The Fuel Cell Today Industry Review 2011
ACKNOWLEDGEMENTS

Fuel Cell Today gratefully acknowledges the contribution of many individuals and companies within the fuel cell industry in providing information for and assistance with the compilation of the Fuel Cell Today Industry Review 2011.

The Fuel Cell Today Industry Review 2011 is based for the most part on information available up to July 2011.

COPYRIGHT & DISCLAIMER

Fuel Cell Today Industry Review 2011 is the copyright of Johnson Matthey PLC trading as Fuel Cell Today. Material from this publication may be reproduced without prior permission provided that Fuel Cell Today is acknowledged as the source.

Johnson Matthey PLC endeavours to ensure the accuracy of the information and materials contained within this report, but makes no warranty as to accuracy, completeness or suitability for any particular purpose. Johnson Matthey PLC accepts no liability whatsoever in respect of reliance placed by the user on information and materials contained in this report, which are utilised expressly at the user’s own risk.

In particular, this report and the information and materials in this report are not, and should not be construed as, an offer to buy or sell or solicitation of an offer to buy or sell, any regulated products, securities or investments, or making any recommendation or providing any investment or other advice with respect to the purchase, sale or other disposition of any regulated products, securities or investments including, without limitation, any advice to the effect that any related transaction is appropriate or suitable for any investment objective or financial situation of a prospective investor.

A decision to invest in any regulated products, securities or investments should not be made in reliance on any of the information or materials in this report. Before making any investment decision, prospective investors should seek advice from their financial, legal, tax and accounting advisers, take into account their individual financial needs and circumstances and carefully consider the risks associated with such investment decisions. This report does not, and should not be construed as acting to, sponsor, advocate, endorse or promote any regulated products, securities or investments.

PICTURE CREDITS

Fuel Cell Today is grateful to the following people and organisations for their help in providing illustrations for the Fuel Cell Today Industry Review 2011. For copyright information or permission to use any of these images, please contact the relevant organisation.

Artist’s impression of the new World Trade Centre, outside covers
Silverstein Properties
Bloom Energy Servers, inside covers
Alan Russo
Map of geographical regions, p.5
Fuel Cell Today
Schematic of PEMFC, p.6
Fuel Cell Today
William Grove, p.8
Wikimedia
GM Electrovian, p.8
John Lloyd. Creative Commons
Bacon fuel cell, p.8
Dr. Bagotsky
Apollo Lunar Module, p.8
NASA
Fuel Cell Powered Campervan, p.8
SFC Energy
Honda FCX Clarity, p.8
Honda (UK)
Toshiba Dynario, p.8
Toshiba
h-tec fuel cell demonstration kit, p.14
h-tec
Horizon MiniPak, p.15
Horizon Fuel Cell Technologies
UTC PureCell 400 in operation at Coca Cola Refreshments, p.16
UTC Power
Panasonic Ene-Farm micro-CHP unit, p.17
Panasonic / Ene-Farm
Daimler B-Class F-CELL vehicle, p.20
Daimler
London fuel cell bus, p.22
Transport for London
Danish hydrogen filling station, p.26
Hydrogen Link Denmark Association
Core–shell catalyst, p.31
Johnson Matthey

www.fuelcelltoday.com

Design: Wonderberry UK Ltd.

Print: Fulmar Colour Printing Co. Ltd.
Contents

Executive Summary 2

Portable Applications 2
Stationary Applications 3
Transport Applications 3

Introduction 4

Overview 4
Introduction to Fuel Cells 5
Fuel Cells: A History 7

Current State of the Industry 13

Introduction 13
Developments by Application 14
Developments by Region 25
Developments by Electrolyte 30

Outlook 32

Portable 32
Stationary 32
Transport 33
Conclusion 33

Data Tables 34

Unit Shipments 2007-2011 34
MW Shipped 2007-2011 35
Table Notes 36
Fuel cell technology offers clean, efficient, reliable power generation to almost any device requiring electrical power. It competes to replace a range of power supplies in many portable, stationary and transport applications, from battery chargers to home heating and power to cars. Arguably, fuel cells represent the most versatile energy solution ever invented.

In this Review we begin with an introduction to fuel cell technology, discussing the six main types of fuel cell in use today. We also include a history of the fuel cell, from its invention by William Grove in 1839, through developments in the twentieth century such as its use in the space programme, to the present-day commercialisation of the technology which, for some applications, began in 2007. In the Current State of the Industry chapter, we present developments in unit shipments and megawatts shipped during the period 2007 to 2010, as well as a forecast for the full year of 2011. Unit and megawatt shipment totals are broken down by application, region and electrolyte, and developments in fuel and infrastructure are analysed. The final section of this Review presents an outlook for fuel cell adoption in the future, analysing planned demonstration projects and commercial roll-outs and reporting Fuel Cell Today’s expectations for unit shipment growth. The final chapter presents Fuel Cell Today’s unit shipment and megawatt data for the period 2007 to 2010, together with a forecast for the full year of 2011.

Over the last five years there has been a twenty-fold increase in shipments of fuel cells with year-on-year growth in both units and megawatts shipped. In 2010, total shipments of fuel cells grew by 40% compared with the previous year, approaching a new high of 230,000 units. Portable fuel cells accounted for 95% of this total but there was substantial growth in other sectors. Over 97% of fuel cells sold worldwide in 2010 used proton exchange membrane fuel cell (PEMFC) technology, and most were hydrogen-fuelled. Europe has been the leading region of adoption for fuel cells since 2009, followed by North America and Asia (including Japan), with all four regions (including the Rest of the World) seeing substantial increases in shipments over that time.

Viewing the sum of all fuel cell shipments worldwide offers an insight into metrics such as regional adoption and can provide striking headlines, but our analysis in this Review reveals it is more informative to view the fuel cell industry as a collection of sectors at different stages of development. Thus with the increasing diversity of fuel cell applications and the varying speed of adoption Fuel Cell Today considers it no longer accurate to describe the fuel cell industry as a unified whole, but as a number of disparate commercial applications sharing the same technology and developing at different rates.

Portable Applications

In terms of shipments, the portable sector is the largest by a considerable margin, accounting for at least 75% of total shipments in each year since 2007. There has been impressive growth in shipments of fuel cell toys and educational devices, which dominate the portable sector over the five-year period under review. In the consumer electronics segment, there have been notable developments in miniaturisation for use in external battery chargers, and thousands of units have been sold to consumers. While the opportunity for fuel cells in consumer electronics still holds promise for the future, this market has not been the near-term commercial success story it was once predicted to be, with some companies ceasing development in this field. By contrast, cumulative sales of methanol-powered fuel cell auxiliary power units (APU) have reached tens of thousands during the last five years, principally in the camping and leisure sector where they offer a longer-running power solution than batteries and a cleaner alternative to internal combustion engine (ICE) generators.
Stationary Applications

The market for stationary fuel cell systems is currently dominated by North America and Asia. Fuel Cell Today sub-divides the stationary sector into three main parts: megawatt-scale units used for prime power, smaller uninterruptible power supply (UPS) units for backup power and combined heat and power (CHP) units such as those for residential use.

Fuel cells have found significant commercial interest in UPS applications, where they are used to provide backup or standby power to telecoms sites and other critical infrastructure. The North American market has dominated shipments of these units due to the predominance of US companies selling this technology and also government incentives available for fuel cell installations. Fuel cell UPS technology has now proved its ability in this application. The global potential for emergency power, guaranteed backup and off-grid operation is only beginning to become apparent; backup power for the rapidly growing global mobile telecommunications industry is just one example with significant potential for fuel cell UPS.

The adoption of stationary fuel cells in Japanese homes has been a particular success, with tens of thousands of micro-CHP fuel cell units sold cumulatively since 2007 under the Ene-Farm brand, providing residential heat and power. This is a success Fuel Cell Today expects to be replicated in other markets such as Korea, parts of Europe and the USA. Our analysis shows that, in addition to the current Japanese case, if only four projects worldwide are implemented at the same rate as Ene-Farm, we expect 20,000 micro-CHP units to be sold annually from 2014, and 100,000 units to be cumulatively installed globally by 2015.

Transport Applications

Unit shipments of transport fuel cells have been in the thousands per year since 2009, with hundreds of megawatts shipped cumulatively in the last five years. Government assistance in the USA has led to fuel cells achieving a true commercial position in the electric forklift market, and this is expected to continue as the technology is exported to other regions worldwide. Fuel cell buses have been commercially available for many years and their usefulness has been demonstrated globally in terms of low emissions and high efficiency compared with their diesel counterparts.

Fuel cell electric vehicles (FCEV) are currently available for lease in several countries by many of the world’s major manufacturers, where operational experience is being gained ahead of the planned commercial launches from 2015. From this time, if only three of the major automakers succeed with their plans, Fuel Cell Today would expect twenty to thirty thousand vehicles to be introduced globally each year. Around 75 million light duty vehicles are produced worldwide at present, meaning the ultimate potential for this market in terms of fuel cell shipments outweighs that of any other application.

