Fuel Cells for Stationary Applications

Highlights

■ **PROCESS AND TECHNOLOGY STATUS –** Fuel cells are one of the cleanest and most efficient technologies for electricity and heat generation. They can achieve electrical efficiencies of up to 60% net AC, produce negligible air pollutants such as sulphur and nitrogen oxides, and emit relatively little CO_2 per unit of energy produced. Where they are fuelled with hydrogen they emit no CO_2 at all. The fundamental operating concept is the direct electrochemical conversion of a fuel (e.g. methane, hydrogen) into electricity and heat: charged ions passing through an electrolyte create a voltage difference between an anode and a cathode, and an electric current in an external circuit. This can be achieved in a variety of ways and as such there are several types of fuel cells, each of which utilises a different electrolyte material, operates at different temperatures (from ambient to >1000°C) and faces their own unique technical challenges. Fuel cell systems are applicable in a wide range of stationary applications, including large scale power generation, combined heat and power (CHP) for industry and buildings, off-grid energy and backup power services, but also in transport (vehicles) applications and for mobile power-packs. At present they are best categorised as an emerging class of technologies beginning to enter a phase of commercialisation, where cost reductions must be achieved alongside improvements in technical performance, particularly in relation to increasing their operating lifetimes. The recent successes in small scale residential cogeneration devices in Japan, and in large scale power supply projects in South Korea, suggest a bright future for this class of technologies is possible.

■ **TECHNOLOGIES, PERFORMANCE AND COSTS –** The main varieties of fuel cells in stationary applications are Polymer Electrolyte Membrane Fuel Cells (PEMFC), Solid Oxide Fuel Cells (SOFC), Molten Carbonate Fuel Cells (MCFC) and Phosphoric Acid Fuel Cells (PAFC). At present, PEMFC is the technology of choice for small scale residential applications with 40,000+ installations in Japan, whilst MCFC is mostly used for large stationary applications. However, SOFC is a strong contender in both of these segments with potential long-term advantages in terms of reduced balance-of-plant (BoP) requirements and top-end electrical efficiency. SOFC-based products are now entering the commercial market with rapidly growing market share. The performance of stationary fuel cell systems is focused on three high-level parameters; net electrical efficiency, overall efficiency in the case of cogeneration, and durability. Net AC electrical efficiencies are currently in the range of 30% - 50%, with overall (i.e. heat plus power) efficiencies up to 90%. In the future, net AC electrical efficiency could increase to 60%. Durability continues to be the crucial technical challenge, with lifetimes exceeding 40,000 operating hours required. Research on methods to avoid fuel cell power output and efficiency degradation over time is a focus of activity. In terms of costs, fuel cell systems are currently much more expensive than conventional alternatives such as gas turbines. Micro-CHP systems (with a typical size of 0.7 to 1kW_e) are currently approx. US$25,000 per system in Japan, whilst larger systems range from US$4,000 to US$12,500 per kW_e. However, larger systems may reach costs as low as US$3,000 per kW_e by 2020 while micro-CHP could become competitive at approximately US$3,500 per system in the long term.

■ **POTENTIAL & BARRIERS –** Given the range of applications, it is clear that fuel cells have enormous market potential. For the residential sector, a 10% market share in home heating is not unreasonable within the coming two decades. This would result in cumulative installation upwards of 70GW_e if limited to the key markets of Japan, South Korea, USA and Europe. Furthermore, scale-up of the size of large scale installations will drive growth over the coming decade and will push down costs. The IEA has projected a possible 5% share of total global capacity in 2050, but this could be an underestimate depending on technological progress. The positioning of fuel cells as ultra-clean flexible low-carbon generators opens opportunities for them to play an important role in emerging "smart" energy networks, balancing output from intermittent sources such as wind, and potentially being a cost-effective partner to other technologies such as heat pumps in the decarbonisation of heat supply. The key barriers for fuel cells are a current lack of appropriate financial support to underpin their market introduction and cost reduction by increased production, and some examples of poorly structured regulatory and market arrangements for small generators. Ultimately, fuel cell systems will need to be at least partially fuelled with renewable gases (e.g. hydrogen, bio-methane) to play a significant role in very low carbon energy systems.

