Fuel Cell Technology from Materials to Application: A Comprehensive Review

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Abstract: The renewable energy problem is becoming more vital due to increasing environmental pollution and instabilities in oil prices globally. Among numerous renewable energy sources fuel cell has been consider one of the most beneficial energy conversion system due to its low cost, high efficiency and low emission of environmental pollution. However, before gaining a significant share in power market, some important points need to be addressed. These points are choice and selection of proper fuel, introduction of new materials as alternate in the fuel cell stack. The present paper provide a comprehensive review on fuel cell technologies, advantages/disadvantages and appropriateness towards commercial application. We also review the advances in the field of materials design in fuel cell and analyze the challenges in the development of new models and application.

Keywords: Renewable energy; Fuel cell;Solid electrolyte; Cathode; Interconnects.

1. Introduction

Fuel cell is an electrochemical energy-conversion device, which offers tremendous promise for delivering high electrical efficiency and significant environmental benefits in terms of fuel flexibility (hydrocarbons, and municipal waste), as well as clean and efficient (>70% with fuel regeneration) electric power generation [1-2]. A SOFC produces useful electricity by the reaction of fuel with an oxidant via diffusion of oxide ions (or protons) through an ion-conducting solid-electrolyte layer [3]. The life time of PEM fuel cell is a prominent problem in its use, and is also one of the main factors hindering its commercialization. The life time of a fuel cell on a vehicle is about 2500–3000 h [4] much shorter than the life time of a fuel cell operating as a fixed power sources which is over 30 thousand hours [5]. Regarding the application of fuel cells in a vehicle, many factors affect its life time, as fuel cells make use of the air in the outer environment during its operating, hence the impact of environmental pollution factors are a reason for its degradation [6–9]. Fuel cells operating at lower current may cause degradation of the catalyst layer and lead to the reduction of the fuel cells voltage [10-11]. Poor control of the anode and cathode pressure difference, low humidity, high stack temperature, and shortage of reaction gas may lead to gas

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starvation [12–14]. Successive hydration and dehydration process of the membrane electrode assemble may cause permanent damage to the fuel cells [15]. Effective diagnostic techniques are particularly important to the attenuation and degradation of the fuel cells. Tian *et al.* [16], through the analysis of experimental data, showed a diagnostic method of practical significance, ensuring that the diagnosis does not open the stack and does not destroy the proper functioning of other single cells.

The power output of a stack is ideally a linear sum of the power output of all the individual cells placed in series or parallel in the stack, and its durability and lifetime should be that of the worst cell of its all corresponding cells in the stack. However, these ideal targets have not yet been achieved. he question of how to bring these technologies out of the laboratory and engineer practical systems for power production at industrial scales are particularly challenging and exciting [17–21]. Critical areas being addressed by DOE's Fuel Cell Technologies Office (FCTO) [20] include low durability and high cost, advanced manufacturing, improvements in hydrogen storage and production technologies, and mechanisms to achieve cost-effective hydrogen distribution and dispensing infrastructure. Despite several successful pilot projects around the world, to date none have proven to be cost-effective, durable, reliable and efficient enough to widely replace the traditional methods of generating power, such coal-fired, IC engine, gas turbine, hydroelectric, or even nuclear power plants except for some specific applications [21]. Major technical barriers of fuel cells are not only durability but also reliability. The reliability may be more important than durability for acceptance by endusers but receives a little attention. Reliability is the likelihood that a fuel cell stack will not fail without maintenance, repair and overhaul within a specific time period [19]. Therefore, the durability, reliability and cost of fuel cell systems after scaling-up remain the most critical issues before fuel cells can achieve a reasonable penetration into the portable, stationary, and transportation energy production markets [17–19,22,23].

Heat generation in buildings and industry accounts for more than half of global final energy consumption and a third of global energy-related carbon dioxide (CO_2) emissions [24]. There is widespread acceptance that current hydrocarbon fuels used for heat generation will need to be substituted by low-carbon alternatives if global greenhouse gas emissions are to be reduced sufficiently by 2050 to avoid dangerous climate change [25]. Electrification of heat provision, using air or ground-source heat pumps, is one strategy. District heating (using low-carbon fuels), solar heating and biomass are other potential options [26-27]. Fuel cells and hydrogen have received less attention in the literature, but could potentially generate low-carbon heat and electricity while avoiding some of the practical consumer acceptance issues faced by other low-carbon technologies (see Refs. [28-29] for examples of these issues). Japan and Korea have deployment programmes for residential fuel cell micro-CHP1 [30-31], while larger fuel cells have penetrated the commercial heat market in the USA [32].

PEMFCs are ideally suited for transport [33], Combined Heat and Power (CHP) and mobile auxiliary power applications. Among the many attractive features, the high power density, rapid start up and high efficiency makes the PEMFC the system of choice for the

transport manufacturers. The aforementioned features are further enhanced when combined with their simple modular design [34], low weight and the stationary electrolyte in the form of a solid polymer membrane [35]. There have been many advances in the development of low temperature PEMFC (LT-PEMFC), for example power densities have increased when varying the electrode assembly methodology. Power densities increased from approximately 93mWcm_2 at 0.6 V when using the PTFE bound method to 147 mWcm_2 at 0.6 V when using a thin film transfer method [36]. Higher power densities of 233 mW cm_2 have been achieved by using commercially available electrodes [37]. Recent studies show that power densities of 680mWcm_2 can be achieved [38] for LT-PEMFC. A power density of 100 mWcm_2 at 160 _C was obtained when using a commercial HTPEMCELTEC-P1000 MEA produced by BASF [39]. This is a much lower power density than that found for the LT-PEM electrodes because of the large activation loss found with the use of acid based membranes.

The objective of this paper is to review advances in flow field of materials and designs of fuel cells, and analyze main issues and challenges in concepts and criteria of flow field of designs and in the development of application models. We focus on why uneven flow distribution is a root cause of low durability and reliability at the industrial scale and why flow field designs are a strategic solution to integrated performance, flow conditions, structure and electrochemical processes. Finally, we will discuss fundamental materials, characteristic parameters and procedures to tackle the challenges of uneven flow distribution during fuel cell scaling-up as well as critical issues of durability, robustness and reliability in the application field.

2. Materials

The development of high-performance SOFC involves materials selection and operational-related issues (of anode, cathode, electrolyte, sealant, and interconnects), Fig. 4. These challenges open up myriad research opportunities for researchers in the field of SOFC. A list of various materials used in SOFC is presented in Fig. 5. From 2010 to the present, the electrolyte-free fuel cell with one layer/single component devices were proposed to fulfill low temperature operation requirement [40]. Two-phase nanocomposite functional materials for low temperature (LT: 300–600 _C) SOFCs were successfully developed and demonstrated. Since 2010, many researchers from all over the world (see Table 1) have worked on ceria-carbonate composites for low temperature SOFCs following Zhu *et al*. introduction to nanocomposite electrolyte [40]. In two-phase nanocomposite materials, the desired superionic conduction occurs at the interfaces of the electrolyte at low temperature (300–600 °C) [41]. Zhu [42] has also worked on single component/layer fuel cell devices by integrating both ionic and semiconducting material in a single layer. This single-component alone can perform the function of energy conversion; so this is a very new approach to fuel cell research and development, and would serve as a great breakthrough in the arena of hydrogen production and fuel cell development [43-44]. In spite of the consistent progress by researchers regarding the understanding of the material requirement and their electrochemical behavior, the commercialization of SOFC is still inadequate because of significantly high cost of SOFC-based power systems, which is a

key issue to pervasive commercialization of SOFCs. To make SOFC systems more economically viable, and thus, reduce system costs, the incorporation of lower cost stainless steel into the stack design is one of the solutions.

