Ltd. and Kyocera. The research and development stage began with the production of a 1kWe PEMFC CHP system that runs on natural gas. Demonstration has been carried out in three stages. Stage 1; small scale demonstration where 50 units were installed in homes between 2003 and 2005. Stage 2; large scale demonstration of 3,000 PEMFC CHP units ran until 2009. Stage 3; commercialisation phase ran from 2009 onwards and as of 2012 there were more than 20,000 units installed with the aid of Japanese government grants [12]. The current EneFarm PEMFC model has an electrical capacity of 700-750W, with an overall efficiency of 95%. The fuel cell system developed can be operated both grid connected or disconnected. The PEMFC system is designed, due to its operational characteristics, not to run continuously. It is on during the day when demand is high and hot water can be stored. The system is then turned off at night when demand is low. EneFarm users benefit from a discounted gas price, further incentifying the use of the units [50]. Highlights for the EneFarm project include; the very first fuel cell CHP system in the world supplied to the Japanese Prime Minister's residence in April 2005 and the world's first general launch of a household fuel cell CHP system in May 2009. The EneFarm project has facilitated the continual improvement (cost, size and efficiency) of the initial fuel cell system for housing integration, seen in Figure 7.

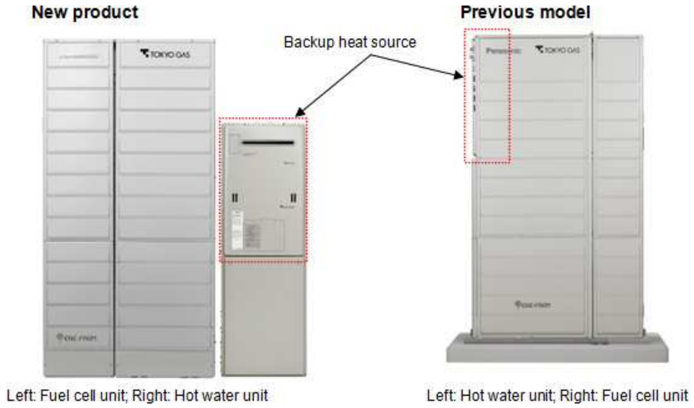

Figure 7 the latest (left) and previous (right) EneFarm PEMFC CHP system for domestic homes [51]

By the end of 2010, cumulative shipments of the EneFarm units had reached 13,500 [42]. The devastating events of the Tohoku earthquake and tsunami that struck Japan in March 2011, leading to the Fukushima nuclear incident had a profound impact on the sales of EneFarm units. More than twice as many fuel cell units were sold in 2011 than in 2010 as consumers sought to reduce energy bills and reliance on the grid. An estimated 20,000 EneFarm units were sold in 2012 , effectively doubling the number of fuel CHP units in Japanese homes to around 40,000 [10]. Sales targets of 50,000 by 2015 and 2.5 million by 2030 are currently being proposed [50]. With such large volumes of sales it can be anticipated that the cost of these systems will continue to decrease, hopefully permitting the widespread uptake of fuel cell technology in the domestic built environment, not only in Japan but across the world.

Fuel Cell Toady [42] expects the EneFarm demonstration programme to be replicated in other developing markets such as Korea, Europe and America. Analysis has shown that if in addition to the Japanese EneFarm case, if four additional projects worldwide can be implemented at a similar rate, sales of up to 20,000 units annually can be expected by 2014 and 100,000 units cumulatively installed globally by 2015. The EneFarm project has facilitated the wider use of fuel cell technology in the domestic built environment with many valuable lessons learnt. EneFarm is forming a suitable platform on which to base future fuel cell RDD programmes on across Asia and the rest of the world, such as The Green Home Project in South Korea where more than 350 PEMFC units have been installed [42]. EneFarm has now expanded its RDD base with a newly introduced SOFC system from Kyocera. The SOFC will operate continuously to avoid damage due to thermal cycling. The introduction of a SOFC to the programme has been spearheaded due to its promise of lower capital cost and further efficiency gains [34]. Furthermore, due to EneFarm’s success, companies such as Honda are now considering SOFC for domestic CHP applications [10].

(ii) Europe

The European market for domestic fuel cell CHP is growing rapidly. Currently, under the Callux project, Germany is second to Japan in terms of fuel cell CHP applications in domestic homes. The Callux project is the largest national field test of fuel cell heating appliances for homes [52]. The project has installed over 350 systems produced by Baxi, Hexi and Vaillant, between 2008 and the end of 2012. The products are a mix of PEMFC and SOFC. The Callux project is scheduled to run until 2015 [10]. Further to the Callux project is the launch of the ene.field project in October 2012. ene.field aims to bring together 27 project partners with the aim of installing 1000 fuel cell CHP systems (both PEMFC and SOFC) across 12 member states of the EU [53]. It is believed ene.field will create a dramatic increase in the deployment of fuel cell CHP in Europe, and a meaningful step towards commercialisation of the technology [54]. CFCL has also made large in-roads into the European fuel cell market. CFCL and E.ON have now formed a partnership as part of the European Union Fuel Cell and Hydrogen Joint Undertaking's Joint Technology Initiative (JTI) fuel cell demonstration programme, with the aim to demonstrate 100 domestic fuel cells in Europe. CFCL now have manufacturing capabilities in Europe to produce up to 1000 units per annum. CFCL have received an order for 60 units from German power company EWE, and now with the introduction of new capital based subsidies from the German government for highly efficient CHP systems for domestic applications, the sales of CFCL's unit are set to increase, with the aim of 600 units to be in operation across Germany by 2015 [10]. In the UK, E.ON has placed an order for 45 of CFCL's units as part of a demonstration period, after which, subject to a minimum order of 100,000 units, E.ON would become the sole UK supplier of CFCL products [55], an arrangement E.ON has successfully maintained in the past with the commitment to purchase 80,000 Whispergen units from Powergen in 2005 [35]. Finally, EneFarm is looking to expand its customer base to the European market, with Panasonic collaborating with Viesssmann to help bring the EneFarm product to Europe.