PROCESS & TECHNOLOGY STATUS

Fuel cells are one of the cleanest and most efficient technologies for generating electricity and heat [1]. They convert a range of gaseous fuels, primarily methane or hydrogen, into electricity and heat. No combustion of the fuel is involved. Instead, the fuel undergoes electrochemical conversion directly into electricity and heat [2]. The fuel cell stack has no moving parts, operates without noise, and has zero or low pollutant and CO_2 emissions at the point of use. Their adoption can reduce national dependence on fossil fuels as an energy source, improve energy security and energy system reliability, and can be cost-effective [2].

Fuel cell systems are applicable in a large range of applications, including heat and power in residential and commercial buildings, high temperature processes and power in industry, off-grid power, backup power services, both light and heavy transport, and portable micro-scale

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power generation. This briefing covers only the "stationary" uses of fuel cells (i.e. it excludes transport, portable, and auxiliary power unit applications). Transport-related fuel cell information can be found in the ETSAP technology briefing T07.

There are a number of types of fuel cells. These are classified based on the chemistry of their operation. This in turn relates to the electrolyte material utilised and thus the electrochemical reaction of interest. The primary classifications are Polymer Electrolyte Membrane Fuel Cells (PEMFC), Direct Methanol Fuel Cells (DMFC), Solid Oxide Fuel Cells (SOFC), Molten Carbonate Fuel Cells (MCFC), Phosphoric Acid Fuel Cells (PAFC), and Alkaline Fuel Cells (AFC). A detailed description of each of these chemistries can be found in the Fuel Cell Handbook [1]. In the stationary energy sector, four chemistries are currently dominant; PEMFC, SOFC, MCFC and PAFC. The size range, operating temperatures, global production zones and other important metrics relating to each of these are presented in Table 1.

Figure 1 presents the basic concept: Each fuel "cell" is made up of the electrolyte material, anode and cathode, and supporting interconnect. In this case (SOFC), negatively charged ions pass through the electrolyte, creating the potential across an external circuit, leading to the flow of electrons (i.e. electricity generation). Numerous cells are connected to create the fuel cell "stack", and thus increase electricity generation capacity. Finally, a full fuel cell "system" is created by integrating the stack with all required balance-of-plant (BoP) including heat exchangers, control system, after burner, blower, and (potentially) a fuel reformer (Fig. 2).

■ Key Applications of Stationary Fuel Cell Systems

The main applications for stationary fuel cell systems are: large prime power and combined heat and power (CHP, also known as cogeneration) systems, micro-CHP, uninterruptible power supply (UPS), and off-grid power. Each of these applications is described in the paragraphs below. An example schematic of a simplified full fuel cell system, in a CHP configuration, is shown in Figure 2.

Large stationary systems are configured to provide either power only, or combined heat and power. System sizes range from tens-of-kilowatts to tens-of-megawatts. The main technology in this size range is currently MCFC, but SOFC systems are experiencing very rapid growth. PAFC also has some market share, while PEMFC is primarily focused on smaller stationary applications. A good example of application of large stationary MCFC systems is that of POSCO Energy, which is installing MW-class systems to meet a Renewable Portfolio Standard in South Korea [3].

Fuel cell micro-CHP systems are typically in the range of 0.7 to 1kW$_e$, sized to serve a single-family dwelling. However, the definition can include larger systems to serve multi-family dwellings, up to 5kW$_e$. At present the main fuel cell technology type in this market is PEMFC, principally the ENE-FARM brand in Japan [4]. However, SOFC and high-temperature PEMFC chemistries are also beginning to enter this market with demonstration projects underway in several regions including Japan and Europe

Table 1 – Key technical characteristics of the main fuel cell systems in the stationary market [6]

	PEMFC & HT PEMFC*	IT SOFC & SOFC*	MCFC	PAFC
Typical capacity range (kW$_e$)	0.3 - 250	0.7+	100+	50+
Typical electrical efficiency (%, LHV, gas fuelled)	30-40%	47%	45-50%	26-35%
Operating temperature range (C)	80 - 200	650 - 1100	650	200
Units shipped in 2011	20,400	600	<500	<500
Capacity shipped in 2011 (MW$_e$)	49.2	10.6	44.5	4.6
Main production zones	North America, Asia, Europe	North America, Australia, Europe	USA, Korea	USA, Japan

*"HT PEMFC" refers to high temperature PEMFC, operating in the 160-200C range. "IT SOFC" refers to intermediate temperature SOFC, operating in the 500-700C range.