In summary, fuel cells have never been in a better position to positively impact our everyday lives and enjoy the commercial success promised for so long. Hundreds of thousands of fuel cells around the world will provide clean power for vehicles and buildings, and will also help to decarbonise national electricity grids by generating safe, clean energy. The continued commercial success of fuel cells is vital to help meet the world’s accelerating energy demands in a sustainable way.
Fuel cells have been developed for more than 170 years and there have been some notable successes of the technology in the space programme and in transport and stationary applications. There are various types of fuel cell technology, which over time have developed to suit particular applications. However, it is only in the last five years that fuel cells have become truly commercial in that they are now sold to consumers, supported by warranties and service capability.

The advantages provided by fuel cells often outweigh those of incumbent technologies such as combustion engines. Fuel cells offer genuinely unique operational characteristics, such as low emissions, exceptional efficiency and reliability, and are capable of offering combined heating, cooling and power in certain applications. The value proposition represented by fuel cells has been realised in the last five years in end-use applications as diverse as auxiliary power units (APU) for campervans; stationary prime power for large industrial installations; micro combined heat and power (micro-CHP) for homes; clean city buses; and materials handling vehicles.

Fuel Cell Applications

Fuel Cell Today categorises the use of fuel cells into three broad areas, defined as follows:

- Portable fuel cells encompass those designed to be moved including APU;
- Stationary power fuel cells are units designed to provide power to a fixed location;
- Transport fuel cells provide either primary propulsion or range-extending capability for vehicles.

Fuel Cell Today also considers fuel and infrastructure, relating to the production, storage and distribution of fuels for fuel cells, as this is crucial to implementing fuel cell technology. Each of these topics is discussed in more detail in the Current State of the Industry chapter.

<table>
<thead>
<tr>
<th>Application Type</th>
<th>Portable</th>
<th>Stationary</th>
<th>Transport</th>
</tr>
</thead>
<tbody>
<tr>
<td>Definition</td>
<td>Units that are built into, or charge up, products that are designed to be moved, including auxiliary power units (APU)</td>
<td>Units that provide electricity (and sometimes heat) but are not designed to be moved</td>
<td>Units that provide propulsive power or range extension to a vehicle</td>
</tr>
<tr>
<td>Typical power range</td>
<td>5 W to 20 kW</td>
<td>0.5 kW to 400 kW</td>
<td>1 kW to 100 kW</td>
</tr>
<tr>
<td>Typical technology</td>
<td>PEMFC, DMFC</td>
<td>MCFC, PAFC, PEMFC, SOFC</td>
<td>PEMFC, DMFC</td>
</tr>
<tr>
<td>Examples</td>
<td>- Non-motive APU (campervans, boats, lighting)</td>
<td>- Large stationary combined heat and power (CHP)</td>
<td>- Materials handling vehicles</td>
</tr>
<tr>
<td></td>
<td>- Military applications (portable soldier-borne power, skid-mounted generators)</td>
<td>- Small stationary micro-CHP</td>
<td>- Fuel cell electric vehicles (FCEV)</td>
</tr>
<tr>
<td></td>
<td>- Portable products (torches, battery chargers), small personal electronics (mp3 players, cameras)</td>
<td>- Uninterruptible power supplies (UPS)</td>
<td>- Trucks and buses</td>
</tr>
<tr>
<td></td>
<td>- Large personal electronics (laptops, printers, radios)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>- Education kits and toys</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Geographical Regions

In this review, Fuel Cell Today distinguishes four main geographical regions: Asia (including Japan), Europe, North America and the Rest of the World (RoW).

Supply Chain

Shipments are reported by numbers of units (systems) and by total megawatts. The individual components that make up a fuel cell, for example the membrane electrode assembly (MEA), humidifier, stack and power electronics, may be manufactured in a variety of regions and shipped elsewhere for final assembly into a fuel cell system. The finished system may then be shipped to the final region of adoption, used in our shipment by region classification. In terms of the supply chain, it is worth noting that there are complex international arrangements of suppliers, stack manufacturers and system integrators. We report shipments from the final manufacturer (usually the system integrator), for example Plug Power’s materials handling systems use Ballard PEMFC stacks.

The development of the supply chain has been an interesting feature of the fuel cell industry over the last several years. As system integrators have begun to sell commercial products, they have tended to move away from making components such as bipolar plates themselves and either contracted out the manufacturing of certain components or sought external suppliers. This has enabled an expansion of the component supply chain, while the number of stack and system manufacturers has not grown as substantially. Therefore there remains something of a bottleneck in stack and system manufacture which may have acted as a constraint on growth in some sectors in recent years. Much of the component supply chain is presently focused in North America, although there are signs that a growing number of low-cost, high-volume suppliers are being sought in Asia, which will help to ultimately reduce the unit cost of fuel cell systems.

Introduction to Fuel Cells

Fuel cells generate electricity from an electrochemical reaction in which oxygen and a hydrogen-rich fuel combine to form water. There are several different types of fuel cell but they are all based around a central design. Fuel cells have a broader range of application than any other currently available power source. The electricity produced can be used in many portable, stationary and transport applications, and the by-product heat can also be used for heating and cooling.

A fuel cell unit consists of a stack, which is composed of a number of individual cells. Each cell within the stack has two electrodes, one positive and one negative, called the cathode and the anode. The reactions that produce electricity take place at the electrodes. Every fuel cell also has a solid or liquid electrolyte, which carries ions from one electrode to the other, and a catalyst, which accelerates the reactions at the electrodes. The electrolyte plays a key role. It must permit only the appropriate ions to pass between the electrodes.
If free electrons or other substances could travel through the electrolyte, they would disrupt the chemical reaction.

Fuel cells are generally classified according to the nature of the electrolyte (except for direct methanol fuel cells which are named for their ability to use methanol as a fuel), each type requiring particular materials and fuel.

The significant fuel cell types are described below, in order of commercial importance:

**Proton Exchange Membrane Fuel Cells (PEMFC)** use a water-based, acidic polymer membrane as the electrolyte, with platinum-catalysed electrodes. PEMFC operate at relatively low temperatures (below 100°C) and can tailor electrical output to meet dynamic power requirements. They typically run on pure hydrogen, though many use reformed natural gas. This reformate must undergo purification to remove carbon monoxide, a known poison for platinum catalysts.

A variant of this, which operates at elevated temperatures, is known as the high temperature PEMFC (HT PEMFC). By changing the electrolyte from a water-based to a mineral acid-based system, HT PEMFC can operate up to 200°C. This overcomes some of the current limitations of PEMFC with regard to fuel purity as HT PEMFC are able to process reformate containing small quantities of carbon monoxide. The balance of plant (BoP), such as humidifiers and pumps, can also be simplified.

**Direct Methanol Fuel Cells (DMFC)** are similar to PEMFC in that they use a polymer membrane as the electrolyte. However, the platinum–ruthenium catalyst on the DMFC anode is able to draw the hydrogen from liquid methanol directly, eliminating the need for a fuel reformer.

**Molten Carbonate Fuel Cells (MCFC)** use a molten carbonate salt such as zirconium dioxide or cerium dioxide suspended in a porous ceramic matrix as the electrolyte. They operate at high temperatures of around 650°C and can be fuelled with coal-derived fuel gas, methane or natural gas, eliminating the need for external reformers. However, the operating life of these cells is somewhat limited by the corrosive nature of the electrolyte.
Phosphoric Acid Fuel Cells (PAFC) consist of an anode and a cathode made of a finely dispersed platinum catalyst on carbon and a silicon carbide structure that holds the phosphoric acid electrolyte. They are resistant to poisoning by carbon monoxide but tend to have lower efficiency than other fuel cell types in producing electricity. However, these cells operate at moderately high temperatures of around 200ºC and overall efficiency can be over 80% if this heat is harnessed for cogeneration. They are usually fuelled by reformed natural gas.

Solid Oxide Fuel Cells (SOFC) use a solid ceramic electrolyte, such as zirconium oxide stabilised with yttrium oxide, instead of a liquid or membrane. Their high operating temperature means that fuels can be reformed within the fuel cell itself, eliminating the need for external reforming and allowing the units to be used with a variety of hydrocarbon fuels. They are also resistant to sulphur in the fuel, compared to other types of fuel cell, and can hence be used with coal gas.

Alkaline Fuel Cells (AFC) use an alkaline electrolyte such as potassium hydroxide in water and are generally fuelled with pure hydrogen and oxygen as they are very sensitive to poisoning by carbon monoxide. The first AFC operated at between 100ºC and 250ºC but typical operating temperatures are now around 70ºC. They offer relatively high fuel to electricity conversion efficiencies; as high as 60% in some applications.

The above list is not comprehensive in that it does not include certain types of fuel cell, such as microbial fuel cells, which are largely at the R&D stage and are unlikely to be commercialised in the near future.