In summary, it is clear that Asia, particularly Japan, lead the way in terms of the deployment of fuel cell CHP in domestic buildings. The work carried out by EneFarm has, and will, continue to facilitate the wider use of fuel cell CHP in the domestic built environment, seen in the increasing number of units installed in Europe and Korea. EneFarm has formed the most suitable case study for the use of fuel cell technology in the domestic built environment to date, consistently illustrating the operational advantages of the adoption of the technology. Future projects such as the European ene.field program should look to EneFarm as a suitable case study.

3.6 Commercially available fuel cell CHP units for domestic application

Currently, commercial suppliers of fuel cell CHP units intend that them to be installed alongside a highly efficient condensing boiler and thermal energy store. Depending on system capacity and application, the fuel cell provides the base load electrical power and domestic hot water, as this provides greatest energy savings to the consumer [14]. In this section, fuel cell CHP units that are currently available on the commercial market, or are close to market application are introduced, summarised in Table 3 and discussed.

A number of operational configurations are possible for the fuel cell CHP systems shown in Table 3, and largely depend on the type/size of fuel cell used, application and the market they are being used within. Continuous baseload operation is suited to units with high electrical efficiencies and a lower heat output, such as the BlueGEN SOFC. The unit would be operated continuously and its thermal output will be used to meet the DHW load throughout the year with a supplementary burner used to meet variable space heat requirements. This operating strategy avoids the need for power modulation to prevent heat dumping and thus thermal cycling of the stack is minimised [39, 56]. However products with lower electrical efficiencies and consequently higher heat to power ratios such as PEMFC systems need to modulate their output to maintain the heat production below the daily hot water demand of the home, and thus they can be sized bigger [10].Many manufacturers (Kyocera, JX Eneos) have however concluded that the future of fuel cells in domestic built environment applications lie with SOFC, and have therefore stopped PEMFC development.

Two European marketed PEMFC and SOFC CHP systems (as shown in Table 3) are now discussed.

Baxi – GAMMA series 1.0

Extensive demonstrations and field trials of the GAMMA series 1.0, shown in Figure 8, have been carried out in Germany as part of the Callux project. The unit consists of a PEMFC, heat storage and energy manager. Due to the fuel cells low thermal output, there is a requirement of an auxiliary heater. This adds cost and complexity to the system; however it does mean the system can be operated in an electrical led manner, thus adding greater benefit to the consumer. Baxi state that the fuel cell CHP system will provide 100% of the heating demand of a single family home using the fuel cell and auxiliary heater and produce 5000-6000 kWh of electricity per annum, covering roughly 73% of the annual electrical load. Baxi have produced a development road map of where they believe the GAMMA series technology will progress. By 2013/2014 it is planned the DELTA will be introduced with electrical efficiency of 35%, CHP efficiency of >90% and a durability of 60,000 hours [57].

Figure 8 Baxi GAMMA series 1.0 [57]

Cermaic Fuel Cells Ltd - BlueGEN

The CFCL BlueGEN unit, shown in Figure 9, is currently the only fuel cell product on the UK market to be certified under the Micro-generation Certification Scheme in the UK, making it eligible for the CHP FiT. Under this tariff, 10.5p/kWh of electricity produced is paid to the homeowner, with a further 3.1p/kWh paid for surplus electricity exported [42]. CFCL is now collaborating with HOMA Software BV under the JTI project, and is aiming to develop a ‘virtual’ grid. The proposal aims to conglomerate many homes’ fuel cell CHP capacity and remotely manage generation in response to utility scale power demands. With enough combined units, the generation capacity could be equal to several centralised power plants. However, electrical and system efficiencies would be much higher [11]. Pade, Schröder et al. [46] state that operating SOFC CHP units as a virtual power plant in response to spot market prices seems promising, offering a lower price premium compared to other financial support mechanisms for domestic fuel cell CHP.

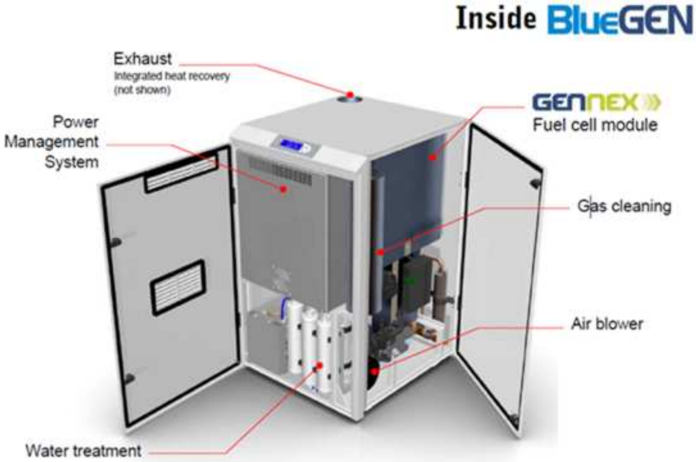

Figure 9 the CFCL BlueGEN unit [39]