However, these steel parts need coatings against protection of air-facing surfaces from high temperature oxidation. In addition, it is also necessary to minimize volatilization of chromium from the alloy, as chromium vapors poison the cathode and degrade the cell's overall SOFC performance. Lowering the operation temperature of SOFC and using a less expensive metallic interconnects is one of the solutions for reducing the maintenance cost. But, this occurs with high ohmic losses of the electrolyte (i.e., reduced ionic conductivity) and lower catalytic activity of the electrodes, which deteriorate the cell performance. In order to improve the cell performance at lower temperatures, the proposed alternates are use of very thin electrolyte (few micrometers) and nanoscale materials for the electrodes and electrolytes [45]. Apart from cost, thermal–mechanical stability is one of the key issues for SOFC fabrication. Residual compressive or tensile stresses generating from CTE mismatch with the substrate, may result in buckling and failure of the each component layer of SOFC. It was reported by Baertsch [46] that deposition technique can also affect the extent at which residual stress is generated in the electrolyte films. The main challenges of the operation of SOFCs at high operating temperatures (800–1000 ºC) include: 1. Extended startup times: Herein, a period of fuel burning is required in order to reach the operating temperatures. Hence, start-up times for SOFC operation are prolonged. 2. Exert sealing problems and requires expensive interconnect and integration of materials for SOFC stacks. The relative CTE of adjoining materials mandates good sealing that does not react with joining parts. In addition, tapping of useful power requires the connection of SOFC units with interconnects, and thus, the balance of the stack also requires a good integration of these sections. 3. It can induce thermal stresses at electrolyte–electrode interfaces, as well as cause interdiffusion between cell components. High temperature thermal cycles not only induce a substantial thermal stress on the materials, but it also increases the diffusion kinetics which can change the chemistry of the adjoining components. Hence, these aspects must also be kept under consideration during SOFC operation. Fig. 1 shows the detail of fuel cell structure and related information.

The main objectives for all researchers in the development of novel membrane materials are to increase the performance and durability and to reduce the overall cost of fuel cells [47]. The targets incorporate the most important characteristics for PEMs, i.e. high conductivity, good thermal, mechanical and chemical stability, acceptable durability, compatibility with other fuel cell components, materials that are easy to work with and that can be recycled in an environmentally friendly manner [48-49]. Although the DoE target temperature is 120 ºC, many researchers are aiming for temperatures up to 200 ºC as increased temperature leads to increased CO tolerance of the electrocatalyst [50]. CO tolerance is understood to mean operation in the presence of CO with voltage loss at the hydrogen electrode of less than 10-20 mV [51]. CO tolerance is related to the thermodynamics of competitive CO and H_2 adsorption (and fractional coverage, q) on the platinum surface of the catalyst. Fig. 2 shows the fractional coverage for different
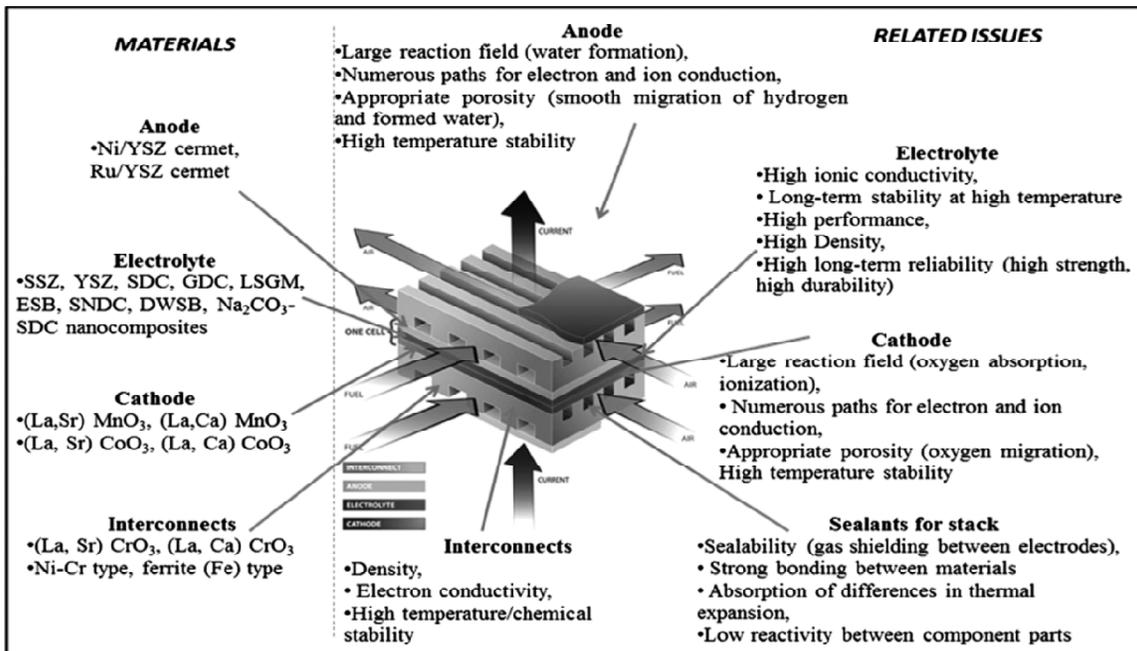
Figure 1: Materials and related issues for SOFC. (Adapted from Ref. [41] and ttp://nino.mse.ufl.edu/ Nino_Research_Group_research_electronics.htm).
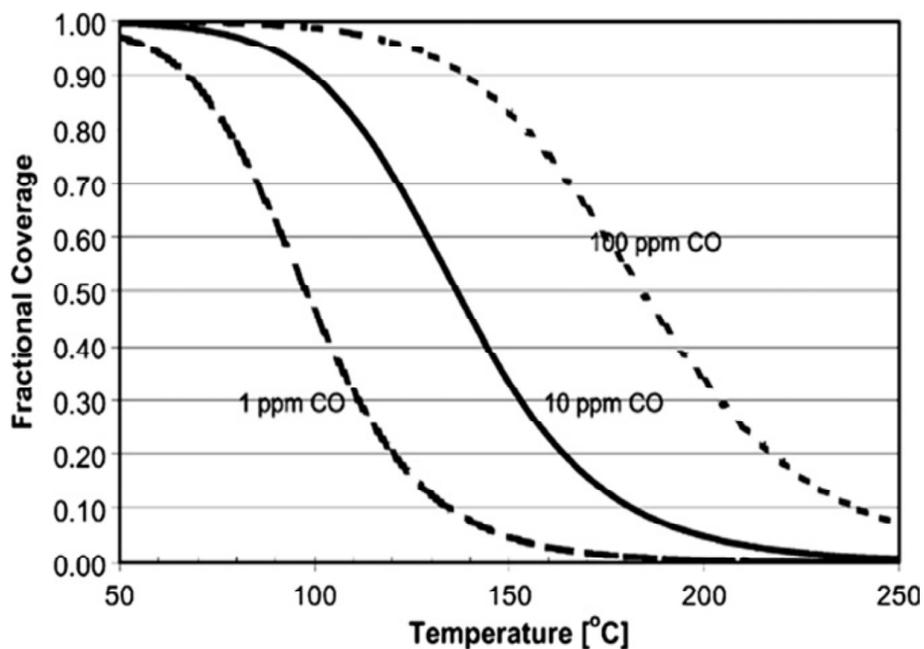
Figure 2: CO coverage on a platinum surface at a hydrogen pressure of 0.5 bar. Different concentrations of CO is shown [53]