Fuel Cells: A History

Origins

The concept of a fuel cell had effectively been demonstrated in the early nineteenth century by Humphry Davy. This was followed by pioneering work on what were to become fuel cells by the scientist Christian Friedrich Schönbein in 1838. William Grove, a chemist, physicist and lawyer, is generally credited with inventing the fuel cell in 1839. Grove conducted a series of experiments with what he termed a gas voltaic battery, which ultimately proved that electric current could be produced from an electrochemical reaction between hydrogen and oxygen over a platinum catalyst. The term fuel cell was first used in 1889 by Charles Langer and Ludwig Mond, who researched fuel cells using coal gas as a fuel. Further attempts to convert coal directly into electricity were made in the early twentieth century but the technology generally remained obscure.

In 1932, Cambridge engineering professor Francis Bacon modified Mond’s and Langer’s equipment to develop the first AFC but it was not until 1969 that Bacon demonstrated a practical 5 kW fuel cell system. At around the same time, Harry Karl Ihrig fitted a modified 15 kW Bacon cell to an Allis-Chalmers agricultural tractor. Allis-Chalmers, in partnership with the US Air Force, subsequently developed a number of fuel cell powered vehicles including a forklift truck, a golf cart and a submersible vessel.

The Space Programme

In the late 1950s and early 1960s NASA, in collaboration with industrial partners, began developing fuel cell generators for manned space missions. The first PEMFC unit was one result of this, with Willard Thomas Grubb at General Electric (GE) credited with the invention. Another GE researcher, Leonard Niedrach, refined Grubb’s PEMFC by using platinum as a catalyst on the membranes. The Grubb-Niedrach fuel cell was further developed in cooperation with NASA, and was used in the Gemini space programme of the mid-1960s.
<table>
<thead>
<tr>
<th>Year</th>
<th>Event</th>
</tr>
</thead>
<tbody>
<tr>
<td>1801</td>
<td>Humphry Davy demonstrates the principle of what became fuel cells.</td>
</tr>
<tr>
<td>1889</td>
<td>Charles Langer and Ludwig Mond develop Grove’s invention and name the fuel cell.</td>
</tr>
<tr>
<td>1839</td>
<td>William Grove invents the ‘gas battery’, the first fuel cell.</td>
</tr>
<tr>
<td>1959</td>
<td>Francis Bacon demonstrates a 5 kW alkaline fuel cell.</td>
</tr>
<tr>
<td>1950s</td>
<td>General Electric invents the proton exchange membrane fuel cell.</td>
</tr>
<tr>
<td>1960s</td>
<td>NASA first uses fuel cells in space missions.</td>
</tr>
<tr>
<td>1970s</td>
<td>The oil crisis prompts the development of alternative energy technologies including PAFC.</td>
</tr>
<tr>
<td>1990s</td>
<td>Large stationary fuel cells are developed for commercial and industrial locations.</td>
</tr>
<tr>
<td>2007</td>
<td>Fuel cells begin to be sold commercially as APU and for stationary backup power.</td>
</tr>
<tr>
<td>2008</td>
<td>Honda begins leasing the FCX Clarity fuel cell electric vehicle.</td>
</tr>
<tr>
<td>2009</td>
<td>Residential fuel cell micro-CHP units become commercially available in Japan. Also thousands of portable fuel cell battery chargers are sold.</td>
</tr>
</tbody>
</table>
International Fuel Cells (IFC, later UTC Power) developed a 1.5 kW AFC for use in the Apollo space missions. The fuel cell provided electrical power as well as drinking water for the astronauts for the duration of their mission. IFC subsequently developed a 12 kW AFC, used to provide onboard power on all space shuttle flights.

While research was continuing on fuel cells in the West, in the Soviet Union fuel cells were being developed for military applications. Although much of this early work is still secret, it did result in fuel cells being used to provide onboard power to a submarine and later to the Soviet manned space programme.

The 1970s

The 1970s saw the emergence of increasing environmental awareness amongst governments, businesses and individuals. Prompted by concerns over air pollution, clean air legislation was passed in the United States and Europe. This ultimately mandated the reduction of harmful vehicle exhaust gases and was eventually adopted in many countries around the world. The 1970s was also the era of the OPEC oil embargoes, which led governments, businesses and consumers to embrace the concept of energy efficiency. Clean air and energy efficiency were to become two of the principal drivers for fuel cell adoption in subsequent decades, in addition to the more recent concerns about climate change and energy security.

Earlier, General Motors had experimented with its hydrogen fuel cell powered Electrovan fitted with a Union Carbide fuel cell. Although the project was limited to demonstrations, it marked one of the earliest road-going fuel cell electric vehicles (FCEV). From the mid-1960s, Shell was involved with developing DMFC, where the use of liquid fuel was considered to be a great advantage for vehicle applications. Concerns over oil availability in the 1970s led to the development of a number of one-off demonstration fuel cell vehicles, including models powered by hydrogen or ammonia, as well as of hydrogen-fuelled internal combustion engines. Several German, Japanese and US vehicle manufacturers and their partners began to experiment with FCEV in the 1970s, increasing the power density of PEMFC stacks and developing hydrogen fuel storage systems. By the end of the century, all the world’s major carmakers had active FCEV demonstration fleets as a result of these early efforts. The focus by then had shifted back to pure hydrogen fuel, which generates zero harmful tailpipe emissions.

Prompted by concerns over energy shortages and higher oil prices, many national governments and large companies initiated research projects to develop more efficient forms of energy generation in the 1970s. One result of this was important advances in PAFC technology, in particular in stability and performance. There were significant field demonstrations of large stationary PAFC units for prime, off-grid power in the 1970s, including a 1 MW unit developed by IFC. Funding from the US military and electrical utilities enabled developments in MCFC technology, such as the internal reforming of natural gas to hydrogen. The use of an established natural gas infrastructure was a key advantage in developing fuel cells for large stationary prime power applications.

The 1980s

Substantial technical and commercial development continued in the 1980s, notably in the area of PAFC. A bright future for the technology was widely predicted around this time for stationary applications and buses. Ambitious conceptual designs were published for municipal utility power plant applications of up to 100 MW output. Predictions of tens of thousands of units in operation by the end of the century were made, but only hundreds were to actually appear by that date. Several experimental large stationary PAFC plants were built, but
saw little commercial traction in the 1980s. With subsequent advancements in membrane durability and system performance, PAFC were rolled out in greater numbers almost two decades later for large-scale combined heat and power applications.

Also in the 1980s, research, development and demonstration (RD&D) work continued into the use of fuel cells for transport applications. The US Navy commissioned studies into the use of fuel cells in submarines where highly efficient, zero-emission, near-silent running offered considerable operational advantages. In 1983 the Canadian company Ballard began research into fuel cells, and was to become a major player in the manufacture of stacks and systems for stationary and transport applications in later years.

The 1990s

Attention turned to PEMFC and SOFC technology in the 1990s, particularly for small stationary applications. These were seen as offering a more imminent commercial possibility, due to the lower cost per unit and greater number of potential markets – for example backup power for telecoms sites and residential micro-CHP. In Germany, Japan and the UK, there began to be significant government funding devoted to developing PEMFC and SOFC technology for residential micro-CHP applications.

Government policies to promote clean transport also helped drive the development of PEMFC for automotive applications. In 1990, the California Air Resources Board (CARB) introduced the Zero Emission Vehicle (ZEV) Mandate. This was the first vehicle emissions standard in the world predicated not on improvements to the internal combustion engine (ICE) but on the use of alternative powertrains. Carmakers such as the then-DaimlerChrysler, General Motors, and Toyota, all of which had substantial sales in the US, responded to this by investing in PEMFC research. Companies other than automakers, such as Ballard, continued PEMFC research for automotive and stationary clean power. Ballard went on to supply PEMFC units to Daimler and Ford. The programmes initiated in the 1990s still continue, albeit with some changes to the strategic focus of some key players.

Significant advances in DMFC technology occurred around the same time, as PEMFC technology was adapted for direct methanol portable devices. Early applications included portable soldier-borne power and power for devices such as laptops and mobile phones. MCFC technology, first developed in the 1950s, made substantial commercial advances in the 1990s, in particular for large stationary applications in which it was sold by companies such as FuelCell Energy and MTU. SOFC technology also underwent substantial developments in terms of power density and durability for stationary applications. Boosted by general optimism in high-technology industries, many fuel cell companies listed on stock exchanges in the late 1990s, only for prices to fall victim to the crash in technology stocks shortly after.

The 2000s

The last decade was characterised by increasing concerns on the part of governments, business and consumers over energy security, energy efficiency, and carbon dioxide (CO₂) emissions. Attention has turned once again to fuel cells as one of several potential technologies capable of delivering energy efficiency and CO₂ savings while reducing dependence on fossil fuels.

