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MARK THROWER MANAGING EDITOR

Fuel Cells for Stationary Applications

By Dr Chris Jackson MBA, B.Eng, C.Eng, FEI

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In 2015 the global fuel cell industry comprised around 200 companies, with sales revenues of about $2.2bn, shipping 50,000 fuel cell systems with a total capacity of 180MWe. The global installed fuel cell generating capacity is 1 GWe. Major uptake continues in North America and Asia Pacific, accelerating more slowly in Europe.

Within the last decade, fuel cells (FCs) have been widely demonstrated in markets (and applications) such as portable power (consumer electronics and generators), transport (automotive, material handling, locomotive, marine, submarine and aerospace) and stationary power generation (combined heat and power (CHP) and backup power).

Fuel cell systems are currently operated by 10 per cent of Fortune 500 companies and 25 per cent of the top 100. This includes: Walmart, Apple, General Motors, General Electric, Ford, IBM, Boeing, Microsoft, Procter & Gamble, UPS and Google. It is not surprising therefore that local governments, particularly in the US and Korea, are now installing FCs at facilities that provide critical city and county services, such as administrative centres, prisons and wastewater treatment plants.

A fuel cell is an electrochemical device which converts the chemical energy of a reaction directly into electricity, without intermediate steps. It is therefore inherently more efficient and significantly less polluting than combustion-based technologies.

The phenomenon was first demonstrated in the 1830s, however, its application at the time was overshadowed by the internal combustion engine. Development continued at a comparatively slow pace, and in the 1960s and 70s NASA employed the technology as a reliable source of electricity and drinking water for astronauts.

In recent decades, FCs have been the focus of a great deal of research due to their combination of high efficiency (about two times that of incumbent power generation) and absence of combustion, resulting in substantial CO_2 emission savings and the near elimination of pollutants and particulates from power generation. High efficiency, power quality, low emissions, grid-independent and oil-independent credentials are all of particular strategic interest to governments.

Conceptually, a fuel cell is similar to a battery. The anode and cathode are separated by an electrolyte, through which ions can flow, but electrons cannot. Electrons are freed in an electrochemical fuel oxidation reaction, occurring at the anode. The electrons are then forced by the electrolyte to flow as direct current through an external circuit (e.g. an electric engine). Finally, they take part in a subsequent oxidant reduction reaction at the cathode. Simultaneously, ions flow through the electrolyte, which completes the electrochemical circuit.

The fuel used at the anode varies depending upon the type of FC; hydrogen and natural gas being the most common, while the oxidant is the oxygen contained in air. Unlike a battery, which may require replacement or recharging for extended periods, the FC can be fed continuously with fuel and oxidant and operate indefinitely.

In addition to the direct current generated, water and heat are also useful by-products lending fuel cells to both heat and power-led CHP applications.

The voltage of an individual FC is limited by thermodynamics, however, like batteries, FCs can be connected in series to increase net voltage, creating a fuel cell stack. In doing so, one must ensure that there is a suitable strategy for replenishing fuel and oxidant, and for removing by-products of water and heat from each cell in the stack. Employing balance of plant components (pumps, fans and heat exchangers) to do this incurs some small parasitic losses.

In order to increase current, one can increase the size (reaction surface area) of each cell. Additionally, the rate of reactions at the anode and cathode must be accelerated by either catalyst materials or high temperature operation. These strategies have advantages and disadvantages, as catalysts are costly and sensitive to impurities, while high temperature operation limits system flexibility.

As power is the product of voltage and

Produced in Association with energy institute current, the above factors are optimised to design a system for a specific application. The electrolyte performs several key roles. Direct interaction between the fuel and oxidant would result in combustion and fuel inefficiency. To prevent this, the electrolyte must act as an impermeable physical separator. It must also allow ions flow through it, hence it must be thin and conductive enough to minimise ohmic losses (compounded by the addition of many cells to form a stack, resulting in electrical inefficiency).

There are four main fuel cell types, classified by electrolyte, that represent the majority of sales to date including PEMFC, PAFC, MCFC and SOFCs.