concentrations of CO at varying temperature. It has been shown that CO should be below 0.9 for tolerance. The dissociative adsorption of H_2 becomes more thermodynamically beneficial at higher temperatures than the associative adsorption of CO so at higher temperatures enough hydrogen is adsorbing on platinum sites for adequate hydrogen reduction. A 2005 cost analysis [52-53] of an 80 kW HT-PEMFC system projected a cost of 56 US $/kW for the MEA, assuming production of 500,000 units which represents 83% of the cost of the stack.

There have been many comprehensive reviews on PEMs[54-73]. The PEM can be considered in two parts. Firstly, the polymeric membrane material, including the backbone, the side chains and any fillers or support materials that have been added to enhance the material desirable properties. Secondly, the proton carrier, which is either water or an ionic medium such as phosphoric acid (H3PO4) or an ionic liquid such as 1-butyl-3-methylimidazolium tetrafluoroborate (BuMeImBF4) [74]. For all types of proton carriers there are similar considerations. Firstly, the membrane material must absorb an optimum amount of this medium; too much weakens the membrane, too little results in inadequate proton conductivity. Secondly, the membrane material must retain the maximum amount of the medium under operating conditions over a long period of time (5000 h for transport use, 40,000 h for stationary use). The loss of the conducting medium results in the reduction of conductivity, degradation of the membrane, damage or flooding of the electrodes and blockage of flow field plate (FFP) channels. Conductivity takes place via diffusion or proton hopping. The mechanism that takes place depends upon which proton conducting medium is present. Fig. 3illustrates the different mechanisms for water, phosphoric acid and an ionic liquid (1-butyl-3-methylimidazolium bis (trifluoromethyl sulfonyl) imide). Water containing membranes include Nafion_, other fluorinated membranes and a large class of sulfonated aromatic hydrocarbons. The non-water membranes include acid base systems such as polybenzimidazole (PBI) doped with phosphoric acid and materials rendered conductive by ionic liquids. To increase the uptake of the proton carrier, the concentration of the polar group (acid or base) on the polymer backbone must be maximized. In Table 2 the chemical structure for some of the most common base polymers used for PEM materials are shown. Nafion is usually obtained commercially as a film or as a 5 or 10 wt% solution in water and alcohol. Nation_ is synthesized by reacting tetrafluoroethylene (TFE) with sulfonic acid to form a sultone. The sultone is converted into an acid fluoride with a sulfonyl fluoride end group which is then reacted with hexafluoropropylene oxide and pyrolysed to form sulfonyl fluoride perfluorovinyl ether. Copolymerization of this product with TFE in a per fluorinated solvent leads to a fluorinated precursor (SO3F) which can be neutralized to the salt form (SO3Na) or hydrolysed to the acid form (SO3H) [75]. The alternatives to Nafion_ are described below:

3. Load Cycling

Many scholars studied the dynamic process of the fuel cellsdegradation in the past. Silva *et al*. [76] conducted 8 small fuel cellsstack load cycling aging test, where they discovered that after 1500 h test the power of the stack have decayed 34%. Since Load
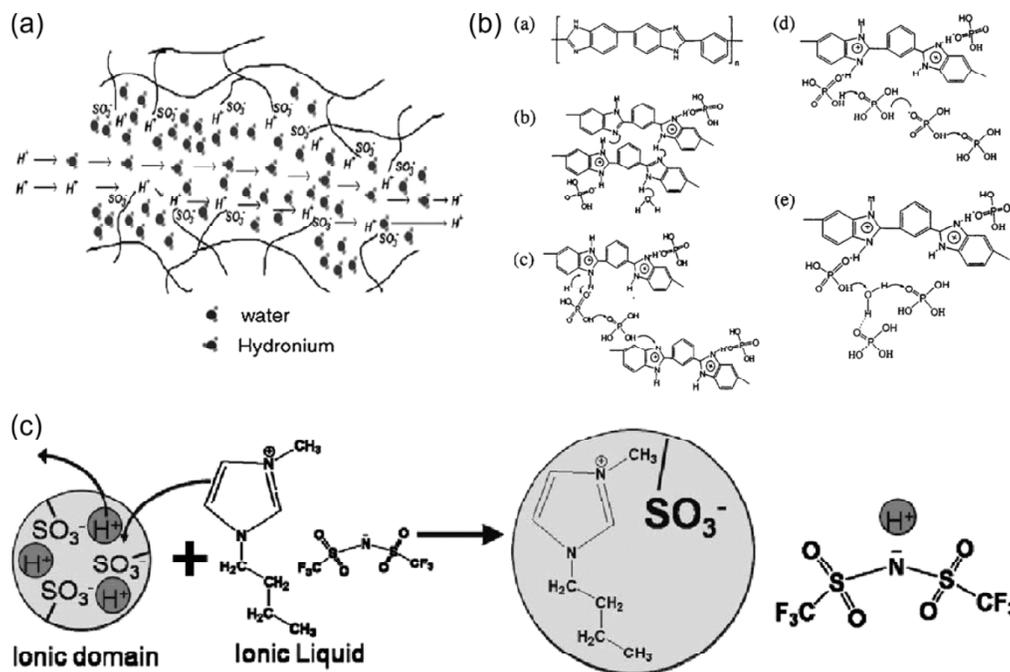
Figure 3: Proton conduction in (a) water, (b) phosphoric acid and (c) ionic liquids (1-butyl-3-methylimidazolium bis (trifluoromethyl sulfonyl) imide) [74-75].