Government and private funding for fuel cell research has increased markedly in the last decade. There has been a renewed focus on fundamental research to achieve breakthroughs in cost reduction and operational
performance to make fuel cells competitive with conventional technology. A good deal of government funding worldwide has also been targeted at fuel cell demonstration and deployment projects. The European Union, Canada, Japan, South Korea, and the United States are all engaged in high-profile demonstration projects, primarily of stationary and transport fuel cells and their associated fuelling infrastructure. The genuine benefits that fuel cell technology offers over conventional technologies has played a part in promoting adoption. For example, the value proposition that fuel cell materials handling vehicles offer in terms of extended run-time, greater efficiency and simplified refuelling infrastructure compared with their battery counterparts makes them attractive to warehouse operators. Tens of fuel cell buses were deployed in the mid-2000s as part of the HyFleet/ CUTE project in Europe, China and Australia. Buses were, and still are, seen as a promising early market application of fuel cells due to their combination of high efficiency, zero-emissions and ease of refuelling, and due to the vehicles running on set routes and being regularly refuelled with hydrogen at their bases.

2007: Fuel Cells Commercialise

Fuel cells began to become commercial in a variety of applications in 2007, when they started to be sold to end-users with written warranties and service capability, and met the codes and standards of the markets in which they were sold. As such, a number of market segments became demand driven, rather than being characterised by oversupply and overcapacity. In particular, thousands of PEMFC and DMFC auxiliary power units (APU) were commercialised in leisure applications, such as boats and campervans, with similarly large numbers of micro fuel cell units being sold in the portable sector in toys and educational kits. Demand from the military also saw hundreds of DMFC and PEMFC portable power units put into service for infantry soldiers, where they provided power to communications and surveillance equipment and reduced the burden on the dismounted solider of carrying heavy battery packs.

A large-scale residential CHP programme in Japan helped stimulate commercial stationary PEMFC shipments. These units began to be installed in homes from 2009, and more than 13,000 such units have been installed to date. Demonstration programmes for backup power systems in the USA gave further impetus to the stationary sector. This was also driven by practical concerns over the need for reliable backup power for telecoms networks during emergencies and rescue operations. The inadequacy of diesel generators was illustrated during the Gulf of Mexico Hurricane Katrina disaster, when many ran out of fuel, disrupting the telecoms network and hampering relief efforts. The need for reliable on-grid or off-grid stationary power in developing countries also gave a boost to fuel cells. In the late 2000s, hydrogen and natural gas fuelled PEMFC units began to be sold in parts of India and east Africa to provide primary or backup power to mobile phone masts. The rapidity of mobile phone adoption in these regions means that the conventional grid infrastructure cannot keep pace with new power demands, or is too unreliable for an effective mobile network. Fuel cells provide a solution to this previously unmet need.

In transport applications, the greatest commercial activity occurred in the materials handling segment, where there is a strong business case for their use in place of the incumbent technology, lead acid batteries. Funding for demonstration fleets of fuel cell materials handling vehicles saw increasing numbers deployed in warehouses across the USA, although the overall numbers remained small compared with those for stationary and portable fuel cells. Fuel cell buses have been commercially available for several years and their usefulness has been well demonstrated. However their cost, at around five times that of a diesel bus, plus the cost of hydrogen infrastructure means that they are only used where a city deems the environmental benefit to be worth the extra investment. Fuel cell cars are currently only available for lease; these vehicles are being made available by manufacturers to gain experience ahead of a commercial launch planned from 2015.
In the past decade, PEMFC and DMFC have dominated the total market share in the portable, stationary and transport sectors. Their uptake by consumers has been facilitated by the development of codes, standards and government policies to lower the barriers to adoption; such as allowing methanol fuel cartridges on board aircraft and feed-in tariffs for fuel cell CHP installations.

Recent Developments

Over the last five years, as shown in the data tables in this Review, growth in shipments of fuel cells has accelerated rapidly as various applications have become commercial. Portable fuel cells saw the most rapid rate of growth over the period since 2009 as increasing numbers of fuel cell educational kits were sold to consumers. This genuine commercial market generated much-needed revenue for several key players and has allowed those companies to invest in research into larger stationary and transport applications. The portable sector has also been boosted by shipments of APU products for the leisure market, in particular camping and boating. Shipments in the portable sector were also augmented by the launch of Toshiba’s Dynario fuel cell battery charger in 2009. On a limited production run of 3,000, demand for the Dynario far outstripped supply.

Stationary fuel cell adoption has increased rapidly as the roll-out of the Japanese Ene-Farm project took place and fuel cells for uninterruptible power supplies (UPS) were adopted in North America.

The supply chain has also been steadily growing alongside the increase in the number of fuel cell system manufacturers. There has been an expansion of the component supply chain and related services, from the manufacturers of MEA to fuel and infrastructure providers. Manufacturing capacity has tended to increase more rapidly than output. This is particularly true in North America, one of the leading regions for fuel cell manufacturing.

The global economic recession of the late 2000s undoubtedly had negative effects for certain fuel cell companies. Limited credit availability and restrictions in government funding, as well as lack of profitability for organisations that were still mainly RD&D focused, caused a number of firms to go out of business. However, it gave other companies the impetus to become more commercially orientated and to pursue opportunities for revenue generation that could support further R&D in their core competencies. Since the recession, governments around the world have come to see fuel cells as a promising area of future economic growth and job creation and have invested further resources in their development, something fuel cell companies have not been slow to capitalise on. As many Western countries seek to rebalance their economies towards high-value manufacturing and environmental technologies, fuel cells seem poised to enter a period of sustained growth.

The fuel cell industry has faced and continues to face challenges as it comes through a period of recession and completes the transition from R&D to commercialisation. On the whole, it has survived extremely difficult circumstances. Although many fuel cell companies are still far from being profitable, the opportunities for growth in the future are very promising. The success of certain application segments in recent years means that there has been a move to consolidate particular technologies into a standard reference design for a particular type of fuel cell. This has led to fuel cells increasingly being developed as scalable energy solutions capable of serving several different market segments, for example being used in APU or to power unmanned aerial vehicles (UAV).
In 2010 total shipments of fuel cells grew by 40%, reaching a new high of almost 230,000 units. Portable fuel cells accounted for 95% of this total and over 97% of fuel cells sold worldwide in 2010 used PEMFC technology. In this Review Fuel Cell Today publishes figures dating back to 2007, and significant growth can be seen year-on-year, including a twenty-fold increase since that date.

While viewing all fuel cell shipments together in this way does provide striking headlines, our analysis in this Review shows that it is more informative to regard the fuel cell industry as a collection of different sectors at different stages of development. Therefore the term fuel cell industry could be considered a misnomer.

Fuel cell technology offers arguably the most versatile energy solution ever invented. It competes to replace a range of power supplies from batteries to internal combustion engines in a huge variety of applications from home heating to mobile phone chargers and cars. The range of fuels which fuel cells can use also separates them from competing technologies. While ICE technology is normally limited to a few types of liquid fuel, and batteries need electricity for recharging, fuel cells can utilise any fuel which can provide a source of hydrogen. This opens up enormous possibilities for the technology, from integrating directly into existing natural gas infrastructure, to processing waste hydrogen from chemical plants, and to using bio-methane from landfills.

The advantages provided by specific types of fuel cell often outweigh not only the performance of incumbent technologies, but also that of other fuel cell types so that over time, application-specific fuel cell electrolyte preference has developed. Examples include the portability of DMFC technology and the prevalence of high-temperature fuel cells in power generation where the by-product heat can be used for space heating or steam production, greatly enhancing total system efficiency. Also fuel cell applications have developed at different rates, with the full range currently spanning experimental one-off prototypes, to larger projects relying heavily on government funding, right through to tens of thousands of fuel cell units being sold to the public.

These differences will continue as already commercial applications advance towards maturity, development projects reach commercialisation and new ideas spawn areas where fuel cell solutions meet a need in power-
Current State of the Industry

and heat-hungry markets. Each end-use sector is subject to its own drivers and barriers which ultimately dictate the extent to which fuel cells will penetrate the respective markets, or even if they can provide a solution at all. The following sections break Fuel Cell Today’s global totals into more meaningful pieces and consider both numbers of units and total megawatts shipped in each case. Viewing the two together in this way can offer insight into trends such as where fuel cells are finding commercial success, whether the units are getting larger or smaller and which type of fuel cell solution fits best.

Portable

In terms of unit shipments, the portable sector is the largest by a considerable margin, accounting for at least 75% of total shipments in each year since 2007. This contribution increased to more than 95% of total shipments from 2009 onwards with growth in shipments of micro-portable fuel cells. However, it represents only 2.6% of the global megawatts supplied in 2010 because the vast majority of these units are small (<5 W) fuel cells intended for use in educational systems and in toys.