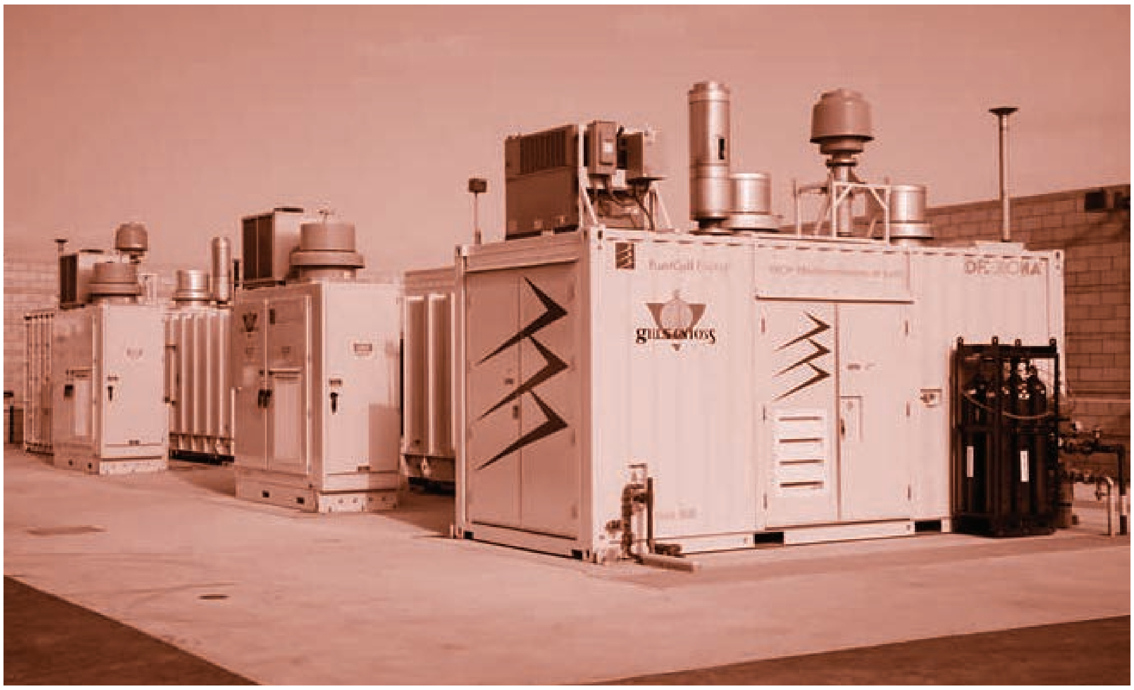
Polymer Electrolyte or Proton Exchange Membrane Fuel Cells (PEMFCs) power 90 per cent of systems shipped to date. They have an efficiency of 50 per cent and typically operate at 80°C, as their thin membrane electrolyte must remain hydrated to maintain suitably low ionic resistance (high proton conductivity). Low temperature operation dictates the use of platinum-based catalysts, which are sensitive to impurities, however it also avoids the production of NOx and the clean hydrogen fuel requirement ensures that SOx is minimal.

PEMFCs offer rapid start-up and dynamic response and the highest volumetric and gravimetric power densities of all the FC types. This lends them to fuel cell electric vehicles (FCEVs) including bikes, cars, buses and material handling vehicles up to around 200kWe.

PEMFCs are also the most widely used type in stationary, residential and light commercial mCHP systems (1 to 3kWth) due to their 1:1 heat to power ratio and generation of low grade hot water. Their demonstrated lifetime for stationary applications is in the order of 30,000 hours on-load.

Phosphoric Acid Fuel Cells (PAFCs) have been commercially available for three decades. There are more than 400 systems installed in 15 countries with a total capacity of 85MWe. Units have efficiencies of 35-50 per cent and are appropriate for mid- to large-scale commercial and industrial buildings (100 kWe-1 MWe). PAFC systems employ hydrogen fuel and liquid acid electrolyte that operates at about 150-220°C. At this temperature they are less sensitive than PEMFCs to fuel impurities, but they also have a much larger footprint and slower start-up times.

Molten Carbonate Fuel Cells (MCFCs) employ a molten alkali carbonate electrolyte operating at 600°C, with up to 55 per cent efficiency. At this temperature nickel catalysts can be used with a wider range of fuels including hydrogen, reformate, synthetic natural gas and synthetic coal gas; internal reformation is also possible. MCFCs are the market leader for large stationary applications and grid-scale electricity production (3 to 60MWe). Research is focused upon improving stack lifetimes, which currently stand at five years due to the aggressive chemistry of the system. Despite this, sales are growing and prices have fallen by ca. 60 per cent since initial field trials in 2003.