cyclinghas a great impact on the catalyst layer, active area of the catalystdecreased 17.6%. With the carbon corrosion, the thickness ofthe electrode decreases, and the Teflon ionomer on the catalystlayer also decays severely. Rong *et al*. [77-78] exploited the rate-dependentisotropic plasticity model, using finite element analysis tostudy the microstructure change of the catalyst layer caused bythe load cycling process. Simulation indicates that after series ofload cycling test, cracker and lamination emerged on the catalystlayer. They pointed out that these phenomena can be used as thebasis to judge the fuel cells performance degradation. Jung *et al*. [79] studied the durability of PEM fuel cells using an accelerated degradation technique. The technique was performed by applying 1.5 V to an MEA with hydrogen and nitrogen feeding to the anodeand cathode, respectively, to simulate the high voltage generated during fuel cell shut down and restart. Bose *et al*. [80] used a100W 10 cells stack conducted load cycling test, and observed irreversible degradation at about 480 h. According to the attenuation, the predicted life of the stack is 1700 h. In order to simulate the real driving condition of the automotive fuel cells, Liu *et al*. [81] conducted fuel cells degradation test through load cycling, they found the hydrogen stoichiometric ratio in creased due to the pinhole formed in the membrane. On the contrary, the hydrogen permeability keeps constant under steadystate. And the fluoride-ion concentration under load cycling is 30times of under steady state. Fig. 4 depicts the fuel cell performance and degradation due to different operating conditions.
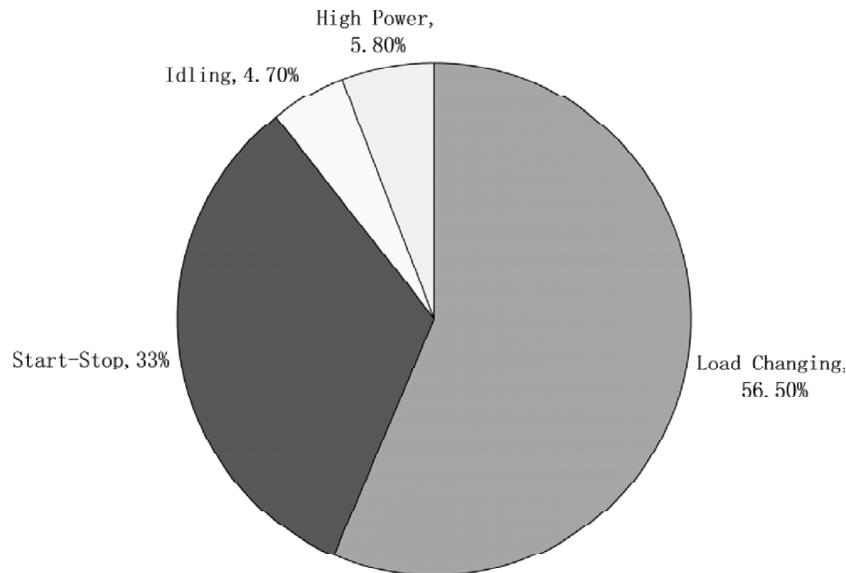
Figure 4: PEM fuel cell performance degradation rate caused by different operation conditions [76]

Pei *et al.* [82] studied fuel cells performance degradation underdifferent operating conditions, they distinguished the effect of loadchanging cycles, start–stop cycles, idling time and high power loadfour typical driving conditions on PEMFC lifetime. The degradationrate of the fuel cells performance on the simulating driving conditionis proved to be a sum of the degradation rates of four typicaldriving conditions. And they presented a prediction equation forfuel cells lifetime that relates to load changing cycles, start–stopcycles, idling time, high power load conditions, and air pollutionfactor [83]. Based on the practical data gathered from a fuel cellbus and the test results of a fuel cell stack in laboratory, the calculatedlifetime matches the fuel cell bus real working lifetime verywell. The study showed that automotive fuel cell lifetime heavilydepends on driving cycles. They presented the results of a fuel cellbus trial which run at an average speed of 32 km h^{-1}. After the fuelcell bus ran 35,000 km, in about 1100 h, the cell voltage dropped10% below the limiting electrical voltage, which caused the fuel cellstack power decrease more rapidly [84].Fig. 5 shows a fuel cell stack continuous operation 1800 h with hydrogen stoichiometric number was two and oxygen stoichiometric number was four. They observed the uneven cell voltage distribution inside the stack. It operated 300 h under full load and 1500 h under partial load.

4. Electrode assembly

A typical stack setup can be seen in Fig. 6 the components of which are described in the following section with respect to their role in mechanical compression Fig. 6 demonstrates the basic components that make up a single cell. Hydrogen is fed to the anode and air/ oxygen to the cathode through flow field plates, which distribute the reactants evenly
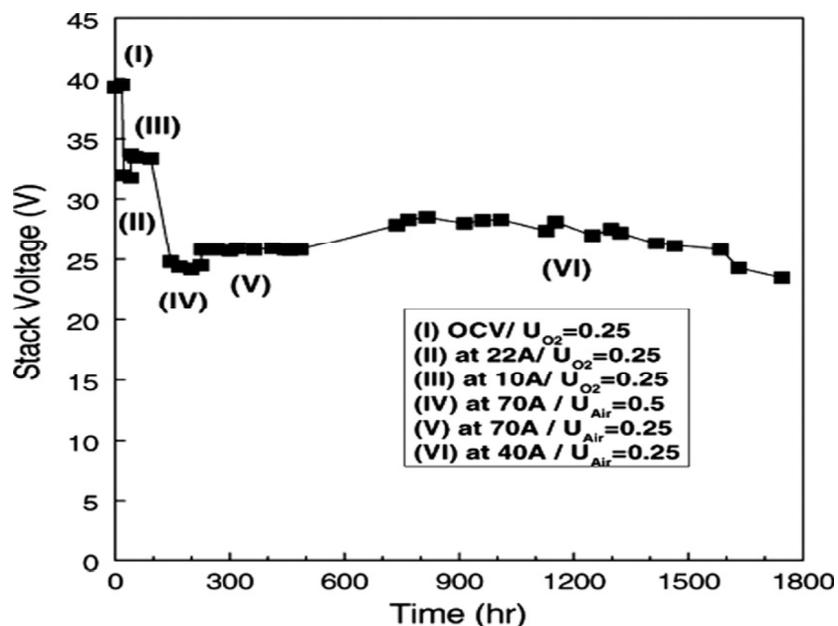
Figure 5: Fuel cell stack continuous operation 1800 hwith hydrogen stoichiometric number was two and oxygenstoichiometric number was four [84].
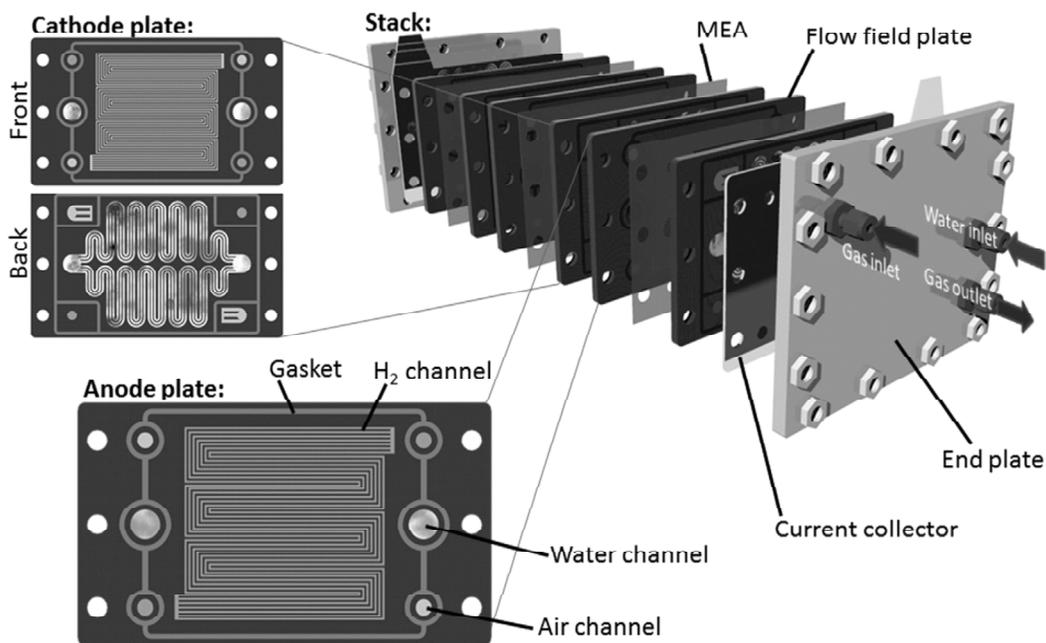
Figure 6: Stack assembly of PEFC including 'exploded' stack shown in upper right, cathode and anode plates shown on left highlighting gas, water and sealing channels. Bipolar plate design shown is based on that of Pragma Industries, France. [85]