Educational Fuel Cells

Fuel Cell Today has always included shipments of toys and educational fuel cells, considering them to be as valid as any other small fuel cell unit including those intended for powering consumer electronics. This market has provided an entry point for a number of fuel cell companies, enabling them to improve the technology and make commercial sales, all the while helping fund the development of larger products which it is hoped will ultimately drive sales in the future. The educational aspect of familiarising children with fuel cells and hydrogen technology should also not be underestimated. Dispelling the myths which seem perpetually associated with the technology (especially hydrogen) is a good thing, and the next generation of engineers will support commercialisation by considering the integration of fuel cell solutions at the design stage of projects.

Auxiliary Power Units (APU)

Fuel cell APU designed to provide hotel loads of up to 100 W, either as stand-alone units or integrated into vehicles, are included in the portable sector. The industry leader in this application is SFC Energy with its range of DMFC powered units. Having spent the past few years proving the viability of its technology, mainly in the European market, it has sold almost 17,500 units cumulatively between 2007 and 2010. The bulk of these have been its EFOY range of units, for use in the leisure, mobility and industrial markets. SFC Energy has also developed the necessary refuelling infrastructure in parallel with this, enabling cartridges of methanol to be bought from vendors across Europe. Its military portable fuel cells continued to receive interest from the German military in 2010 with a repeat order placed towards the end of the year. Offering the potential to reduce the weight of batteries carried by soldiers by up to 80%, fuel cells can be used to power a range of military equipment such as portable computers, night vision and navigational equipment.

The APU market holds great promise for growth as additional markets are identified, costs are reduced and the fuel distribution infrastructure is enhanced further. Legislation preventing the idling of heavy duty truck engines when parked overnight is one such opportunity where fuel cells can offer a low-emission and low-noise option.
Consumer Electronics

Portable fuel cells for consumer electronics applications remain a challenge, with problems relating to miniaturisation and system integration preventing the commercial release of a fully integrated device to date. Since the launch of the Toshiba Dynario in late 2009, with a limited production run of 3,000 units, portable fuel cell announcements have been scarce. As a result of the integration problems, the units closest to commercialisation are external chargers. These units are aimed at outdoor use in remote locations, for example hiking and camping, where ready access to power can be problematic. These fuel cells find a niche here, but compete with external battery packs, which can be significantly cheaper. Fuel Cell Today believes the ultimate goal of selling millions of portable fuel cell devices is only likely to be reached once the fuel cell can be integrated into laptops and phones, similar to the lithium-ion batteries of today.

A prototype of a fuel cell integrated into a Windows 7 based tablet computer was demonstrated at the 2011 Consumer Electronics Show by start-up company Fluid Computer Systems (FCS). FCS walked the floor of the show with its prototype, powered by a Horizon Fuel Cell Technologies hydrogen fuel cell, but admitted it was still heavy, and was searching for development partners with the aim of targeting commercial sales by 2012. Tablet computers would be an appropriate format for the integration of fuel cells in portable electronic devices, with miniaturisation not such a critical factor as for modern mobile phones. Durability, grid independence and long run times provided by fuel cells are particularly valued in this type of mobile device. Sales of the iPad since its launch in Q2 2010 have exceeded 15 million units, according to press statements; even a small percentage of that market would be significant for the industry, and potentially accelerate the development and integration needed for wider adoption of fuel cells in consumer electronics. Unfortunately FCS was forced to cease trading after its financial backers withdrew, citing concerns over competing with established giants in the tablet industry.

Numerous companies, including Antig, CMR Fuel Cells, Nomadic Fuel Cells and Samsung, have also attempted to develop portable fuel cells during the past few years, but have ultimately restructured or withdrawn from the fuel cell market due to the lack of a commercially viable product. Fuel Cell Today has seen a great deal of activity and speculation surrounding portable devices in the past few years, including estimates reaching millions of units for fuel cell consumer electronic devices. Unfortunately the technology has to date been unable to match these levels of optimism and, although power densities are improving and units are being made smaller, a fully integrated portable fuel cell for the consumer electronics market is likely to be some years away.

Integration problems aside, a number of companies are currently offering external fuel cell charging products aimed at the lucrative consumer electronics market. In June 2010, Horizon Fuel Cell Technologies introduced its pocket-sized consumer electronics fuel cell charger, called MiniPak, which can deliver up to 2 W of continuous power using a standard USB port, and uses refillable fuel cartridges able to store up to 12 Wh of net energy.

In early 2011, Swedish company myFC introduced its PowerTrekk fuel cell and PowerPukk fuelling cartridges aimed at outdoor enthusiasts. Using sodium silicide storage, the fuel cartridges are activated by a small quantity of water and produce 4 litres of hydrogen. The company claims a rated output of 5 V from the hybridised battery via its USB port. It is in the process of setting up a distributor network.

Aquafairy showcased its portable electronics charger at the 2011 FC Expo in Japan. The unit is fuelled by hydrogen generated by adding water to a metal hydride cartridge and currently provides sufficient energy to charge a smartphone to 50%
capacity. Initially targeting business customers, and with a limited production run, Aquafairy hopes to reduce costs once the unit reaches mass production, from ¥26,250 ($322) down to under ¥10,000 ($123), and sell to the general public.

Potentially one of the best routes to market for portable fuel cell companies is to partner with large multi-national manufacturers to develop bespoke solutions and indications are that a number of companies are considering this route. One notable announcement in the past year was from Lilliputian Systems which is working with Intel to provide silicon wafer manufacturing capacity for its butane powered USB Mobile Power System (MPS). Since it has secured mass production capability Fuel Cell Today anticipates a commercial launch in the near future.

Stationary

Stationary fuel cell shipments in 2010 grew by 10% compared to 2009, reaching 7,400 units. This application ranges from micro combined heat and power (micro-CHP) and uninterruptible power systems (UPS), all the way up to multi-megawatt prime power installations. Key areas for deployment are those which allow the power generated to be fed into the grid through feed-in tariffs, or for other credits or subsidies to be earned. In terms of total megawatts generated, this application has remained fairly consistent, with between 30 and 35 MW per year. In 2007 the stationary sector accounted for 83% of total megawatts shipped; this has since decreased to around 40% due to growth in the transport sector.

In the small stationary sector (≤10 kW), residential micro-CHP systems dominate in terms of shipments, enjoying seven times as many units shipped in 2010 compared to those for uninterruptible power systems (UPS).

Prime Power

In the large stationary sector, a handful of companies dominate the market with systems using a range of electrolytes. FuelCell Energy has been partnering with POSCO Power of South Korea to market its MCFC technology for grid-connected prime power applications in Asia. Having already installed more than 40 MW of fuel cell generation capacity in Korea, POSCO Power completed the construction of a 100 MW Balance-of-Plant (BoP) facility located outside Seoul. With this new manufacturing capacity, POSCO Power is aggressively targeting the deployment of multi-megawatt scale power plants as part of the recently confirmed Renewable Portfolio Standard (RPS), discussed in more detail in the Development by Region: Asia section of this Review. POSCO Power’s BoP facility will take stacks from FuelCell Energy and integrate the necessary parts for application in the Korean market. As part of the RPS, POSCO Power announced plans to build a 60 MW fuel cell power plant in two stages by 2013, which once complete would be the largest fuel cell installation in the world.

UTC Power continues to ship its PureCell 400 kW PAFC systems to customers throughout the USA, including six units to the new buildings on the site of the World Trade Center. In total, twelve units will provide 30% of the energy needs of Towers 3 and 4 on the site. PureCell 400 kW fuel cells are also operating across America in supermarkets, office buildings and residential properties, proving the versatility of the technology for both power and heating/cooling applications.

In Japan, Fuji Electric continues the development of its PAFC system to further reduce costs and increase sales to both domestic and international customers. Its 100 kW systems can operate in a number of useful conditions and can provide power for both heating and cooling applications.
modes even when the heat and power are not required. For example, when running on methane, the systems can produce up to 8 Nm³ of hydrogen per hour – so the system could provide electricity and heat during the day, and produce hydrogen overnight which could be used to fuel a bus, or a small fleet of light duty vehicles. Another innovative market for its product is in the provision of low oxygen-content air for fire suppression systems. The exhaust gas can be used to create a reduced oxygen environment, suitable for fire suppression in computer data centres and similar environments. Containing around 15% oxygen, the exhaust gas is too low in oxygen to support combustion, but high enough for humans to work safely.

Having previously been considered something of a dark horse in the industry, Bloom Energy emerged to great fanfare in 2010, announcing the launch of its Bloom Box. The 100 kW SOFC system, called the Bloom Energy Server, has been bought by household names such as Walmart, Google, eBay and Coca-Cola and runs on natural gas or biogas.

An event of perhaps greater significance, not only for Bloom Energy but for all current and potential users of fuel cells, came later in the year with the launch of Bloom Electrons; this is offered as a service whereby customers can purchase the power produced by Bloom Energy Servers without incurring the upfront cost of purchasing the unit. Bloom Energy owns and services the units, with electricity prices fixed for a period of ten years and savings of up to 20% being claimed in comparison to using grid electricity. Early customers for the service include health care provider Kaiser Permanente and the California Institute of Technology.