Solid Oxide Fuel Cells (SOFCs) represent 10 per cent of global sales; they operate at temperatures from 750°C up to 1,000°C. SOFCs provide the highest electrical efficiency (60 per cent) and greatest fuel-flexibility, but their ceramic electrolyte tends to be operated in "always-hot" mode to improve durability and avoid material fatigue. SOFCs have achieved 40,000 hours on-load and are available in mCHP (1 to 3kWth), CHP and large-scale stationary generation (100kWe to 1MWe).

Other fuel cell types include the Alkaline Fuel Cell (AFC), which is still used by NASA in space missions, and the Direct Alcohol Fuel Cell (DAFC), which is a subset of PEMFCs being used to extend the run times of portable electronic devices.

Capital costs remain a major hurdle for fuel cell proliferation. The cost of residential mCHP has fallen by 85 per cent in the last decade in Japan, as production has expanded. If these trends continue, one might expect a cost of £4,500 to £9,000 for the millionth residential system in five years. However, currently the price of a 0.7 kWe PEMFC or SOFC is ca. £12 to 16,000 in Japan; while the larger MCFC and PAFC systems cost £2,500–£3,500 per kWe.

The main areas for further cost reduction include: reduced system complexity, fundamental design improvements, reduced catalyst content, extended lifetime, standardisation of auxiliary components and mass production techniques.

TÜV-SÜD has developed a 'green hydrogen' standard for the sustainability of hydrogen fuel sources. Hydrogen is not readily found in nature and is currently generated most cost-effectively by Steam Methane Reforming (SMR) of natural gas. On a well to wheel basis, the hydrogen produced in this way (and used in FCs) remains more efficient than internal combustion. There is also tremendous scope for biogas from anaerobic digestion and potentially wastewater treatment plants, with the number of German biogas feed-in stations more than quadrupling over the past five years. Increasingly, direct electrolysis of water is also used.

General understanding of FCs and hydrogen as safe, reliable and comparable to existing boiler technology is key to their acceptance. The chemical properties of hydrogen are well understood, and safety standards exist for its generation, storage, transportation and use. Hydrogen has no smell, its flame is invisible and its overall risk of ignition within a building (or confined space) is higher than for natural gas. However, in natural gas-based FC mCHP systems, hydrogen is generated on-demand as it is used. Hence, very small amounts of hydrogen are present at any given time, making safety considerations very similar to those for conventional gas boilers.

Residential fuel cells are currently larger than gas boilers, comparable to a fridge-freezer, weighing ca. 200 kg and having a 2m2 footprint (including the hot water tank and supplementary boiler). Noise levels are also similar to those of a boiler, and recent improvements in both PEMFC and SOFC technology project operating lifetimes of up to ca. 60-80,000 hr for PEMFCs and up to 90,000 hr for SOFCs.

Commercial fuel cells are also larger than boilers, with 400kWe systems occupying a small shipping container and weighing ca. 30 tonnes. Systems are modular and allow for modular maintenance without full system down time. Larger 2MWe systems would occupy the area of a tennis court.

Cradle to grave emissions averaged over the system lifetime for FCs equate to ca. 10–20 gCO_2/kWhe, or 8-16 gCO_2/kWhth of heat, these are comparable to solar PV and Nuclear power, at 40–80 gCO2/kWh and 10–30 gCO_2/kWh, respectively.

The stationary FC market includes prime power, backup power, combined heat and power and residential applications. Systems can range from several kilowatts to multiple megawatts in size. FCs exhibit particularly high energy efficiencies (electrical efficiency of up to 60 per cent, and greater than 90 per cent in CHP), resulting in considerable primary energy savings, while avoiding transmission losses.

Backup and Remote Power: FCs provide reliable power for telecommunications networks, which, in many cases, are located in remote areas without a reliable grid. Greatest activity is in India and Africa, with increasing interest in the Middle East and China.

Micro Combined Heat and Power: PEMFC and SOFC systems of 0.7-0.75kWe and total efficiencies of 80 to 95 per cent outsold engine-based micro-CHP systems for the first time in 2012, taking 64 per cent of the global market (28,000 sales worldwide). When deployed in the UK, such systems are reported to cut emissions to 1.3-1.9tCO2/year in a four-person household (35-50 per cent reduction).

In the domestic and light commercial market segments there are three large field trial projects that demonstrate the maturity of the technology and reduce the cost: Ene-farm, Ene-Field and Callux.