across the electrodes. The gas diffusion layer (GDL) allows these reactant gases to diffuse under the lands of the flow-field plate (Fig. 7) to the catalyst layer (CL) where reaction occurs. Often, a micro porous layer (MPL) made up of carbon and a hydrophobic agent, is applied to the GDL surface between the CL and the GDL. In order for reaction to take place in the catalyst layer, reactant gas, catalyst particles and ionic conductor (electrolyte) must all meet to create a triple phase boundary (TPB) [85]. Protons generated by the hydrogen oxidation reaction (HOR) migrate through the electrolyte to react at the cathode with oxygen and recombine with the electrons that have travelled through the external circuit, creating useful current and water by-product. Water can travel through the membrane via two different mechanisms; from anode to cathode via electro-osmotic drag arising from the movement of protons through the membrane, and from cathode to anode due to the higher concentration of water at the cathode creating a hydraulic diffusion gradient. The PEFC electrode is made up of the GDL, MPL and CL and when the electrolyte is sandwiched between two electrodes and hot-pressed together, under pressure and heat, they form the membrane electrode assembly (MEA) which can be considered as the essence of the fuel cell [86].

Flow field plates (FFP) provide the structural integrity to the stack, along with gas distribution and heat dissipation. The flow field grooves within the plate are referred to as the 'channel'. The plates also act as current collectors allowing for transport of electrons
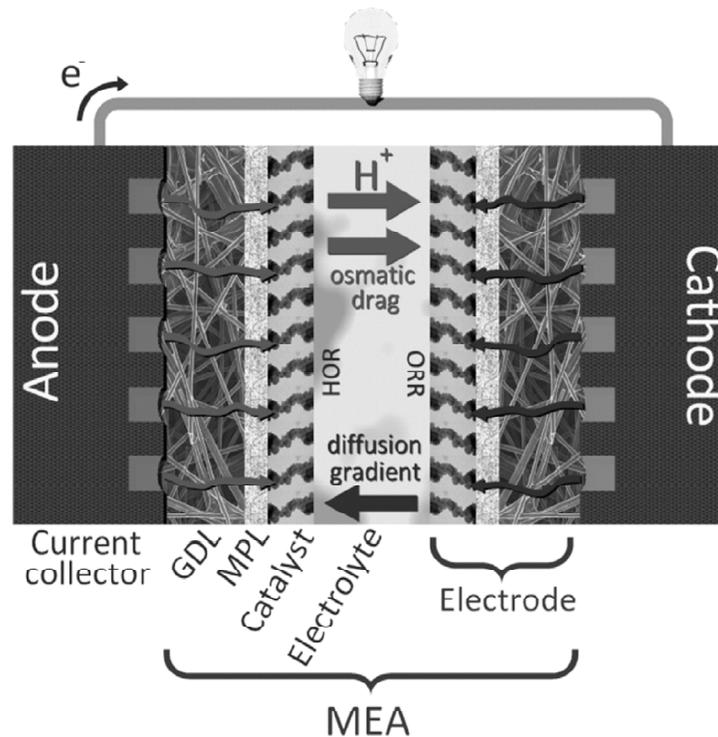
Figure 7: Schematic of a PEFC showing proton, electron and reactant movement throughout the cell as well as water transport [86]

to and from each cell; the term bipolar plate is used when a single plate acts as the current collector for both the cathode of one cell and the anode of another. Electrical connectivity is achieved where the FFP is in contact with the electrode, known as the 'land'. Each end of the stack houses the final current collectors where the electrons are passed onto an external circuit, on the outside of which are the endplates which house the whole stack and introduce the gas reactants and coolant fluid for internal manifold flow plates. The fuel and oxidant manifolds are distributed across each MEA by individual fuel networks. Pin flow fields have a network of series and parallel flow paths. This design has a low reactant pressure drop across the plate, but can lead to channeling and stagnation as the gases will follow the path of least resistance, which can cause reactant depletion in some areas. Parallel/straight flow designs often have poor gas distribution and water management and can also lead to different gas distribution across the whole stack. Serpentine flow fields solve many of the issues with parallel flow, as the reactant is forced to travel across the whole area of the electrode. However, as there is a long path length, there can be a significant pressure drop and flooding can occur. Using multiple serpentine fields can ensure water removal and lower the reactant pressure drop; however, the path length is still relatively long. Inter-digitated designs consist of interlocking, dead-ended flow fields which force convection of gases through the diffusion media,normal to the electrode surface (as opposed to parallel, as with thepreviously mentioned designs). As this involves forced convectioninstead of diffusion, the gas delivery to the electrode is muchimproved, as well as the removal of water from the electrodestructure. However, it involves a large pressure drop and thereforemay require compression of the gases which increases the parasiticpower loss in the stack.
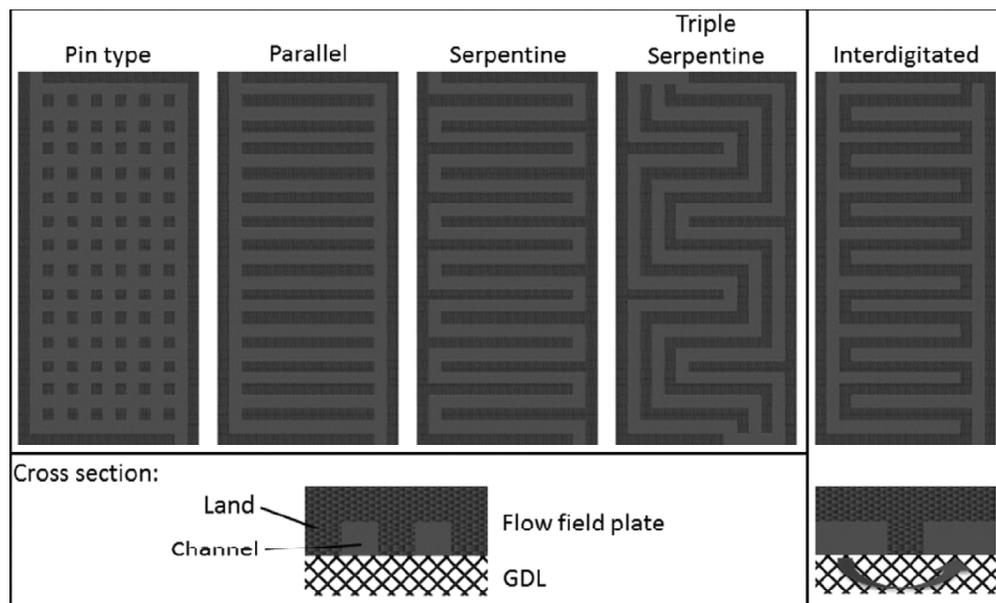
Figure 8: Examples of flow field design. Only the interdigitated design forces convection through the GDL to the electrode surface [85].