From Table 3 it is apparent that a large proportion of fuel cell CHP units commercially available are Japanese, this is due to Japan holding such a large segment of the market. Many of the non-Japanese units are currently still in the RDD stage and not offered on the commercial market, seen in the lack of data for these units in Table 3. Many of these Japanese manufactures - Toshiba, Panasonic and JX Eneos - have launched their own branded fuel cell units on the back of the developments made by the EneFarm project discussed in Section 3.5. This market dominance illustrates why initial funding and support for RDD projects such as EneFarm are critical for the development of the fuel cell CHP industry in domestic homes. EneFarm should serve as precedence to the European and American markets looking to match the work done in Japan. The Japanese fuel cells, particularly the SOFC variety, presented in Table 3 have smaller electrical capacities (~0.7 kWe) compared to the European units (~1.5kWe). This is for two reasons (1) to minimise electrical export, which is discouraged in the Japanese market, and (2) to prevent the need to cycle power output to minimise heat dumping. The issue of electrical export illustrates a clear difference between the Japanese and European markets in which fuel cells are being placed. In the European market electrical export is actively encouraged with schemes such as the UK’s Feed-in-Tariff (FiT) and could be a reason why there is a continuing trend of higher electrical capacities seen in the European units - Baxi GAMMA and CFCL BlueGEN. This fundamental difference in unit capacity and operation could pose a significant challenge when trying to bring the European and Asian fuel cell markets together. For example with the EneFarm product being launched in Germany, issues such as unit capacity will need careful consideration in order to assure successful product integration into a market where competitors already exist.

To summarise, this section has provided an overview of all the current fuel cell CHP units on, or on their way to, market. Japan currently dominates, largely as a result of the initial stimulus from the EneFarm project which started over 20 years ago. EneFarm and the Japanese market will be a motivating and fundamental reference point for the future European market, particularly for projects such as ene.field which aims to have over 1000 units in operation in the next couple of years. The European and rest of the world markets (Australia) are responding to the Japanese developments with their own commercially available products (CFCL, Baxi etc.), however the volume of companies manufacturing these units and sales volumes are currently not commensurate with the Japanese. External support, subsidies and stimulus are essential in order to overcome the inertia experienced in the deployment of novel technology such as fuel cell CHP in a competitive commercial market. From the products reviewed, it is clear that the type of fuel cell used and the market it is being integrated into have a marked impact on fuel cell capacity, operating strategy and system design. There is currently a noticeable difference between the Japanese (Asian) and European market design. This could pose a significant challenge, even barrier, when companies wish to expand their fuel cell CHP products to different regions of the world.

Table 3 fuel cell CHP products on the market

Manufacturer (country of origin)	Stack type	Electrical capacity (kWe)	Electrical efficiency (%)	Thermal output (kWth)	Auxiliary heater included	Cost	Commercially availability	Partners/projects	Comments	Reference
Baxi (UK)	PEM	1	32	1.7	20kWth	---	2015	Ballard/Callux	Requires external heater	[57]
Toshiba (JPN)	PEM	0.7	35	1	---	$20,000	Japan 2009 EU - 2015	EneFarm	80,000 operational hours expected	[58, 59]
Viessmann (GER)	PEM	0.75	37	1.3	19kWth	€35,000	Germany -2014 Europe - 2015	Panasonic	Uses Japanese stack	[58, 60]
Elcore (GER)	PEM	0.3	33	0.6	---	€9,000	Enefield - 2013	Enefield	Low electrical/heat output means fuel cell runs continuously	[61]
Dantherm Power (DEN)	PEM	1.7, 2.5 and 5	---	---	---	---	Danish field trials	Ballard	Only short duration tests thus far	[62]
Panasonic (JPN)	PEM	0.7	40	0.9	Yes	€25,000	Japan – 2011 Europe - 2014	EneFarm	European R&D stared in 2012	[59, 60]
JX Eneos (JPN)	PEM	0.7	40		---	---	Japan – 2011	EneFarm	Now pursuing SOFC technology	[59, 63]
Vaillant (GER)	PEM	5		25-50	---	---	---	PlugPower	Aimed at multi-family homes	[58, 64]
CFCL (AUS)	SO	1.5	60	0.6 – 1	No	£20,000	Yes	E.On	Highest electrical efficiency on market	[10, 39]
Hexis (SUI)	SO	1	30 – 35	1.8	20kW	---	Callux - 2012	Viessmann/Callux	Electrical efficiency similar to PEMFC	[58, 65]
Ceres Power (UK)	SO	1	---	---	---	---	2016	British Gas/KD Navien	External reformer	[58, 66]
Vaillant (GER)	SO	1	30	1.7	---	---	2013	Staxera/Callux	Unit focussed on reliability	[58]
Kyocera (JPN)	SO	0.7	46.5	0.65	---	---	Japan - 2012	Osaka Gas	Uses flat tubular cells	[58, 67]
Aisin Seiki (JPN)	SO	0.7	46.5	---	Yes	£21,000	Japan – 2012 Europe - 2014	Osaka Gas/Bosch	Highest Japanese SOFC product efficiency	[58]
JX Eneos (JPN)	SO	0.7	45	---	40kWth	$31,000	Japan - 2012	Kyocera	Robust unit	[63]
Topsoe (DEN)	SO	1		---	---	---	---	Wärtsilä/ Dantherm	Robust cells	[68]
Acumentrics (US)	SO	0.25 - 1.5	<35	---	---	---	2013	---	Able to respond to thermal cycling	[58]
SOFC power (SUI)	SO	0.5 / 1	30 - 32	---	---	---	---	---	Poor electrical efficiency for SOFC	[58, 69]

UK = United Kingdom, JPN = Japan, GER = Germany, DEN = Denmark, AUS = Australia, SUI = Switzerland, US = United States of America

3.7 Fuel cell system optimisation for domestic housing integration

Fuel cell system optimisation for domestic built environment applications is an essential research topic if the benefits of their operation are to be fully realised. This area of optimisation work is mainly focused on thermal energy because the majority of fuel CHP systems in use are grid connected. In many counties, grid interaction offers the option to sell surplus electrify back to the grid, therefore optimisation methods to maximise surplus electricity use in individual homes is not such an issue.