In Japan, the Ministry of Economy, Trade and Industry (METI) outlined its plan to expand hydrogen and fuel cell mCHP roll out to 1.4m by 2020 and 5.3m by 2030. By the end of 2015, their Ene-farm initiative had deployed 140,000 Toshiba, Panasonic and Kyocera natural gas fuelled FC systems, with accelerating uptake, despite reducing subsidies.

Table 1 – Applications for fuel cells in the UK

Location	Wattage
Walkie Talkie Building, London	300 kWe
Woking Park Leisure Centre	200 kWe
Berwick Housing Association	1.5 kWe
West Beacon Farm	2 & 5 kWe
BRE Garston, Watford	2.4 kWe
Black Country Housing	1.5 & 5 kWe

More recently, the latest EU-wide initiative, Ene.field, has begun to deploy 1,000 systems across 12 member states. This project involves nine manufacturers (including Baxi, Bosch, Viessmann and Vaillant) and utilities (including E.ON, British Gas, Dong Energy). The EU forecasts 50,000 systems deployed by 2020.

Industrial: The market for industrial and utility scale units is largely in South Korea and the US, due to state and federal programmes focused on energy security. In South Korea, Seoul City intends to increase its electrical independence to 20 per cent by 2020. In related projects, Gyeonggi Green Energy Park became the largest FC park in the world (59 MWe) in 2014, comprising 21 fuel cell power plant modules and providing continuous base load to the electric grid, as well as heat for a district heating system. Other installations include Pyeongteak City power plant (100 MWe), receiving an additional 360MW by 2018, and West Incheon Power Plant (16 MWe), which sells heat energy to district heating schemes.

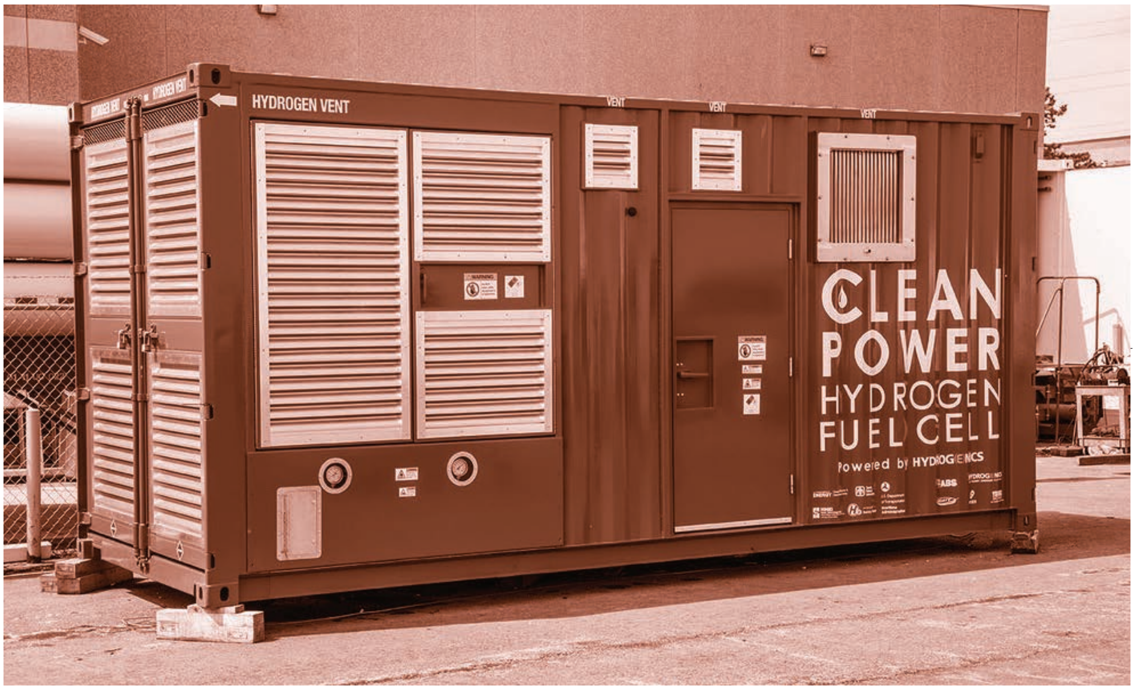
In the US, Apple operates a facility with a 10-MW FC system (providing 37 per cent of site energy) with a solar PV, in North Carolina, completely off grid. This facility eliminates 92 kTCO2 per year. In California, Sutter Santa Rosa Hospital operates a 375 kWe FC system generating 70 per cent of the hospital's electricity. While in Santa Clara County four FC installations power the county's Government Center (400 kWe), Main Jail North (1 MWe), Berger Service Center (400 kWe) and Elmwood Correctional Facility (800kWe). Washington Gas Energy Systems will finance, build, own and operate the fuel cell system, selling all energy generated to the County under a 20-year power purchase agreement.