5. Impedance Analysis

The performance analysis described in this section has demonstrated desired lower contact resistance verses unwanted mass transport increases from higher compression levels. However, for practical operation, a cell will not undergo the extremes in current densities experienced during a polarization sweep. Within the conventional range of operation, differences in performance become less obvious, hence contact resistance and mass transfer limitation effects are not discernable using simple polarization analysis alone. Electrochemical impedance spectroscopy (EIS) is a technique that can be used to distinguish between the respective losses mechanisms that dominate the corresponding regions of the polarization curve at a particular current density. For more information on the fundamentals of EIS the reader is directed to Yuan *et al.* [87]. The EIS analysis is built up by the different electro kinetics of the cell components' response visualized by varying the AC frequency applied across the system. Therefore, the contact resistance, charge transfer, and mass transport of the anode and cathode can be deconvoluted and observed. However, because of the high speed electro kinetics of the HOR (anode) in comparison to the ORR (cathode), as well as the higher diffusion coefficient of pure hydrogen compared to the binary diffusion coefficient of 21% oxygen in nitrogen, the process is cathode dominated and therefore so too is the EIS response. By altering the location of the reference electrode it is possible to provide localized impedance measurements of the fuel cell system. A comparison between electrode response can also be viewed by carrying out EIS of a symmetrical anode and cathode [88]. The arc profile produced by EIS analysis can be modelled using an equivalent circuit which is shown in Fig. 9 (a), made up of the bulk resistance (Rs) driven by contact resistance, a charge transfer arc shown as a resistor (Rct) and constant phase element (CPEct) in parallel, the mass transport arc is made up of another resistor and CPE (Rmt, CPEmt). Mason et al. presented EIS data of this system under ranging compressions, with the results shown in Fig.9 (b). Notethat the time constants for the charge transfer and mass transport processes are not sufficiently different to be reliably separated, however total arc width was reported with the knowledge that arc variance was due to mass transport [75]. At the chosen voltage operating point of 0.7 V, the contact resistance is reduced while the combined charge transfer/mass transfer arc increases in size, in agreement with the performance testing data presented in the previous section.

6. Uniform Compression

It is possible to house the tie-rods within the gas and/or water manifolds that pass through the stack. By doing this, the size of the endplate can be reduced and the stress is distributed much more centrally to the MEA, hence providing a more uniform compression. The effect of the design adaptation can be visualized in Fig. 10(b) and the patent can be found in Section 1 of Table 2 [89]. Section 2 of Table 2 describes a range of clamping methods that are variations of the conventional tie-rod design, each with its own unique way to reduce end-plate mass and improve the uniformity of compression applied. The strap devices work by using several bands of different materials and wrapping them around the stack; by doing this a much greater area compressed against the end-plate is achieved,
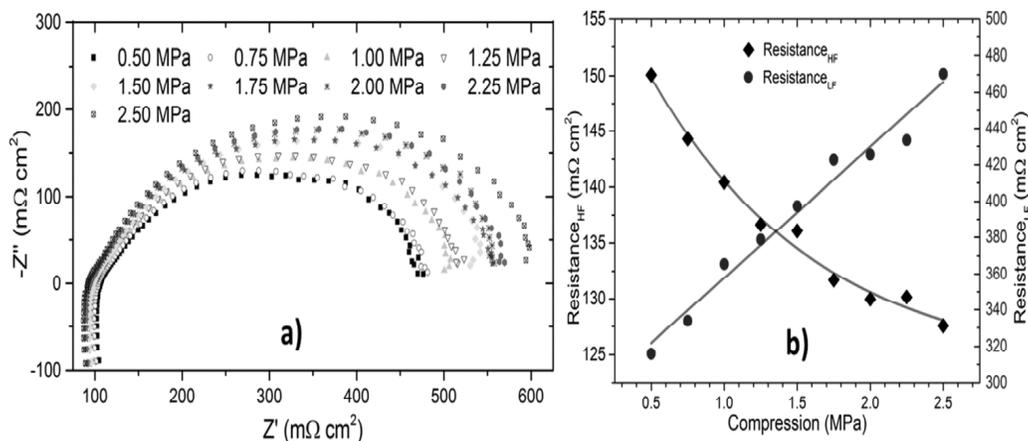
Figure 9: (a) Nyquist plot of fuel cell operating from 0.5 to 2.5 MPa. Fuel cell operating at 0.7 V, 80 °C, with constant anode and cathode flowrates of 100 ml min^{-1} at 100% RH. Impedance data taken with an amplitude of 15 mV over a frequency range of 20 kHz to 0.5 Hz. (b) Relationship between the high and low frequency resistance with compression [88].

thus providing more even distribution of force [90-93]. Furthermore, it allows for not only thinner endplates, but more variations in design; for example, curving edges to prevent higher compressive loads at the corners. A representation of this form of stress distribution method can be seen in Fig. 10(c). A crimp system allows for a much larger number of compression points to provide more even compression and a lower weight to the tie-bars method [94]. However, these are still applied around the outer edge causing higher clamping forces at the outside of the MEA, unless appropriately thick endplates are used (Fig. 10(d)). By curving the endplates, strap designs can allow for a more even compression force; Fig. 10(e) [95].