The heat led nature of combustion based CHP technologies means they should only be in use when demand for thermal energy is present, however, because their operation can be of an intermittent nature, their output can be modulated in response to a home's energy demands [14]. Due to PEMFCs low temperature operation, they also have the ability to quickly respond to varying energy demands, and therefore they may be operated in a similar manner to conventional combustion based CHP technologies. This means maximising the energy outputs from the system is relatively simple. Kato, Iida et al. [70] investigated the use of thermal energy storage (TES) in a residential PEMFC application. It was found that a high level of temporal precision was required in order to match the domestic hot water demand and to correctly size the system components. However, for a 2kWe installation, a 200 - 350 litre TES was required to effectively maximise the use of the PEMFCs thermal output, a similar requirement of combustion based CHP systems.

SOFCs with their promise of lower capital cost, high electrical efficiency and thus greater economic benefit to the consumer, are predicted to be the fuel cell of choice in the future domestic built environment [10, 34]. However, SOFCs have very different operational characteristics to combustion and even PEMFC technologies, most significantly; the requirement of constant operation, at least on a diurnal basis, to avoid thermal cycling and long start-up and shut down times. Constant operation does yield benefits in terms of extra electrical generation, and in the UK case, payment through the FiT. However, the majority of UK and northern European housing stock is characterised by peak morning and evening heating demands, shown in Case 1, Figure 10. How a SOFC with their preference for constant operation is thermally integrated into domestic buildings in order to maximise system efficiency is a challenging task.

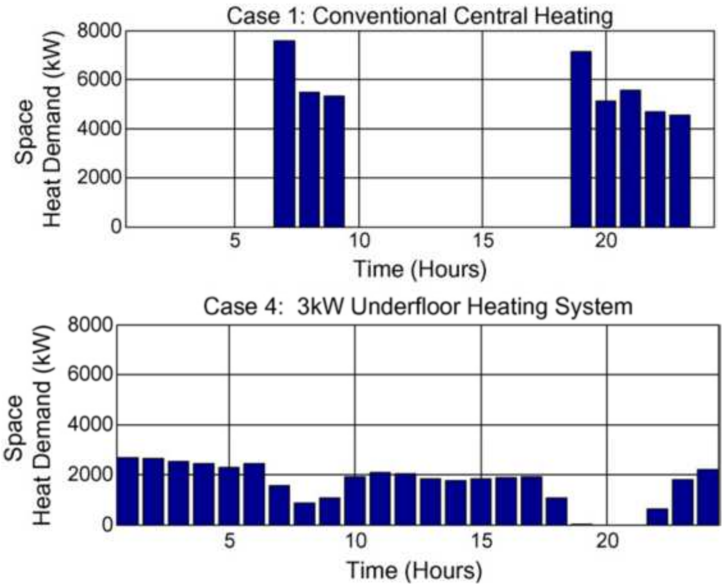

Figure 10 case 1: conventional UK heating profile, case 4: slow heating demand [56]

Hawkes, Aguiar et al. [56] present a SOFC CHP model for use in a techno-economic analysis to determine options in the provision of residential heat demand in the UK. Four different UK heating demand profiles were considered to see which profile best suited that of a SOFC CHP system using a cost minimisation model. The model also included the use of a TES. The base case model, shown in Case 1, Figure 10 was based on a typical UK heat load profile. Results showed that a 'slow' space heating demand, seen in Case 4, Figure 10, running constantly in winter with under floor heating was most suitable for the SOFC due to maximum thermal energy utilisation. This profile achieved highest cost and CO_2 savings compared to the reference study of grid electricity and gas fired boiler. The slower heating demand is also a better match for SOFC technology due to the avoidance of thermal cycling. TES provided added benefit to the system. In an operational strategy and system integration study of SOFC CHP systems, Pade, Schröder et al. [46] state that a relatively small 100-200 litre heat storage can limit, but not eliminate the number of required cold starts required for a SOFC CHP system.

District scale fuel cell operation and interaction has been cited as an effective way to optimise the use of fuel cell technology in the domestic built environment [36]. Work has been carried out by the EU funded FC-DISTRICT project to optimise individual building SOFC CHP systems using district heat storage and distribution networks. This concept is being used on account of district systems potential to increase thermal energy utilisation due to the dynamic heat exchange possible with collective thermal energy storage [71]. Initial results from the project show for a 100 house study, a district heat and electricity network powered by SOFC CHP can reduce annual primary energy demand by up to 50%, in the specific case, equal to 2GWh [7]. The encouraging outcomes achieved thus far from the FC-DISTRICT could pave the way for future integration options for SOFC CHP generators in the domestic built environment, where district scale optimisation favours that of individual buildings. District scale tri-generation systems have been investigated [72]. The authors state that it is highly desirable that more examples of district heating and cooling networks are developed due to their potential for built environment decarbonisation. The economic and environmental performance of these systems could be further improved with the inclusion of fuel cell technology.