In sharp contrast, the UK has few large-scale deployments, see Table 1. One of the more recent examples is the installation of a 300kWe MCFC in the 'Walkie-Talkie' building in London. This system is large enough to power 800 UK households with an efficiency of up to 90 per cent in CHP configuration. In a single year of operation, the fuel cell will prevent the emission of more than 18 tonnes of pollutants and 1,800 tonnes of CO_2.

The UK government has been active in recent years through the H2Mobility UK Project, culminating in binding commitments from Fuel Cell Vehicle OEMs, fuel companies and supermarkets to begin vehicle and hydrogen infrastructure roll out in the UK. Additionally, the Mayor of London has set targets to supply ca. 25 per cent of London's energy from decentralised sources and to reduce CO2 emissions by 60 per cent, both to be achieved by 2025.

The UK has two centres of excellence dealing with demonstration of the technology by the Centre for Process Innovation (CPI) at Teesside and development of the UK industry at Cenex (Centre for Excellence in Fuel Cells) in Loughborough.

It appears that, despite significant global activity and demonstration, designers in large scale UK building projects may be unaware of the benefits presented by fuel cell technology, its readiness and the support available from both the UK and EU.



Web Resources

www.sciencedirect.com, Dodds, (2016), Hydrogen and fuel cell technologies for heating: A review

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http://enefield.eu/
https://www.now-gmbh.de/en

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ENTRY FORM

FUEL CELLS

Please mark your answers on the sheet below by placing a cross in the box next to the correct answer. Only mark one box for each question. You may find it helpful to mark the answers in pencil first before filling in the final answers in ink. Once you have completed the answer sheet in ink, return it to the address below. Photocopies are acceptable.

QUESTIONS

1. Which of these statements about fuel cells is incorrect?

☐ They are electrochemical devices
☐ They convert the chemical energy of a fuel into electricity without combustion
☐ They produce low pollutant emissions
☐ They have a low capital cost

2. Compared with traditional electricity generation a fuel cell is?

☐ Ten times as efficient
☐ Five times as efficient
☐ Twice as efficient
☐ Half as efficient

3. Which pair of the following fuel cell types are suitable for mCHP applications?

☐ Phosphoric Acid (PAFC) and Molten Carbonate (MCFC)
☐ Solid Oxide Fuel Cells and Phosphoric Acid (PAFC)
☐ Phosphoric Acid (PAFC) and Polymer Electrolyte Membrane Fuel Cells
☐ Solid Oxide Fuel Cells and Polymer Electrolyte Membrane Fuel Cells

4. At the time of writing, how many mCHP units were installed by the Ene-farm programme?

☐ 5.3M
☐ 1.4M
☐ 140,000
☐ 1,000

5. What percentage of the top Fortune 500 Companies now operate Fuel Systems?

☐ 50 per cent
☐ 25 per cent
☐ 10 per cent
☐ 5 per cent

6. What generating capacity is provided by the largest UK FC installation?

☐ 1MWe
☐ 400 kWe
☐ 300 kWe
☐ 100 kWe

7. Which of the following is not true of hydrogen as a fuel?

☐ It occurs naturally as a fuel
☐ Can be produced by reforming natural gas
☐ Is available from carbon-neutral sources of methane
☐ Can by produced by the electrolysis of water

8. What is the latest estimate of SOFC operating life time (in hours)?

☐ 100,000
☐ 90,000
☐ 80,000
☐ 60,000

9. Which Fuel Cell Type provides the highest electrical efficiency and greatest fuel flexibility?

☐ Phosphoric Acid Fuel Cells
☐ Molten Carbonate Fuel Cells
☐ Polymer Electrolyte Membrane Fuel Cells
☐ Solid Oxide Fuel Cells

10. Which fuel cell type power ca. 90 per cent of systems shipped to date?

☐ Phosphoric Acid Fuel Cells
☐ Molten Carbonate Fuel Cells
☐ Polymer Electrolyte Membrane Fuel Cells
☐ Solid Oxide Fuel Cells

Please complete your details below in block capitals

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