7. Application

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 [96]. The European Union (EU) has committed to reduce CO_2 emissions by 20% by 2020 compared to 1990 levels [97]. 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 Panelon Climate Change Assessment the built environment was identified as holding the largest economic potential for thereduction of CO_2 emissions [98]. Currently, in Europe, buildings account forover 40%of energy demand [99] and 50% of CO_2 emissions [100]. These figures illustrate the critical importance of decarbonizing the built environment if substantial CO_2 emissions reductions are to be realized on a national and international scale across allemitting sectors. Fuel cells have recently been identified as a key technological option on route to a future low carbon built environment. Thisis 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
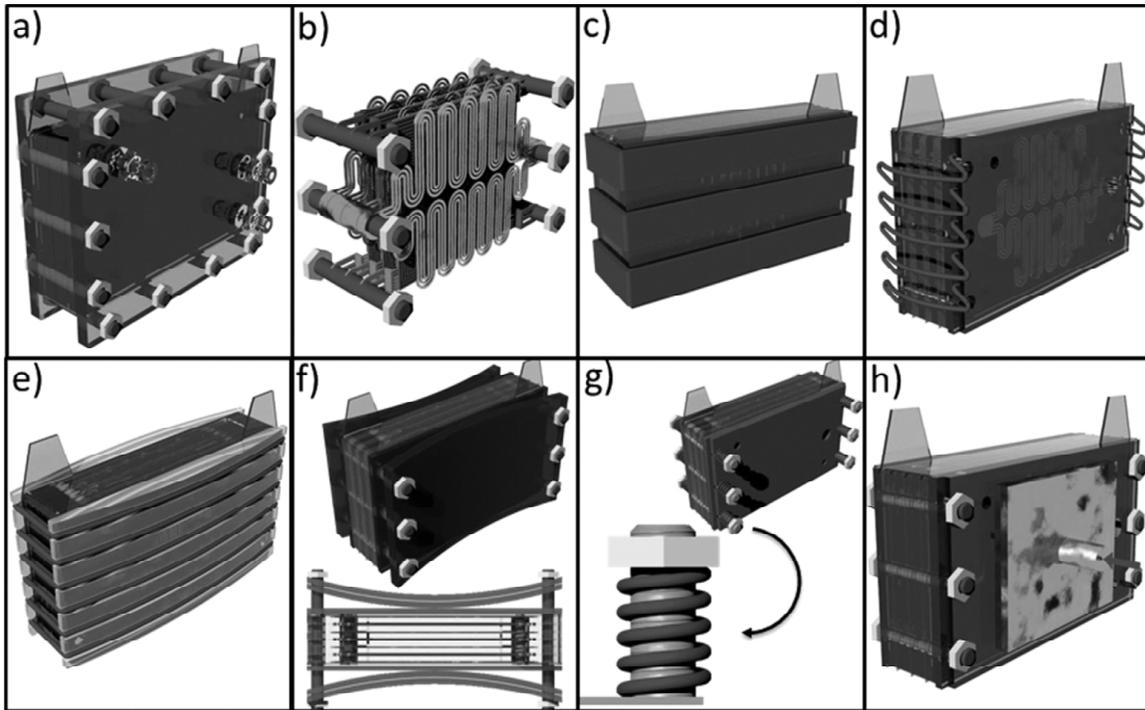
Figure 10: Clamping mechanisms for stacks, (a) standard tie rod setup, (b) tie rods through gas/water manifolds, (c) bands, (d) crimps, (e) straps/curved endplate, (f) leaf-spring, (g) tie rod springs, (h) dynamic fluid compression plate [89]

[101]. 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 [102-103]. In CHP and tri-generation systems, the of ten wasted heat createdin the electrical generation process is utilized 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 [104]. 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 [105]. Fuel cells are now recognized, acrossa variety of markets, most significantly the stationary, as a superior technological option compared to conventional combustion-based generators [106]. As a result, the stationary sector is currently the largest user of fuel cell technology, showing year on year growth, demonstrated in Fig. 11. In 2012 alone, 125 MWof fuel cells for stationary applications were shipped, a 53%increaseon 2011 figures, representing the rapid expansion of the sector. Further-more, Ceramic Fuel Cells Ltd. (CFCL) reported that the domestic housing solid oxide fuel cell (SOFC) marketis around 17,000kW installed perannum, alarge market potential. E.ON believes most UK homes are technically suitable for fuel cell micro-CHP, equalto a potential total installed capacityof 24GWe [107].
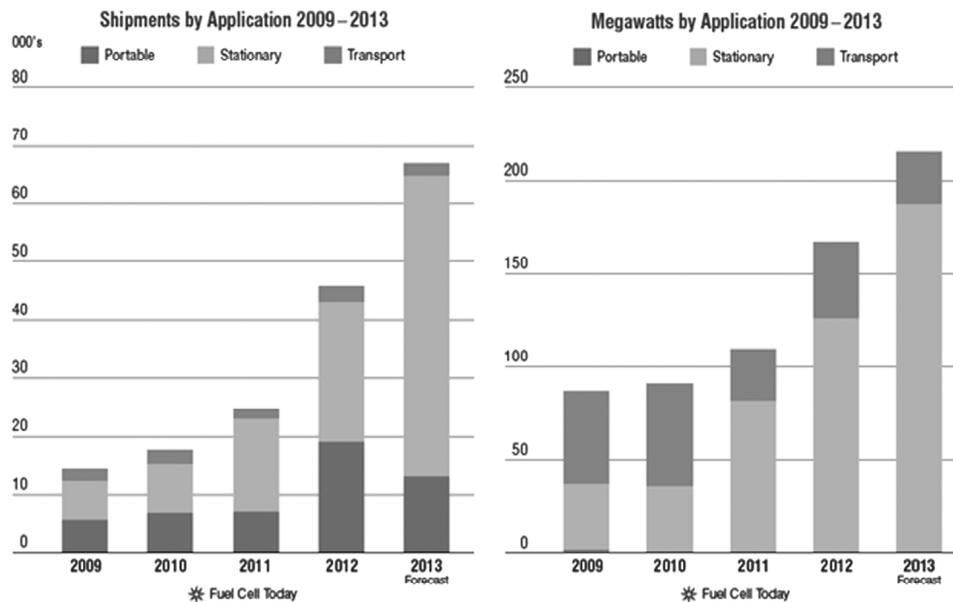
Figure 11: Fuel cellusebyapplication2009–2013 [106]

CHP is defined as the generation of heat and power from a single fuelsource, with the view to using both products. Fig. 12 show satypical domestic CHP system configuration. Fuelis supplied to the prime over technology, in this case a fuel cell, from the central network, to produce electrical power, and in the process create sheat. 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 domestich ot water. By consuming this heat, system efficiency can beelevated from as low as 20%to over 90%, depending on the prime over technology and the extent of waste heat utilization [108]. 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 states, if the thermal output of the CHP system can not be fullyutilized, then the system can not expect to deliver a net benefit relative to grid electricity and a highly efficient condensing boiler. There fore accurate building energy load assessments and sizing of the CHP unitis essential [109].

All the world leading car manufacturers have designed at least one prototype vehicle using fuel cells. Some of the car manufacturers (Toyota, Ford) have chosen to feed the fuel cell with methanol, while others have preferred to use pure hydrogen (Opel has used liquid hydrogen, General Motors has stored hydrogen in hydride form). In the short term there is a general trend for the car manufacturers to use reformed methanol as the fuel type for the fuel cell. However, over in the long term hydrogen remains the fuel of choice for the majority of the car manufacturers. Since 1994, Daimler-Benz working in collaboration with Ballard, built a series of PEMFC powered cars. The first of such vehicles
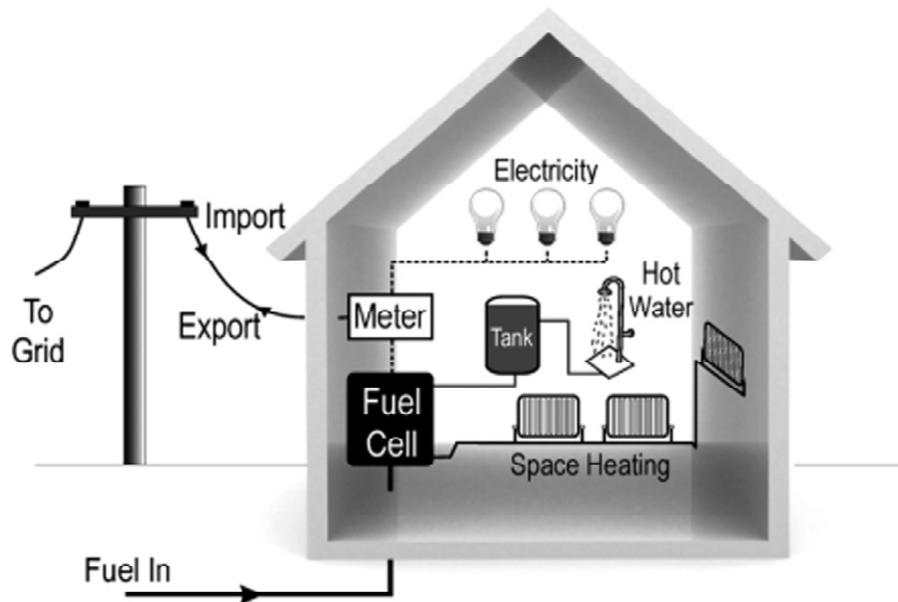
Figure 12: Fuel cell micro CHP in a domestic home [98].