In summary, Section 3 has addressed fuel cells operating as CHP systems in domestic built environment applications. A variety of topics that have and will continue to influence the viability of their use in the domestic built environment have been covered, including; maintenance, durability, cost, emissions saving potential, current state of the industry, commercially available units and housing integration. Currently there is no conclusive set of figures concerning the CO_2 emission savings achievable from fuel cell CHP operating in the domestic built environment; however they are achievable and have the potential to be sizeable depending upon the situation. From this section of the review it can be concluded that currently the main barriers for fuel cell CHP systems in the domestic built environment include [63]:

1. Cost - future systems will need to use using fewer parts and more mass produced components.
2. Reliability - future systems will need to look for simpler design solutions and quality control mechanisms.
3. Current performance - for the more promising SOFC technology this will be the use of lower temperature catalysts and novel materials.

4. FUEL CELL TRI-GENERATION SYSTEMS

This section will examine tri-generation energy systems for domestic building applications, with the specific aim of assessing the potential fuel cell technology has in this area of domestic energy supply. Fuel cells are well suited to tri-generation built environment applications because they produce heat when generating electricity, have high electrical efficiency and excellent load following characteristics [73]. Moreover, continued technological improvements to fuel cells have, in recent years increased interest in fuel cell based tri-generation systems [74]. The discussions covered in the previous section regarding fuel cell CHP systems in domestic built environment applications are also applicable to the tri-generation systems concept because the prime mover technology and operational aims are very similar, thus they will not be re-covered here.

Tri-generation is a well-known technology for energy conservation in commercial and industrial applications. However, very limited work has been completed for tri-generation systems in domestic building applications [75, 76]. Kong et al. [77] states that the concept of tri-generation systems for individual domestic buildings has only be thought reasonable with the more recent development of heat driven cooling technologies with capacities of <10kW cooling, that can operate on low-grade thermal energy (60-90°C). Huangfu et al. [75] believes the main obstacles to any type of domestic scale tri-generation systems is the high initial cost and complexity of optimum matching of different parts of the system i.e. prime mover and chiller.

Due to the limited breadth of literature covering fuel cell tri-generation systems, particularly on a domestic scale, this section of the review will be split into three parts: (1) fuel cell tri-generation systems of all scales, (2) domestic scale tri-generation systems employing combustion based prime mover technology, and (3) domestic scale fuel cell tri-generation systems. This approach has been adopted to achieve a broader context of research. Discussions will cover; what has been done to date, the important lessons learnt from the larger studies and how these might be applied at a domestic level, the advantages fuel cell technology can provide over conventional combustion based prime mover technologies in tri-generation system applications and the future of fuel cell tri-generation systems in the domestic built environment.

4.1 Large scale fuel cell tri-generation systems

Yu, Han et al. [78] have numerically investigated a tri-generation system incorporating a SOFC and a double-effect water/lithium bromide absorption chiller, high total system efficiencies of 84% or more were reported by the authors, illustrating the benefits of tri-generation systems in applications where heating, cooling and power are required. Margalef and Samuelsen [79] numerically examined a 300kW MCFC tri-generation system using absorption cooling, achieving an overall system efficiency of 72%. However, the pairing of two ‘off the shelf’ technologies for tri-generation system construction was shown to be problematic. Margalef and Samuelsen [79] state that the fuel cell and absorption chiller chosen for the tri-generation system were close, but not an ideal match. The fuel cell exhaust gas temperature was higher than the inlet temperature specified for the chiller and the exhaust flow rate was not sufficient to achieve the potential heat recovery within the chiller heat exchanger. Therefore two strategies to overcome this were presented (1) blending the fuel cell exhaust gas with ambient air, and (2) mixing the fuel cell exhaust gases with a fraction of the chiller exhaust gas. Both options worked, however the second option yielded better performance and was thus used. Al-Sulaiman, Dincer et al. [80] presents an energy analysis of a tri-generation plant incorporating a 520kW SOFC, organic Rankin cycle, heat exchanger and single effect absorption chiller. The investigation showed that by incorporating the cooling cycle system efficiency is improved by 22% compared to just having the SOFC and organic Rankin cycle running together. A maximum tri-generation efficiency of 74% has been achieved.

Fong and Lee [8] have studied a SOFC tri-generation energy system for a high-rise building in a hot-humid climate. The study focussed on two sizing options. (1) Full-SOFC, where the system was sized to peak loads, therefore requiring no grid import, and the other (2) partial-SOFC, where the system was sized such that peak loads were met by the SOFC and grid, however over the course of one year the system maintains a net zero grid import. The environmental and energetic performance of both cases was studied over the course of a year using a dynamic simulation. The full and the partial SOFC systems generate a 51.4% and 23.9% carbon emission saving respectively, and a 7.1% and 2.8% electricity saving respectively. As a whole, the full-SOFC tri-generation system had the highest environmental and energetic performance due to the partial-SOFC systems requirement of grid electricity. However the economics of sizing the tri-generation system to meet peak load capacity was not studied, and should be the focus of future work to determine the optimum sizing and operating strategies for such systems.

Zink, Lu et al. [81] have examined a 110kW SOFC based tri-generation system employing absorption cooling technology. Results show that total system efficiency can reach 87% or more and that the combined system shows great advantages both technically and environmentally over other current CHP and tri-generation systems. Since many heat driven cooling technologies such as vapour absorption cycles are already commercially available, the viability of fuel cell tri-generation systems heavily depends on the commercialisation of the fuel cell system. With recent trends indicating a reduction in the cost of fuel cell based CHP systems [10], the authors believe fuel cell tri-generation systems will be commercially viable within the decade. Darwish [82] have studied a tri-generation PAFC system to meet high air conditioning loads in a large building in Kuwait. The PAFCs thermal (105kW) and electrical outputs (200kW) are used in vapour absorption and vapour compression cooling cycles respectively. Cold water storage has been used to allow the fuel cells limited output to meet both average and peak air conditioning loads. It was proposed that the economy of the system only becomes feasible once the fuel cells capital cost drops below $2000/kW. Fuel cell based tri-generation systems show great promise in terms of energy savings. However, the economics of such systems are not yet feasible due to the current price of the fuel cell technology, a finding Malico, Carvalhinho et al. [83] support in their study of a SOFC tri-generation system used for a hospital building.