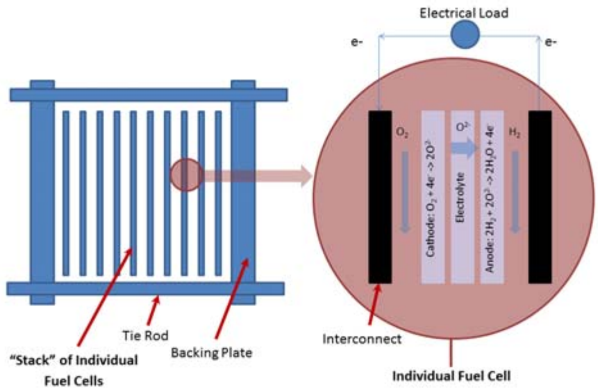

Fig.1 – Diagram illustrating the components of a single SOFC "cell", and "stack" of cells.

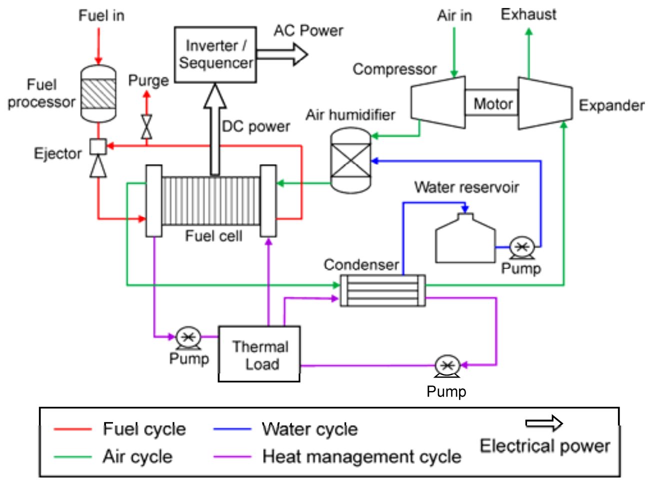

Fig.2 – Diagram illustrating the main features of a fuel cell CHP system.

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(e.g. the Ene.field and Callux projects in Europe). Osaka Gas recently released a 0.7kW$_e$ SOFC-based micro-CHP system in Japan which reportedly achieves a 10-year lifetime [5].

With regard to UPS and off-grid applications, fuel cells have some important advantages over battery banks and engines/turbines. They are able to continuously operate over long periods where fuel is available, have a relatively small footprint, have low maintenance requirements, and can be installed in sensitive environments where low emissions and low noise are required. In remote locations, the higher per-kW$_e$ cost of fuel cell systems is offset by avoiding the cost and environmental impacts of extending the existing electricity grid to the site.

■ Global Fuel Cell Market Developments

While still very small relative to conventional power generation, the commercial market for stationary fuel cell systems is becoming significant. The number of system shipments almost doubled between 2010 and 2011, and the capacity shipped more than doubled. In terms of number of systems, the stationary market is dominated by PEMFC, where small-scale residential systems in Japan, Europe and USA feature prominently. The largest single market is for residential-scale PEMFC in Japan, where the ENE-FARM brand has successfully reduced costs (see the cost section below), and at the time of writing had shipped more than 40,000 systems [7].

In terms of capacity (kW$_e$) of systems shipped, MCFC and PEMFC have approximately equal shares, followed by SOFC which is growing very rapidly, and may have some advantages over other chemistries in the long-term. The size of prime power installations based on multiple parallel fuel cell systems also continues to increase, with installations in the tens-of-megawatts range beginning to emerge (e.g. in Korea [8]). This trend will increase aggregate installed capacity significantly in coming years. Also, applications in data centres continue to drive up demand for large-capacity fuel cell systems [9].