was fuelled with hydrogen, and in 1997 Daimler-Benz released a methanol fuelledcar with a 640 km range. Plans are to offer a commercial vehicle by 2004 [110]. In 1996, Toyota built a hydrogen-fuelled (metal hydride storage) fuel cell/battery hybrid passenger car, which was followed, in 1997 by a methanol-fuelled car built on the same RAV4 platform. Renault and PSA-Peugeot Citroën are currently working on an improved design based on the results obtained fromthe FEVER prototype. General Motors, Volkswagen, Volvo, Honda, Chrysler, Nissan, and Ford have also announced plans to build prototype PEMFC cars operating on hydrogen, methanol, or gasoline. International Fuel Cells, Plug Power, and Ballard Power Systems are each participating in separate programs to build 50 to 100 kW fuel cell systems for cars [110]. The NECAR program, initiated in 1994, was designed in 4 phases leading to 4 prototypes of electric vehicles. The aim of this program was to show the feasibility of such a vehicle and then to improve the technology during each of the design phases. The latest in the series is NECAR 4, which uses the 5-seater Mercedes Class A vehicle as the platform. Incorporating a PEMFC using hydrogen stored in a cryogenic tank, it offers a maximum speed of 145 km/h and an operating range of 450 km. A compressor maintains the fuel cell under pressure. Air and hydrogen pass through a humidifier and a thermal exchanger before enter to the fuel cell. A condenser recovers the water produced by the fuel cell. An air radiator evacuates excessive heat. NECAR 4 can accelerate from 0 to 60 km/h in 6 seconds.

In 1993, Ballard Power Systems demonstrated a 10 mlight-duty transit bus with a 120 kW fuel cell system,followed by a 200 kW, 12 meter heavy-duty transitbus in 1995. These buses use no traction batteries andoperate on compressed hydrogen as the on-board fuel.In addition to large-scale power production, miniaturefuel cells could replace batteries that

power consumerelectronic products such as cellular telephones,portable computers, and video cameras. Small fuelcells could be used to power telecommunicationssatellites, replacing or augmenting solar panels. Micro-machined fuel cells could provide power tocomputer chips. Finally, minute fuel cells could safelyproduce power for biological applications, such ashearing aids and pacemakers [111]. Unlike transportationapplications where fuel cells are competing with theinternal combustion engines to indirectly produce amechanical output, in portable electronic equipmentfuel cells are in competition with devices such asbatteries to produce an electrical output. As a resultfuel cells can offer a viable alternative to batteries andseveral low power fuel cells are currently beingmanufactured for this application.The primary stationary application of fuel celltechnology is for the combined generation ofelectricity and heat, for buildings, industrial facilitiesor stand-by generators. Because the efficiency of fuelcell power systems is nearly unaffected by size, theinitial stationary plant development has focused on thesmaller, several hundred kW to low MW capacityplants. "The plants are fuelled primarily with naturalgas, and operation of complete, self-contained,stationary plants has been demonstrated using

PEMFC, AFC, PAFC, MCFC, SOFC technology" [110].

Clearly there are other technologies that have some of these features. However, FCs have all of these features simultaneously which culminate in significant benefits in certain applications. FCs are a new market entrant, and one that is a disruptive innovation [111]. In order to achieve market penetration, it is necessary to find markets that demand not just one of these features but a multitude of them. In such markets FCs will out-compete incumbent technologies, causing redundancy of existing market leading products. However, niche markets where these benefits are highly valued need to be found. Due to the flexibility and scalability of FCs applications have been considered and successfully implemented in a number of products, including FCs for portable applications [112], buses [113], passenger vehicles [114], scooters [115], remote power [116], forklifts [117], submarines [118], aircraft [119] and more. This paper investigates the potential of FC back-up power, remote power, APUs in aircraft and FCs for fire prevention, this leads to a greater understanding of how FCs can be marketed more effectively. Two companies, SFC Energy and Bloom Energy, have identified markets that demand many FC features and this has led to them achieving successful market entry with significant revenue generation. These companies have been able to achieve market entry firstly due to intelligent product positioning. The companies were able to introduce their products to markets where their features are highly valued by consumers. SFC Energy entered the motorhome and camping market where consumers desire power that is quiet, long lasting and requires minimal user intervention. Further to these examples, two prospective applications of FCs in markets that have yet to be fulfilled are explored. These markets are aircraft APUs and FCs for fire prevention in data centers. In these applications FCs are more beneficial than any other technology the authors are aware of. Indeed, due to the many benefits of FCs in these two markets they are often referred to as Multi-Functional Fuel Cells (MFCs) [119].

Conclusions – Future Outlook

Various fuel cell systems have been reviewed. Fuel cell commercialization, especially for the transport and remote area power is partly hampered by the lack of hydrogen transportation and distribution infrastructure combined with its low volumetric energy density. Materials are an appealing option for use in fuel cells. In comparison with other fuel cells, some kinds of fuel cells are very attractive for a number of applications including transport, portable power, distributed power, backup and remote area power, and large scale stationary power generation. The infrastructure for transportation and distribution of ethanol already exists in most countries. The energy density of some type of fuel cell is 6.32 kW h/L compared to 0.003 kW h/L for H2, 4.8 kW h/L for methanol and 5.80 kW h/L for ethylene glycol. Especially, the ethanol also contains 13 wt% hydrogen. Ethanol can be produced from a range of biomass resources including sugarcane, corn, grasses, wood and straw. The energy output to input ratio is quite high for sugarcane and many cellulosic materials. Global production of ethanol stands at close to 90 billion litres per annum. Ethanol can be utilized directly or indirectly in fuel cells. The primary barrier to the commercialization of fuel cell applications is the associated manufacturing cost. Currently the cost of fuel cell systems is greater than that of similar, already available products, mainly because of small scale production and the lack of economies of scale. The best fuel for fuel cells is hydrogen and another barrier is fuel flexibility. In stationary applications there is a case for using natural gas or electricity from conventional sources, as an intermediate step to reduce the large infrastructure costs associated with implementing a hydrogen economy. In mobile applications particularly transportation there is a case for deriving hydrogen from the onboard reforming of an alternative fuel. This would however seriously limit the flexibility of the fuel source. For this reason a better approach would be the storage of hydrogen directly onboard as demonstrated with the hypercar concept. Finally, the public safety perceptions of hydrogen fuel, and the absence of a history of widespread use of fuel cells are other barriers. As fuel cell application increases and improved fuel storage methods and handling is developed, it is expected that the costs associated with fuel cell systems will fall dramatically in the future.

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