Bloom Energy Servers can cost up to $800,000 per unit, meaning the capital outlay can be prohibitive to adoption of the technology for all but the largest companies; by removing this barrier, the Bloom Electrons business model eases the financial burden of fuel cell adoption. If successful, and if costs can be reduced further, Bloom Energy hopes to expand into the residential market in the future.

Successes for prime power fuel cells thus far will continue as companies and governments alike acknowledge the benefits fuel cells offer as alternatives to nuclear or fossil-fuelled power plants.

**Micro-CHP**

Current successes in the market for residential micro-CHP fuel cells are centred on Asia, specifically Japan, with the continuation of shipments under the Ene-Farm brand. By the end of 2010, cumulative shipments of these units had reached 13,500, all of which are PEMFC. Improvements have been made to the system since the launch of the project, enabling both a smaller footprint and higher efficiencies – both vital for products destined for use in homes and apartments. A solid oxide variant, such as that under development by Eneos Celltech, is planned for inclusion in the scheme in 2011 and boasts further efficiency gains.

Subsidies for these systems are being phased out and it is clear that the cost has reduced in the past five years. During the demonstration phase from 2005 to 2008, costs were reduced from ¥6.0 million ($73,609) to ¥2.2 million ($26,990) per unit. From 2009 onwards, the subsidy is calculated as a proportion of the difference in cost between a fuel cell unit and a conventional boiler plus the cost of installation. The subsidy is capped at a maximum of ¥1.3 million ($15,949) per unit as of 2010, and plans are to eliminate the subsidy once increased production volumes enable economies of scale, making the units affordable and cost-competitive on their own.

A project similar to the Ene-Farm scheme is underway in South Korea with the first phase of field trials continuing in 2010. Known as the Green Home Project, and including fuel cells, geothermal and solar systems, its aspiration...
is to install one hundred thousand 1 kW residential fuel cell systems by 2020. Initial subsidies for Korean fuel cell micro-CHP systems reached 80% of the total costs, significantly higher than in Japan, but like its neighbour, the Government plans to decrease its contribution to around 50% by 2013 and eventually phase it out altogether.

In Europe, the market for residential micro-CHP is still at a relatively early stage, with demonstration projects running in Denmark trialling both PEMFC and SOFC technology. Among others, Germany and the UK are interested in developing this market to replace conventional boiler technology with fuel cells. Ceres Power had planned to begin residential micro-CHP trials in 2010, but was forced to delay its testing until early 2011. The unit has been granted CE mark approval and satisfies requirements under the Gas Appliance Directive and, working with a number of well-known European companies including British Gas, Calor Gas and Daalderop, a small number of Ceres Power’s wall-mounted natural gas powered fuel cells were installed in consumers’ homes during the first quarter of 2011. The second wave of products is planned to follow six months later and will incorporate valuable field experience. The final stage, installing at least 150 field trial micro-CHP products, will take place in 2012 to test the group’s ability to scale up production.

One of the biggest names in the global stationary micro-CHP sector, Japanese manufacturer Panasonic, has signalled its intent to open a development facility for European fuel cell micro-CHP systems, located in Germany. As a result of this commitment from household names in the industry to tailor systems to the European market, Fuel Cell Today anticipates rapid progress for micro-CHP systems in Europe.

The North American market for fuel cell CHP systems differs from those of Europe and Asia, principally in the size of unit which is needed. In Japan and Europe, small units of 1 to 2 kW are sufficient for residential needs, whereas the power demand in the USA is much greater, and so companies like ClearEdge Power are introducing 5 kW fuel cells in this region. ClearEdge Power is not restricting itself to just residential sales, but is offering its fuel cells to commercial customers. Its ClearEdgeS fuel cell system has been adopted by residential customers, schools and hotels, providing both power and high-grade heat.

In the outlook section of this report we consider the potential for further growth in fuel cell CHP applications worldwide, which will be one of the major sources of shipments in the next few years.

**UPS**

In the UPS sector, shipments continued in 2010 and were dominated by orders from the USA. IdaTech continued sales of its ElectraGen series, introducing a methanol-powered variant in addition to its current hydrogen-fuelled backup system. These units provide backup power to telecommunications systems, emergency communications and a variety of other applications around the world. Many fuel cell companies are still privately funded, loss-making enterprises and continually strive for profitability as they grow. IdaTech is no exception but reported in 2010 that 80% of units it shipped were profitable, compared to 2% the previous year; a significant
step forward on its path to profitability. Markets offering the biggest potential for its technology currently lie in Asia; a high-profile agreement with Cascadiant Inc. to install fuel cell backup systems across Indonesia was announced in 2010.

Shipments of ReliOn’s hydrogen PEMFC backup system have remained strong, with its target markets of telecommunications and off-grid power recognising the benefits fuel cells offer over conventional technologies. In 2010 it introduced a bulk refuelling system for use with its installations as part of a US Department of Energy (DoE) funded market transformation project, enabling 72 hours of backup power to be available before refuelling is necessary.

Alteryg Power Systems’ Freedom Power range of UPS fuel cells also continues to prove popular, with installations at home in the USA and significant deals in place to introduce its fuel cells to the African market, covered later in this Review. Its fuel cells have also been used to power lighting at a number of high-profile events, including the Golden Globe Awards and at the final launch of the Space Shuttle Endeavour.

Electro Power Systems, based in Turin, Italy, has attracted €5 million ($7.2 million) private equity investment this year on the back of strong performance. The company launched its ElectroSelf™ UPS product in India in December 2010 and sees a large market for its products in Asia, complementing its growing installed base in Europe. The ElectroSelf™ is a self-recharging backup power system integrating a fuel cell and electrolyser and requiring only minimal maintenance in the form of a water top-up once a year.

As global energy demand increases, the stability of national grid infrastructure will become a key concern. The future contribution to national power supplies from nuclear energy is also increasingly uncertain, possibly making this balance even more precarious. Fuel Cell Today sees strong potential for fuel cell UPS systems globally, providing clean, efficient power and peace of mind to operators of critical infrastructure.

Transport

The transport sector grew by 20% in 2010 to reach a new high of 2,400 units shipped. Fuel cells provide two main solutions in this sector, either contributing to the primary powertrain or fulfilling the role of range extender. Even for transport sub-segments both solutions could prove viable. The transport sector covers a wide variety of end-uses, from the more conventional cars and buses, to more niche uses such as ferries, unmanned aerial vehicles (UAV) and underwater vehicles for the military.

In the materials handling segment, hydrogen PEMFC are being used to provide the main propulsion to fleets of forklift trucks, replacing the current battery technology altogether; fast refuelling times and the facilitation of 24 hour shift patterns make the capital cost of installing refuelling infrastructure acceptable. At the opposite end of the spectrum, liquid methanol powered DMFC are hybridised with the existing battery technology to operate as range extenders for smaller fleets in single shift operation. In this example, the ability of different fuel cells to exploit their advantages in a non-competitive way opens up a much wider portion of the forklift truck market than would otherwise be economical with a single technology; the same can be seen across the transport sector, for example fuel cells as APU in truck sleeper cabs.

Materials Handling Vehicles

Half of all shipments in the transport sector for 2010 were for materials handling vehicles, continuing the success of this application in recent years. The vast majority of these were shipped to the USA, which has
enjoyed significant financial assistance from the American Recovery and Reinvestment Act (ARRA). Plug Power in particular has shipped a large number of its hydrogen powered GenDrive units which find success in replacing batteries in fleets of electric lift trucks operating in multiple shifts. In 2010 Plug Power added high-profile customers like Coca-Cola, BMW and Wegmans to its list of GenDrive users.

In this industry, continuous shift patterns result in a sufficiently high utilisation to mean installation of the necessary hydrogen refuelling infrastructure becomes cost competitive; coupling this with the space savings achieved from the removal of battery charging and exchange equipment means more space is available for warehouse storage. Refuelling takes roughly two to three minutes, much faster than battery charging, and during operation hydrogen fuel cells do not lose power as their fuel levels decrease, unlike batteries which noticeably lose performance as charge levels drop. For the first time in the materials handling sector a successful business case for sales has been made without the need for subsidies, something of great importance to any emerging industry and crucial here since ARRA funding in this sector is likely to reduce in coming years with projects drawing to a close.

During 2010, Plug Power focused on its domestic market in North America, but the first quarter of 2011 saw it successfully enter Europe, securing an order for ten GenDrive fuel cell units destined for France. These units will be modified to make them compatible with European materials handling equipment and signify Plug Power’s intent to grow its interest globally.

Unit shipments of DMFC range extenders for materials handling equipment are also continuing to grow, with leading provider Oorja Protonics securing orders from high-profile US food distribution companies such as Martin-Brower (the sole distributor to McDonalds) to grow its fleet of fuel cell vehicles. DMFC technology works together with the existing batteries to extend the operating range and therefore utilisation of materials handling fleets. Additionally, by managing the charge–discharge cycles more effectively, the lifetimes of batteries are increased, offering additional cost savings.