According to a recent industry review [6], the increasing market size trend is set to continue, with the number of systems shipped projected to triple in 2012. Looking further into the future there is no immediate reason to expect market growth to slow, with increasingly diverse applications of fuel cell systems, and a number of active demonstration programmes underway.

TECHNOLOGIES & PERFORMANCE

The fundamental characteristics of performance for stationary fuel cell technology relate to engineering design to improve system efficiency, and stack durability to ensure adequate longevity. System size and power density are also relevant metrics, although less important for the stationary sector. The following sub-sections describe the current status of the four main fuel cell technologies in the stationary sector, focusing on their inherent qualities in this regard.

■ Solid Oxide Fuel Cells (SOFC)

Solid oxide fuel cells utilise ceramic electrolytes. Relative to other chemistries, they may have important advantages due to the reduced need for fuel reforming (e.g. methane can be fed directly to the stack in some systems, a process called “direct internal reforming”), and high temperature operation leading to high grade heat output. The ceramic electrolyte materials become oxide ion conductors at relatively high temperatures of 500-700°C for “intermediate temperature” (IT) varieties, and 850-1000°C for regular systems. The conversion efficiency performance of SOFC systems can be exceptional, with reported electrical efficiencies up to 60% [10]. However, the majority of systems occupy the 40%-50% net AC range, such as the recently released Osaka Gas unit at 46.5%, and overall efficiency of 90% [11].

The high operating temperatures bring opportunities and challenges. The challenges revolve around the reliability of materials and balance-of-plant (BoP) at high temperatures, and stresses created in the stack during thermal cycling (i.e. intermittent on/off operation of high temperature fuel cell systems can cause rapid degradation). Intermediate temperature systems have advantages in this regard because they can be supported by conventional metal (steel) interconnects, whereas higher temperature systems must rely on more exotic materials such as chromium alloys or electrically conducting ceramics. The benefits of high temperature operation are primarily high grade heat output from the system, opening opportunities in combined cycle applications, serving industrial process heat demands, or easily heating buildings and providing steam or hot water.

In general the durability of the stack is a primary challenge, where material degradation reduces efficiency and capacity of the system over time, sometimes leading to failure. This degradation can be rapid, limiting stack lifetime to a few years. Yet for systems to be economically competitive, lifetimes of 40,000-50,000 hours are needed. Low degradation and improved lifetime, along with cost reduction, are primary technical challenge for SOFC developers.

■ Polymer Electrolyte Membrane Fuel Cells (PEMFC)

PEMFC systems exist in low (~80°C) and high temperature (~180-200°C) varieties, and use proton conducting ionomer (ionic polymer) electrolytes in modern cells. PEMFC systems currently achieve relatively long lifetimes with good tolerance to thermal cycling, but face challenges in long-term cost reduction due to fundamentally complex BoP requirements whenever pure hydrogen is not available. Reported electrical efficiencies are in the range of 30-40% LHV (net AC), and overall (heat + power) efficiency approaches 90% in CHP mode in some models.

Most PEMFC systems rely on platinum catalysts to ensure adequate reaction kinetics and thus power density. These materials are expensive and effective substitutes are scarce. However, good progress has been made to reduce platinum loadings (e.g. [12]), and this issue is less pronounced in terms of contribution to PEMFC system cost.

In low temperature systems, very pure hydrogen is required to fuel the stack, and certain impurities in the fuel

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can cause rapid degradation in performance. Higher temperature varieties of PEMFC can reduce but not remove the impact of some of these issues, with improved tolerance to carbon monoxide and sulphur, and therefore reduced requirement for complex BoP in the fuel processing stages (and thus potentially lower production cost).

The primary technical challenges for PEMFC developers are simplification of design and improvement of the efficiency in fuel processing stages. Any reduction in the number of stages of fuel processing or efficiency enhancement in this area will improve system performance by reducing parasitic loads on the system and reducing thermal losses.