The above investigations have been for large, commercial applications. The work does show great promise for fuel cell tri-generation systems in terms of primary energy reduction, improved system efficiency and associated CO_2 emissions. However the capital fuel cell cost currently seems the largest inhibitor to the wider use of fuel cell based tri-generation systems.

4.2 Combustion based tri-generation systems for domestic built environment applications

Tri-generation is a well-known technology for energy conservation in commercial and industrial applications. However, very limited work has been completed for tri-generation systems in domestic building applications.

Khatri et al. [84] state that the use of tri-generation systems of less than 10kWe for domestic applications is feasible and an effective technique to utilise resources efficiently. The authors tested a 3.7kW compression-ignition engine (CI) tri-generation system in a laboratory. Results showed the thermal efficiency in tri-generation mode reached 86.2%, compared to 33.7% in single generation mode. This illustrates great promise for domestic scale tri-generation systems. However, optimisation and energy utilisation is not a large issue in theoretical or laboratory based projects, thus high system efficiencies have been reported in various pieces of literature. However in a real world working environment, effective energy utilisation could pose a serious challenge to the system, specifically how to maximise the utilisation of the energy outputs of the system in order to improve system efficiency. If this cannot be addressed it will have a large impact on the final feasibility of the system. Future work, such as that presented below, should focus on this consideration.

An experimental, tri-generation system for domestic buildings, employing a combustion based prime mover is summarised below. This assessment is used is to illustrate the benefits of, and any operational considerations for, the tri-generation concept in domestic buildings, and to demonstrate the added value fuel cell technology can bring to the system. Kong et al. [77] have developed a novel tri-generation system aimed at domestic built environment applications. The system comprises a 12kW electrical / 28kW thermal ICE and a 9kW closed cycle adsorption chiller. Initial experimental studies carried out by Kong et al. [77] show the system can achieve an overall thermal and electrical efficiency of over 70% under real life operating conditions. Huangfu et al. [75] have carried out further investigations into the system developed by Kong et al. [77]. The analysis has focussed on the systems economic, energetic and exergetic performance. The payback period and NPV of the system show the greatest sensitivity to changes in the price of natural gas. Due to the fluctuating nature of natural gas prices in many counties today, this sensitivity highlights the delicate nature of the economic feasibility of tri-generation systems operating on natural gas in domestic applications. Furthermore it is an obvious and extremely important consideration for the economic feasibility for fuel cell tri-generation systems, on account of the fact that the vast majority of current fuel cell CHP systems (BlueGEN, Baxi, EneFarm etc.) require natural gas to operate.

The system was energetically evaluated in terms of its primary energy ratio (PER) - the ratio of required energy output of the system to the primary energy demand. The higher the PER, the superior the system is with regards to energy consumption [85]. The tri-generation system outperformed the comparison independent system of grid electricity, boiler and electrical cooling, when operating as a CHP device, however when operating as a combined cooling and power system (CCP); the independent system had a higher PER. This is because in CHP mode the waste heat is used effectively used. However in the CCP mode, thermal energy is not utilised so effectively due to the low thermal coefficient of performance (CoP) of the adsorption chiller, which was around ~0.3. Thus, the greater the heat demand that can be met by the tri-generation system, the higher the PER achieved, and therefore the greater the energy savings the tri-generation system can expect to achieve in comparison to the independent system. For future tri-generation systems, operating with or without fuel cell technology, the energetic performance of the heat driven cooling technology needs to be higher in order for the system to be competitive in all types of operation i.e. CHP and CCP. Open cycle absorption systems, also known as desiccant air conditioners, have been successfully used in tri-generation applications where cooling capacities of less than 10kW are required. Performance figures for these systems show the potential for a thermal CoP in the range of 1.0 – 1.5 [86], an 80% improvement on the adsorption system used in the system described by Kong et al. [77]. Higher cooling CoP would make the tri-generation system described competitive with the independent system in CCP mode. Desiccant air conditioning systems could therefore be an appropriate and effective technological option for both combustion and fuel cell based tri-generation systems operating in domestic building applications.

Finally, an influence factor analysis was conducted to see the impact electrical efficiency, heat recovery effectiveness, cooling CoP and the ratio of recovered heat for driving the adsorption chiller had on the PER. It was found that the electrical efficiency of the prime mover device had the largest impact on the PER. In addition to this, an exergetic analysis was conducted, with the authors concluding that the complete tri-generation system would benefit from operation that maximises electrical efficiency. Therefore the authors concluded that the tri-generation system should be operated at conditions that maximise its electrical efficiency in order to bring about the best energetic and exergetic performance. As demonstrated in Table 1, fuel cells, particularly SOFCs have much higher electrical efficiencies compared to both the ICE and SE. Fuel cells are therefore a key technological option for maximising the energetic and exergetic and economic performance of tri-generation systems in domestic built environment applications.

Ren and Gao [87] have investigated a gas engine and fuel cell for domestic CHP applications in Japan. It was found that the fuel cell offered superior economic and environmental performance in a domestic application.