**Light Duty Vehicles**

Since the signing in late 2009 by eight of the world’s major automakers of a Memorandum of Understanding (MoU) signalling their intent to commercialise FCEV by 2015, this statement has been confirmed at regular intervals throughout 2010 and into 2011. The introduction of new automobile technology is not a quick process and many years of development and testing must be undertaken to ensure the product is fit for market before introducing it to the public. Historically, FCEV developers may have tried to circumvent this process and shorten the time to market for fuel cell cars, which may have led to deployments either being delayed or the vehicles failing to materialise altogether, outside of test fleets. Current test fleets have accrued millions of miles on the road in real world conditions, with Daimler even circumnavigating the globe using three of its Mercedes B-Class F-CELL vehicles in 2011.

In early 2011, an MoU was signed between Hyundai-Kia Motors (HKM) and representatives of Sweden, Denmark, Iceland and Norway to provide hydrogen fuel cell vehicles and develop the necessary refuelling infrastructure in the region. In 2006 Sweden, Norway and Denmark formed the Scandinavian Hydrogen Highway Partnership to develop and connect hydrogen projects in the region and, as part of the new MoU, HKM will focus deployment of its vehicles here, aiming to establish itself as a leader in the field of FCEV. Copenhagen in Denmark has committed to replacing 85% of the city’s official vehicles with green vehicles by 2015 and has aspirations to
become the world’s first CO₂ neutral city by 2025. Having already mandated an end to the purchase of ICE
vehicles for its municipal fleets, it is keen to adopt fuel cell technology.

Daimler took a step towards establishing production facilities with its decision to lease 21,000 square feet of
production space from Ballard beginning in August 2011 until 2019. The surplus space at Ballard’s Burnaby,
Canada facility was made available through streamlining and the introduction of continuous processing;
Daimler will use this space for automotive fuel cell manufacture for its Mercedes-Benz marque.

In the UK, the iconic London black taxi was remodelled in 2010 by a group of companies including Intelligent
Energy and Lotus to integrate a hydrogen fuel cell and a fleet of twenty vehicles is to be produced in time for
the 2012 London Olympic Games. Two of the taxis are currently operating on the streets of London and the
remainder are due for delivery in 2011.

Alternative deployment models for fuel cell vehicles are emerging from companies such as UK start-up
Riversimple, which intends not to sell its vehicle to customers, but to lease it for around £200 ($326) a month
plus £0.15 ($0.24) per mile including fuel. Leicester has been selected as an initial location to test its hydrogen
fuel cell powered cars. The twelve-month trial should be underway by mid-2012 with 30 of the two-seater
vehicles; the company also plans to site and operate a refuelling point. If the trial is a success, the company
intends to discuss the siting of a production facility in the city to produce 5,000 fuel cell vehicles per year.

Similar to the materials handling market, range extenders also feature in light duty vehicles and companies such
as Proton Power Systems and Volvo are exploiting this niche. Proton is partnering with Smith Electric Vehicles
to integrate fuel cell range extenders into its existing range of electric delivery vehicles. By targeting an existing
electric vehicle manufacturer, Proton avoids the hurdle of convincing its customers to switch from ICE to electric
technology and is able to simply offer the same type of electric vehicle, but with a significantly greater range.
Volvo is working with PowerCell Sweden with backing from the Swedish Energy Agency to assess the feasibility
of coupling a 30 kW range extender to its C30 DRiVe Electric vehicle. Hybridising a fuel cell with a battery in this
manner is expected to offer up to 250 km additional range versus the battery alone and Volvo hopes to have a
product ready for testing by 2012.

The continued focus on 2015 as the commercialisation date for FCEV, and the concurrent announcements
regarding the introduction of infrastructure, give Fuel Cell Today increased confidence in presuming that this
time the technology is ready for market and can be introduced cost effectively to many areas with sufficient
hydrogen refuelling infrastructure.

Fuel Cell Today anticipates the initial commercialisation of fuel cell vehicles will be on the order of tens of
thousands of vehicles from 2015, with the majority of these being adopted by return-to-base fleets, which
can operate the vehicles within the confines of the limited hydrogen infrastructure expected at the time. With
increasing economies of scale, and further expansion in the number of hydrogen filling stations, widespread
public adoption of the technology will begin some years after that, but the early adopters will provide more than
enough demand for the initial stage.

Buses

The market for fuel cell buses is an attractive and high-profile way to highlight fuel cell technology and introduce
it to the public as a viable transportation solution. Fuel cell buses are expensive, due to the small number
produced worldwide, but they are one of the few commercially available fuel cell vehicles currently on the

market. One notable example of efforts to minimise the cost of fuel cell buses is the modular approach taken by Daimler. Two of its B-Class automotive F-CELL units are used in combination to form the powertrain for its Citaro bus system, thereby sharing the development cost between multiple projects. Other projects to coordinate the purchase of fuel cell buses are trying to leverage economies of scale, but these are limited to regions where funding is available. Europe is a good example of this and the current CHIC (Clean Hydrogen In European Cities) project is building upon previous work by the CUTE (Clean Urban Transport for Europe) and HyFleet:CUTE projects and is planning a staged introduction of hydrogen fuel cell bus fleets and supporting infrastructure in Europe. Phase 1 of CHIC plans to roll-out a total of 26 buses across four countries: London (UK), Oslo (Norway), Milan and Bolzano (Italy), and Aargau/St Gallen (Switzerland). In London, five buses are already in operation and Transport for London (TFL) has secured €5.67 million ($8.1 million) in funding from CHIC for a further three buses for use on route RV1. By the end of 2011, once all eight buses are in operation, the entire route will be served by zero-emissions fuel cell buses. The London Hydrogen Partnership also published a hydrogen action plan pledging to support the introduction of more hydrogen-fuelled vehicles in the capital, aiming to encourage a minimum of 150 hydrogen-powered vehicles on the road in London by 2012, including cars, vans, taxis, motorbikes, and lorries.

In the USA, the SunLine Transit Agency took delivery of its latest sixth-generation fuel cell bus, which boasts weight reduction, improved reliability and better performance. The agency has run fuel cell buses since 2002, and also runs hydrogen refuelling infrastructure which it makes available to the public. The sharing of infrastructure in this way benefits both parties, with the bus operator benefiting from increased utilisation and revenues, and early adopters of FCEV enjoying a greater number of locations where refuelling is available. With plans to continue its development of a fuel cell bus fleet, SunLine Transit secured funding from the Federal Transit Administration, CALSTART, California Air Resource Board (CARB), and California South Coast Air Quality Management District for an advanced fuel cell hybrid bus project. The 40-foot bus will be developed in conjunction with Ballard Power Systems and BAE Systems and is scheduled for delivery by the end of 2011. Elsewhere in the USA, AC Transit announced its fleet of fuel cell buses had exceeded 250,000 miles in operation, averaging 65% higher fuel economy than comparable diesel fuelled buses. Powered by UTC PureMotion Model 120 stacks, two of the buses have exceeded 6,000 hours in service with no cell replacements necessary.

In Canada, twenty fuel cell buses were in operation during the 2010 winter Olympics in Whistler. Operated by BC Transit, the buses are powered by fuel cells from Ballard Power Systems and an operating range of 300 miles between refuellings is reported. North America and Europe are not the only regions where fuel cell buses are being developed. Singapore unveiled its first fuel cell bus in 2010, used at the Youth Olympic Games. The 72-seater vehicle was developed by engineers from Nanyang Technological University and China’s Tsinghua University. In November 2010, Air Products provided the hydrogen for a fleet of more than 50 hydrogen fuel cell shuttle buses that transported athletes and government officials at the Asian Games and Asian Para Games in Guangzhou City, China.
Due to the tendency for bus fleet orders to coincide with high-profile events, orders tend to be placed in batches, with large numbers one year, and none placed in subsequent years. The worldwide market for fuel cell buses is currently very small, therefore this erratic ordering can make progress difficult to identify. Fuel Cell Today sees costs decreasing and durability increasing and considering the implementation of low-emission zones in major cities and the desire to encourage public transport, fuel cell buses are perfectly suited to meet these criteria.

**Other Transport**

While units for materials handling, buses and light duty vehicles make up the majority of fuel cell shipments in the sector, ranging from unmanned aerial and underwater vehicles for the military, to fuel cell scooters, trains, ferries and boats. For each of these applications fuel cells offer benefits over incumbent technology. The increased range and time between refuelling is of benefit to virtually all transport users; low noise and heat signatures appeal to military users; powering vessels on inland waterways is increasingly subject to tightening emission legislation, and fuel cells easily meet the required targets.