■ Molten Carbonate Fuel Cells (MCFC)

The electrolyte in MCFC systems is lithium-potassium carbonate salts, operating in molten state at approximately 650°C. Like SOFC systems, MCFC benefits from direct internal reforming of fuels, reducing the need for complex BoP in the fuel processing stages. Also, like SOFCs, they do not require expensive catalyst materials. Both of these aspects favour reduced system costs.

Principal challenges for MCFC systems include relatively low power density, they therefore require large surface areas to achieve adequate power output. MCFC also require carbon dioxide from the exhaust stream to be re-circulated to the cathode to maintain the chemistry of the carbonate electrode, resulting in more complex BoP arrangements and associated cost elements. Furthermore, the carbonate electrolyte is corrosive in nature, leading to materials challenges. Finally, operation of MCFC is complicated by inability to allow the molten electrolyte to solidify without acute degradation. Therefore the system must be maintained at temperature even in standby mode, leading to low average efficiency in situations where the system is not base-loaded [13]. MCFC stacks typically have short lifetimes of the order of 5-years, after which the stack can be replaced within the existing BoP [14].

Despite these challenges MCFC systems currently lead the large stationary market, and have been deployed in arrays of tens-of-megawatts in some instances [8]. The key technical challenge is in increasing longevity.

■ Phosphoric Acid Fuel Cells (PAFC)

PAFCs use a phosphoric acid electrolyte, suspended in a silicon carbide structure. They have a relatively long history of commercialisation, and as such more opportunity to reduce capital cost through learning-by-doing, although sales have not yet been robust enough to support economies of scale in manufacturing. Due to relatively low power density, PAFC systems are best suited to large CHP installations.

Like PEMFC, PAFC stacks require hydrogen to operate, and a fuel reformer is included in the BoP. Even though the stack has relatively high tolerance to carbon monoxide (CO) in the incoming fuel, a gas-shift stage (i.e. CO to CO_2) is still included in the fuel processing BoP to reduce CO concentration. This requirement adds a cost element to PAFC systems.

Furthermore, methods developed in the 1990s to avoid degradation of the catalyst supports resulted in an increase in the necessary platinum loading, which further exacerbated costs [15]. Platinum loadings account for 10 – 15% of total PAFC system cost [14]. Therefore reduction in platinum loadings is an important area for future development.

CURRENT COSTS & COST PROJECTIONS

Details of current and future cost estimates available in the literature are presented in Table 3 (see the final page of this briefing). However, the reader should note that current selling prices may not reflect production cost in this relatively immature market (e.g. in some cases selling price is very high to recover R&D costs, and in other cases subsidised to encourage sales growth), and as such all cost-related estimates, both current and future projections, should be treated with caution.

■ Current Costs

At present, the price of fuel cell systems is relatively high when compared with competing prime power and combined heat and power equipment.

Small PEMFC and SOFC could reasonably be classified as pre-commercial, and system prices are currently in the range of \$25,000 - \$50,000 per kW_e. Despite these relatively high costs, more than 40,000 PEMFC systems have been installed by paying customers in Japan (at the lower end of the price range stated above). And even though this programme has been heavily subsidised by government, consumers are still purchasing the systems at a price several multiples above that of competing home heating and hot water appliances.

MCFCs and PAFCs are fully commercialised and tend to be targeted at larger systems, as a consequence the cost per kW_e of these fuel cell varieties occupy the \$4,000 - \$4,500 per kW_e range [14].

It has been reported that a substantial portion of total fuel cell system cost is attributable to the BoP, rather than the stack itself. For some systems, only 10-20% of total system cost is in the stack for small and large applications [16, 17]. Fuel processing stages tend to occupy a substantial share of system cost.

■ Projected Future Costs

Some government agencies have published targets for future fuel cell system capital cost. In the USA, the Department of Energy (DoE) has revised targets for small PEMFC to \$1,200/kW_e by 2015 and \$1,000/kW_e by 2020 [18]. However, the National Renewable Energy Laboratory (NREL) recently challenged these targets, and instead suggested that selling prices in the range \$5,000 - \$7,000 per kW_e are more reasonable in the near term (if 50,000 systems output were achievable 2012 - 2015) [19]. In essence, it appears there is some gap between technical realities and cost targets, and specifically which components of balance-of-plant are included within each target figure (e.g. DoE targets appear to exclude a backup boiler and hot water storage tank).