This section has discussed the use of combustion based tri-generation systems in domestic built environment applications, and how the use of fuel cell technology can potentially enhance the performance of these systems. With regards to domestic scale fuel cell tri-generation systems, there is a great absence of work. This is mainly due to the current system; size, maturity, cost and complexity. The substantial lack of work and highlighted operational benefits of fuel cell technology signifies the large research potential this topic holds for the future. The work that has been completed to date has mainly focussed on simulation studies and is discussed below.

4.3 Fuel cell tri-generation systems for domestic built environment applications

Míguez [76] and Porteiro [88] state that the introduction of tri-generation systems to the domestic built environment requires the core of the system, the CHP unit, to be compact, cost efficient and easily installed. With the market introduction of commercially available fuel cell CHP units such as BlueGEN and GAMMA, the possibility of fuel cell tri-generation energy systems for domestic homes is becoming more realistic. Gigliucci, Petruzzi et al. [89] have conducted extensive work on fuel cell CHP systems in domestic built environment applications, in particular their thermal management. Conclusions drawn from their work include; the abilities of delivering the waste heat to a useful heat sink (tri-generation applications will increase this), capacity to vary the heat to power ratio and electrical output during operation are all critical for the full potential of the fuel cell device to be realised. Fuel cells with their lower heat to power ratios show great promise in terms of total thermal energy utilisation, illustrating why fuel cell technology has been highlighted as an obvious candidate for tri-generation domestic built environment applications [73].

Bhatti, O'Brien et al. [90] present a patent publication for a SOFC assisted air conditioning system based on solid desiccant and evaporative cooling technology. The aim of the system is to provide both comfort cooling and heating. The authors state that the most common technology to provide heating and cooling is a reversible heat pump; however these use electric power to drive the compressor. Desiccant enhanced systems are a low energy alternative to this. The thermal energy from the SOFC is used to regenerate a solid desiccant wheel which is used to address the latent load, whilst an evaporative cooler is used to address the sensible load. No performance data is available, however it is expected the system will provide a high system efficiency and energy reduction in comparison to a separate vapour compression, boiler and grid electricity system.

Pilatowsky, Romero et al. [91] have carried out simulation based work on a 1kWe PEMFC coupled to an absorption cooling system. The simulations were completed to determine the optimum operating conditions of the absorption cooler during the co-generation process; primarily the cooling capacity at maximum power output from the PEMFC. The absorption cycle was operated with a mono-methylamine water solution, with low vapour generation temperatures of around 80°C, ideal for PEMFC CHP applications. Results show that the co-generation process increases total efficiency of the fuel cell system, illustrating the feasibility of using fuel cells in small scale tri-generation applications. Results from the simulation include; (1) The CoP of the absorption cooler increases as the generation temperature (from the fuel cell) increases, reaching a maximum value and then dropping off (2) The cooling power increases with an increase of the electrical power from the PEMFC and evaporation temperature of the absorption cooler, but decreases with an increase of generation temperature, and (3) The co-generation efficiency is almost independent of the electrical power, but strongly dependant on evaporation and generation temperatures of the absorption cooler.

A 1.5kWe low temperature SOFC liquid desiccant tri-generation system has been proposed by Riffat [32] as an environmentally friendly way of providing heating, cooling and electricity to low carbon domestic buildings. It has been predicted that the described system running on hydrogen from the natural gas network will result in a 70% CO_2 emission reduction compared to a traditional energy production system comprising of separate condensate power plant, boiler and compressor driven cooling unit. The tri-generation system will be constructed at The University of Nottingham as part of the EU funded TriSOFC project [32].

To summarise, Section 4 has addressed fuel cell tri-generation systems. With recent advances in fuel cell CHP systems for domestic applications; the feasibility of fuel cell tri-generation systems for domestic applications is strong and shows great promise. It has been demonstrated that a fuel cell tri-generation systems can create substantial energy savings, leading to reduced atmospheric pollution and operational costs [13]. However, issues such as the accurate pairing of prime mover and cooling technologies needs careful consideration to ensure effective system operation. Also, the presentation of laboratory based results as opposed to real world examples can skew the predicted performance of such systems. The economic viability of any tri-generation system, particularly fuel cell, lies with the capital cost of the fuel cell, not cooling technology, which is already at a level commensurate with economic viability. Darwish [82] estimates a fuel cell cost of $2000/kW or below is required to permit the wider use of fuel cell tri-generation systems, a cost target figure Staffell and Green [44] believe is possible by 2020. The reviewed work on tri-generation systems using combustion based prime mover technology has shown that high cooling CoP, maximised electrical efficiency and low/stable gas prices are all required in order to make the tri-generation system concept a viable option for domestic built environment applications. Conclusions that will be largely applicable to the application of fuel cell technology in the domestic built environment. However, there are several barriers to be overcome in the development of tri-generation systems for domestic built environment applications. Currently, the components, particularly the heat driven cooling technology, of tri-generation systems of less than 10kW are still very much in the research and development stages. Higher initial (capital) cost and less supporting services mean there is less demand for such systems. There is a lack of incentives to stimulate the use of tri-generation systems, particularly on a domestic scale. In general, developmental barriers are more pronounced in smaller (micro) scale systems than they are in larger applications [17]. Currently an extensive gap in the literature exists regarding fuel cell tri-generation systems, particularly in domestic built environment applications. Literature found regarding fuel cell tri-generation systems has predominately been either larger commercial applications or simulation, with little or no work on experimental based domestic studies. There is therefore a clear need for experimental work in the field of fuel cell tri-generation systems in domestic applications. This is due to the large energy saving potential possible with both fuel cell technology and the tri-generation system concept.