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The Japanese ministry METI/NEDO has also published targets for fuel cell system cost in micro-CHP applications, at a more reasonable $3,500 per kW_e [20]. Table 2 shows the selling price reduction of ENE-FARM brand systems between 2004 and 2011. Substantial year-on-year selling price reductions are evident, suggesting that learning rates are fast and fuel cell based micro-CHP may become competitive with conventional technologies in the future.

The future costs of PEMFC and SOFC in micro-CHP applications have been estimated empirically by Staffell and Green [16, 20]. They noted that the prices offered by several manufacturers are falling by 15-18% for each doubling of cumulative systems shipped. They found that despite this, prices are unlikely to reach cost targets proposed by DoE of $1,000 per kW_e. Instead a long term target in the range of $3,000 - $5,000 per kW_e was proposed given the current pace of development and limitations imposed by the fundamentally intricate nature of complete fuel cell systems. However, this analysis only considered learning-by-doing based on relatively limited historical data. Fuel cell technology may jump to a different price reduction trajectory in future if breakthroughs are made.

For larger systems, long term capital cost projections are scarce. Figure 3 shows the projection from the Energy Information Administration's Annual Energy Outlook (AEO) 2010/2011. Substantial cost reductions are predicted. By 2035 cost has been halved, and it is clear the expected downward trajectory should continue further into the future.

As stated above, BoP accounts for a large portion of total system cost. Because much of a fuel cell system BoP employs new techniques and novel engineering solutions, there could be substantial scope for breakthrough cost reduction in this area. It may be possible for fuel cell systems to thereby ultimately reach lower costs.

POTENTIAL & BARRIERS

■ Growth Potential

The fuel cell market has enormous growth potential. The number of fuel cell applications is expanding, average size of installation is increasing for large applications, and important markets are becoming more realistic commercial propositions such as micro-CHP in Japan, South Korea, Europe and the USA. However, there is significant uncertainty regarding when or if future potential will be realised, primarily because significant cost reductions must be achieved and technical barriers overcome.

The residential sector market may be the first to step towards commercialisation, as evidenced by the phenomenal growth of fuel cell micro-CHP in the years up to the time of writing in Japan. The European Commission SETIS project expects "full commercialisation" as of 2015 for the residential market [24]. Likewise, IEA projections indicate a commercial market for fuel cell micro-CHP of 72,000 systems installed per year by 2020 for the European market [25]. However, given the speed of growth in Japan, the projections of developments may turn out to be underestimates.

In the large-size stationary market, economies of scale in

Table 2 – Selling Price for ENE-FARM systems 2004 - 2011

	Average sale price (currency base year)
2004	$106,000 [20] (2004 $US)
2005	$67,000 [21] (2005 $US)
2006	$51,000 [21] (2006 $US)
2007	$42,000 [21] (2007 $US)
2008	$29,000 [21] (2008 $US)
2009	$29,000 [21, 22] (2009 $US)
2011	$24,000 [7, 11, 22] (2011 $US) SOFC released at similar selling price

***US$1 = 115 Yen approximation as per [20]. All figures rounded to nearest $1,000. Selling prices do not necessarily reflect the cost of production of systems, and do not include government subsidies. Installation cost are not included.**

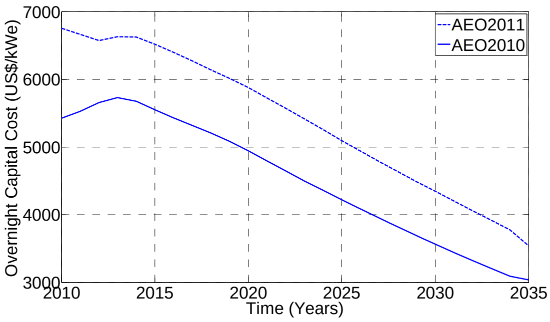

Fig.3 – Projection of overnight capital cost of large stationary fuel cell systems over time used in the EIA Annual Energy Outlook [23].

manufacturing, simplifications in fabrication methods, and technological developments should be able to reduce selling prices in future, but the extent of price reductions may be limited. The increasing average size of installations should fuel significant growth for the coming decade, but given price uncertainties growth beyond that becomes less certain. A market projection study for MCFC and PAFC systems has been undertaken by ORNL [26], suggesting that by 2025 MCFC systems could be entering the US market at approximately $340MW_e$/year, and PAFC systems at $380MW_e$/year. SOFC systems are also likely to become important in this size range, having experienced significant percentage-wise growth in recent years.

The IEA has estimated the total cumulative capacity installed at $200\text{-}300GW_e$ by 2050 [27], but this could be an underestimate given the current levels of growth, rate of selling price reductions, and trends towards low emissions and low pollutant sources of power and heat. A 10% share in the home-heating market is not implausible in Japan, USA, South Korea and Europe. Such a scenario would result in roughly 70 million cumulative micro-CHP installations, as early as 2030. Should long term cost reduction be achieved and micro-CHP becomes competitive with conventional home heating systems, total market share could be even higher.

A further important growth area is in relation to the emergence of "smart" energy networks, and more integrated approaches to energy system decarbonisation. As fuel cells are dispatchable, have high part-load efficiency, and low CO_2 emissions, they could be an ideal balancing partner for intermittent power generation (i.e. the

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fuel cell will generate power to balance system demand and unpredictable output from wind, wave, tidal and solar electricity sources). With regard to integrated approaches to decarbonisation of heating, it has been noted that distributed CHP such as residential fuel cells could offset the need for investment in transmission, distribution and generation assets associated with the electrification of heat, where they are installed alongside heat pump systems [28, 29].

■ Non-technical Barriers

The primary non-technical barriers for fuel cell systems are related to regulation, availability of financial support, and ultimately the availability of renewable or low carbon fuels.

Some connection regulations for decentralised generation are restrictive. For example, some regulations require generators to be periodically switched off, which is not conducive to longevity in fuel cell systems. Some other regulations do not sanction financial reward for generators exporting electricity to the grid. Furthermore, support for emissions reduction achieved from fuel cell systems can be hard to access, with high transaction costs.

Given their early stage of commercialisation, fuel cell systems usually still require financial support. Support mechanisms come in the form of grants (e.g. Japan), enhanced depreciation allowances for commercial applications (e.g. Japan, USA, UK, Germany, Italy), feed-in tariffs (e.g. UK), and fuel price discounts (e.g. Germany). The level of support provided by these schemes varies greatly, with marked impact on uptake in each country. Examples of successful programmes include the grant systems in Japan, and the tax credit system in the USA. In the short-to-medium term, fuel cell systems will require some form of public support to stay on the path to stand-alone competitiveness. At the time of writing the fuel cell industry appears to be going through a maturing phase with focus on manufacturing methods, quality control, safety systems, system control and balance of plant (as opposed to fundamental R&D for stack design). Continued support through this period will be critical.

Finally, for fuel cell systems to play an important role in long-term energy systems, the fuel they use must be at least partially decarbonised (or be renewable). As shown in [29], the emissions reduction achieved by fuel cell systems is related to the CO_2 content of the fuel utilised and the electricity grid emissions rate. As the grid decarbonises (a fundamental aspect of many long term climate stabilisation pathways), the emissions saving afforded by fuel cell power generation reduces where it is fuelled by natural gas. Therefore, in the long term, fuel cell systems should be fuelled by methane or hydrogen from low carbon sources, enabling them to play a significant role in a future long term, low carbon, secure and affordable energy systems.