5. CONCLUSIONS

This paper has served to provide a state-of-the-art review of fuel cell technologies operating in the domestic built environment as CHP and tri-generation systems. The review has been achieved through the assessment of; fuel cell technology, fuel cell CHP systems and fuel cell tri-generation systems. Throughout, up to date specific examples have been used to address the three main aims of the paper; (1) the operational advantages fuel cells offer in CHP and tri-generation system configurations, specifically, compared to conventional combustion based technologies such as Stirling engines, (2) how decarbonisation, running cost and energy security in the domestic built environment may be addressed through the use of fuel cell technology, and (3) what has been done to date and what needs to be done in the future. The paper concludes with an assessment of the present development of, and future challenges for, domestic fuel cells operating in CHP and tri-generation systems.

5.1 Fuel cell combined heat and power systems

This paper has highlighted the significant operational advantages fuel cells offer compared to conventional micro-CHP technologies, such as; higher electrical efficiencies, lower H:P ratios, reduced noise and vibrations during operation and flexibility of fuel use. The use of fuel cell technology can lead to significant reductions in CO_2 emissions and operating costs for the user. With regards to the type of fuel cells being used, the low temperature PEMFC and the intermediate to high temperature SOFC currently show the greatest promise, with most building integrated projects focussing on these two technological variants. The PEMFC offers quick start up time, power modulation and useful direct hot water output, whilst the SOFC provides high electrical efficiency, ability to internally reform hydrocarbon fuels and a high temperature heat output which can be utilised in another cycle. However, issues with the current PEMFC technology include the requirement of additional heating devices – the Baxi unit has a poor heat output and therefore requires an expensive water heater/store costing an additional £3000. The SOFC devices have a long start-up time - BlueGEN takes one day to warm up. It has been reported that in 2012 fuel cell technology outsold conventional combustion based systems for micro-CHP applications for the first time. This signifies a significant shift in the market and shows an exciting future for fuel cell technology. Currently there are many different estimates regarding the extent of CO_2 emission reductions delivered by fuel cells operating in the built environment. Sizeable reductions are achievable in the range of 1 – 2.5 tonnes/annum/house, however they are largely dependent upon a range of factors including; central electricity mix, the home's annual energy demand and electrical / total efficiency of the fuel cell system. Future work will aim to address these discrepancies with a standardised methodology to assess the environmental performance of fuel cell CHP systems in domestic homes. Issues of fuel cell CHP optimisation, particularly thermal, has been addressed, with district scale fuel cell operation and interaction being cited as an effective way to optimise the use of fuel cell technology in the domestic built environment. A variety of demonstration projects have been introduced, with the long running Japanese EneFarm project being by far the largest and most successful to date. EneFarm has facilitated the global expansion of the commercial fuel cell CHP market, seen in the number of commercialised units in Japan today. EneFarm should serve as a suitable case study for any future demonstration projects to learn from.

This paper concludes that fuel cell technology is a feasible technological option for domestic CHP built environment applications. This can be seen in increasing sales figures that now outweigh those of conventional combustion based technologies. However issues with cost, reliability, durability, and fuel supply still need resolving in order to effectively integrate the technology and permit it's wider and more effective use in the domestic built environment.

5.2 Fuel cell tri-generation

This paper concludes that domestic scale tri-generation has the potential to produce higher energy conversion efficiency and hence reduce net fuel cost and CO_2 emissions compared to a conventional combustion based CHP system. Currently there is very limited literature regarding fuel cell tri-generation systems, however one of the main aims of the review was to highlight the significant research potential such systems offer in domestic built environment applications. This has been achieved by looking at three core topics (1) commercial scale systems, which illustrate high system efficiency and reduced primary energy demand, (2) combustion based systems, which would benefit from a prime move technology with a higher electrical efficiency, such as a fuel cell, and (3) fuel cell tri-generation systems, although only simulation based work, they show high energy utilisation and future potential. A common conclusion with the fuel cell CHP review is that the cost of the fuel cell needs to fall in order to effectively facilitate the uptake of fuel cell tri-generation systems. The district concept also represents a significant possibility. By sharing the capital cost of the fuel cell in the CHP or tri-generation system it would make the current use of fuel cell technology a much more viable prospect. Most critically, the tri-generation review has highlighted the current, extensive and valuable research potential fuel cell tri-generation systems for domestic built environment applications offer. These systems should therefore be the focus of future investigations.

To conclude, decentralised energy generation from fuel cells in the domestic built environment can lead to emission reductions, reduced operational cost for the user and increased energy security, all essential objectives for the future built environment. Economic profitability is an essential criterion for any form of sustainable development [17]. Fuel cell CHP and tri-generation systems have shown throughout the review to offer the potential to produce real energy savings and thus economic benefit to the user. However as with any novel technology, a major challenge facing fuel cell technology is its capital cost. Until significant reductions in the capital cost of the technology can be made, be it through government support or technological innovation, the wider use of fuel cell technology in the domestic built environment cannot be expected.

If the UK and other countries are serious about their aspirations of a low carbon future, the built environment and the domestic sector in particular will play a critical role. In order to create a real transformation, both operational and technological changes need to occur. Nations can no longer rely on technologies of the past to help arrive at the destination of a low carbon sustainable society. Fuel cells are a technology of the future here today, providing a change in the way heat and power are supplied to end users. Fuel cells operating in CHP and tri-generation systems could finally provide the means by which energy generation can transfer from centralised to decentralised locales in a sustainable and effective manner.

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