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Table 3 – Summary Table - Key Data and Figures for Fuel Cell Systems

Technical Performance	Typical current international values and ranges			
Energy input	Hydrogen, Natural gas (methane), Biogas, Landfill gas			
Output	Electricity, Low Grade Heat (PEMFC, PAFC), High Grade Heat (SOFC, MCFC)			
Technology variant	PEMFC	SOFC	MCFC	PAFC
Typical capacity size, kW_e (*)	0.3 - 250	0.7 and upwards	100 and upwards	50 and upwards
Net LHV Electrical Efficiency, %	30-40% [19, 22]	47% [11]	45-50% [14]	26-35% [30]
LHV Overall Efficiency (Heat + Power), %	85-90% [19, 31]	85-90% [11, 19]	80%	72% [32]
Lifetime, hours	30,000 [19]	30,000 [19]	40,000 [14]	60,000 [14]
Operating temperature, °C	80-200	650-1100	650	150-220
Start time (from cold), mins	20 [19]	60 [19]	No start/stop	Assume as PEMFC
Availability, %	97% [19]	97% [19]	95% [14]	97% [33]
NO_x (kg/MWh) (#)	Near zero	Near zero	0.005 [14]	0.016 [33]
SO_x (kg/MWh) (#)	Negligible	Negligible	0.0005 [14]	0 [33]
PM_{10} (kg/MWh) (#)	Negligible	Negligible	0.000005 [14]	Negligible

(*) Fuel cells are modular in nature. Therefore many systems can be connected together to create large installations, currently with tens-of-megawatts capacity.
(#) Differences in air pollution metrics between fuel cell varieties could be considered negligible. All systems have extremely low emissions.

FC System Costs	Typical current international values and ranges (2010 US$)			
Technology Variants (*)	PEMFC	SOFC	MCFC	PAFC
Typical investment costs $/$kW_e$ (#)	$25,000 (0.7$kW_e$)	$25,000 (0.7$kW_e$) $7,000-$12,500 (>100kW_e) [34]	$4,000 [14]	$4,500 [14]
Typical O&M costs	$500/year (5$kW_e$) [26]	$100/$kW_e$/year (assumed)	$500/year [26]	$700/year [26]
Typical cost breakdown, %	17% stack, 83% BoP	-	-	-

(*) PEMFC; Polymer electrolyte membrane fuel cell. SOFC; Solid oxide fuel cell. MCFC; Molten carbonate fuel cell. PAFC; Phosphoric acid fuel cell
(#) Exchange rate $US1 = 100 Yen, based on approximate PPP average 2008 – 2012. Higher figure for SOFC >100kW_e range appears to include installation costs, whilst other figures exclude installation.

Data Projections for 2020	Future international values and ranges – 2020-2025			
Technology Variants	PEMFC	SOFC	MCFC	PAFC
Max. LHV Electrical Efficiency (%)	40% [19]	50-55% [11]	48-50%	35%
Max. LHV Overall Efficiency (Heat + Power) (%)	87-90% [19, 22]	90% [19]	85%	85%
Start time from cold (mins)	15 [19]	30 [19]	No start/stop	Assume as PEMFC
Lifetime (hours)	40,000 [19]	40,000 [19]	40,000	60,000 [14]
Investment cost ($/kW) (*)	$4,000-$6,000 [21]	$4,000-$6,000 [21]	$3,000 [23]	$3,000 [23]
Installed capacity	1GW micro-CHP globally (i.e. 1,000,000 1kW_e systems – authors' estimate) 340MW_e/year (MCFC, USA only) [26] 380MW_e/year (PAFC, USA only) [26]			

Data Projections for the long term	Future international values and ranges – long term*			
Technology Variants (*)	HT-PEMFC	SOFC	MCFC	PAFC
Max. LHV Electrical Efficiency (%)	45% [19]	50-60% [11, 19]	50%	35%
Max. LHV Overall Efficiency (Heat + Power) (%)	90% [19, 22]	90% [11]	85%	85%
Lifetime (hours)	40,000 – 60,000	40,000 – 60,000	40,000 – 60,000	60,000 [14]
Investment cost ($/kW)	$3,500 [16]	$3,500 [16]	No data	No data
Cum. installed capacity (GW)	70 (micro-CHP, or 10% market share in home-heating in Europe, Japan, South Korea and the USA), 200-300 [27] (large systems, or 5% global capacity)			

(*) "long term" here refers to achievement of approximately 70 million installations for small scale systems, and/or 200/300GW_e large systems. This could happen as early as 2030. Note that all data presented for "long term" is highly uncertain.