One announcement of note came from Intelligent Energy which revealed its Suzuki Burgman Fuel Cell Scooter had been given Whole Vehicle Type Approval (WVTA). If a prototype passes testing under the EC WVTA system, vehicles or components of the same type are approved for production and sale within Europe without further testing; this is a development easing the path to full commercialisation of fuel cell motorcycles in the region. Global sales of e-bikes are growing rapidly, with China reporting more than 20 million sold in 2009, and Europe and the USA with 2010 sales at 1 million and 300,000 respectively. If a fuel cell e-bike were developed for sale at a competitive price, it would offer emissions-free travel with rapid refuelling and a potentially better range than its battery counterparts. This is one of the few transportation segments which has the potential to grow into a significant market in terms of unit shipments.

**Fuel and Infrastructure**

Due to the diverse range of potential fuels for fuel cells in each market, such as stationary (methane, hydrogen, biogas), portable (methanol, hydrogen, butane) and transport (hydrogen, military fuels, methanol), a universal refuelling network will never be a realistic possibility. Instead, divisions are emerging by application and region where the adoption of fuel cells is most advanced. In the portable sector, a range of fuels are currently in use, including hydrogen and methanol, and others are being developed for the future, including butane. Each individual portable fuel cell manufacturer has had to develop the necessary refuelling system for its device, and also establish a mechanism for distribution, leading to a patchwork of solutions in the sector. For methanol powered systems, SFC Energy is a good example having established distribution of its methanol cartridges at 1,000 retailers worldwide. Hydrogen-fuelled portable devices, such as those sold by Horizon Fuel Cell Technologies, have also required the development of bespoke fuelling systems and interfaces. In addition certification is vital, especially when the intended users have no specific training, therefore sealed systems and safety mechanisms must be included.

In the stationary fuel cell sector, a greater degree of standardisation is possible, with fuel cells integrating into existing infrastructure using municipal gas supplies, hydrogen from cylinders or pipelines and reformed liquid fuels. Fitment and refuelling also tends to be carried out by trained professionals, so while safety is still important, the associated risks are minimised.
In the transport sector, standardisation will be essential to enable the commercial success of fuel cell vehicles; with the model for public fuel cell vehicle deployment mirroring that of current ICE, all refuelling stations and vehicles will have to use standardised fittings. The delivery of hydrogen at high pressure is also a very different challenge from pumping liquid fuels at atmospheric pressure, so the sealing interface will have to be robust and incorporate fail-safe mechanisms to avoid accidents and meet safety regulations.

One high-profile development during 2010 was the launch of ITM Power’s Hydrogen On-Site Trial (HOST) project in the UK. Held at London Stansted Airport, the event attracted 300 attendees, with a mix of investors, analysts, government representatives, industry and the media. The launch included a demonstration of the HFuel refuelling system, which is fully automated using grid electricity and tap water purified inside the unit. The trials will be conducted with hydrogen ICE Ford Transit vans, using hydrogen pressurised to 35 MPa.

Germany is seen as a key region for implementation of a hydrogen infrastructure. Tens of thousands of FCEV are expected to be on the road by 2015, in Germany and elsewhere. These will not be mass-market developments, but rather controlled roll-outs to selected customers with return-to-base fleets. Germany plans a nationwide supply of hydrogen to be developed in time for the planned roll-out to attract fuel cell vehicles to the region, and eventually to link its hydrogen highway with planned developments in neighbouring Scandinavia.

Japan is committed to building its hydrogen infrastructure and a group of oil and gas companies have announced their intention to build 100 hydrogen refuelling stations. JX Nippon Oil & Energy Corporation, Idemitsu Kosan Co. and Tokyo Gas Co. have joined forces with the automakers and plan to install the hydrogen refuelling stations in Tokyo, Nagoya, Osaka and Fukuoka by 2015.

In North America, another region keen to attract fuel cell vehicles, several US states are working to grow their hydrogen fuelling networks. Initially these clusters will not be linked, due to the distances between them, but over time once the vehicles are in operation these may be connected to form a nationwide system. Projects are underway on both the east and west coasts of the USA with California planning to have 20 refuelling stations open to the public before the end of 2011. Hawaii also has plans to use existing hydrogen in its domestic natural gas pipeline, extracting it at strategic points for use in fuel cell vehicles.

The majority of hydrogen used globally is manufactured by steam reforming natural gas, and if this were used in fuel cell vehicles would not make them zero-emissions. Tailpipe emissions for all hydrogen fuel cell vehicles are zero but it is also important to consider the well-to-wheels emissions. Using hydrogen from reformed methane, on a well-to-wheels basis, would represent a 50% reduction in carbon emissions when used in an FCEV (compared with a conventional gasoline car). To truly make fuel cell vehicles zero-emissions, the hydrogen must be generated renewably, for example using wind or solar power. Proton OnSite, under its SunHydro brand, is pursuing this route with the deployment of solar-powered hydrogen-refuelling stations in eight states along the east coast of the USA. It is in talks with the Automotive Oil Change Association (AOCA) with a view to installing its refuelling stations at some of AOCA’s 15,000 oil change and quick lube centres in the USA and ultimately has plans to develop its network across the country from New York to California.

Some stationary installations are using biogas in an attempt to improve the overall emissions of methane-powered high temperature fuel cells. Installing fuel cells at, or close to, sites where waste biogas is produced is one method and FuelCell Energy is collaborating on projects doing just this in California. Another approach taken by some fuel cell customers who have no easily accessible source of biogas is to contract the purchase of biogas with a provider who feeds it into the existing natural gas distribution pipeline. This can have the double benefit of stimulating investment in biogas production at the same time as accelerating clean CHP technology.
Where it is possible for fuel cells to take advantage of existing refuelling infrastructure this approach is being implemented, with waste hydrogen, biogas and natural gas as prime examples. The key to enabling the widespread adoption of hydrogen fuel cells in the future will be the introduction of the refuelling infrastructure. Projects to address this are underway in all regions, aiming to supply hydrogen to coincide with the commercial roll-out of vehicles from 2015.

**Developments by Region**

This section of the Review covers regional developments which affect fuel cells as a whole, including changes to industry associations, collaborative projects, subsidies and government funding. Viewing fuel cell shipments by region of adoption, Fuel Cell Today has seen Europe emerge as a leading user of the technology since 2009, led by sales of educational fuel cells in the region. North America follows in second place with Asia third, and Fuel Cell Today expects this trend to continue during 2011. In terms of megawatts, North America and Asia have traded places at the top during the past five years, due to the dominance of stationary systems in these regions, and together they have accounted for at least 85% of the total since 2007.

Fuel Cell Today expects to see markets in all regions continuing to grow as adoption of fuel cell technology continues. Fuel cell technologies such as those in materials handling and UPS, which to date have predominantly been deployed in the USA, are being introduced in other regions, and the micro-CHP systems popular in Asia are being introduced in Europe. The markets fuel cells serve are truly global, and their potential will be exploited in all regions.

**Europe**

The UK Hydrogen and Fuel Cell Association was launched in July 2010 after the merger of Fuel Cells UK and the UK Hydrogen Association. The new industry body is intended to provide a common voice, advocating a positive social, political and economic environment for the development of hydrogen energy and fuel cells in the UK. Membership comprises fuel cell and hydrogen companies and also a wide range of stakeholders from energy utilities to component developers and fuel suppliers.
The UK Government announced a feed-in tariff for residential micro-CHP in April 2010, which includes the fuel cell micro-CHP units currently under trial by Ceres Power. This is intended to encourage the uptake of low-carbon technology. Under the new tariff, a household installing a fuel cell micro-CHP product will receive, for a period of ten years, a generation payment of £0.10/kWh ($0.16/kWh) for all electricity generated plus an additional export payment of £0.03/kWh ($0.05/kWh) for any electricity not consumed in the home that is fed back to the grid.

In June 2011, the UK Government announced it would invest an additional £7.5 million ($12.2 million) in the development of hydrogen and fuel cell technology, aiming to strengthen the UK’s capability in these technologies and attract international investment. The funding will be used to accelerate the adoption of fuel cell technology in low-carbon energy and transport and will take the form of a demonstration programme to be run by the Technology Strategy Board (TSB). Competition for funding under the TSB programme (Hydrogen and Fuel Cells: Whole System Integration and Demonstration) will open in January 2012.

The European Commission Fuel Cell and Hydrogen Joint Undertaking also held its 2010 call for proposals, with a budget of €89.1 million ($127.8 million) available for projects submitted by October 2010. Also in Europe, the H2Mobility programme is continuing its work, planning for the necessary infrastructure to be in place by 2015 to meet the requirements of nascent fuel cell vehicle fleets. Working closely with McKinsey & Co., a wealth of data has been collected from the participants in the programme and published as a freely available report entitled: A Portfolio of Powertrains for Europe: a Fact-Based Analysis. The report found that a combination of battery electric vehicles, FCEV and plug-in hybrid electric vehicles could meet the required emissions reduction targets of 80% by 2050, and that from 2025 the total cost of ownership for the different vehicles converges; no significant barriers were found preventing commercialisation of these vehicles.

A large demonstration project for FCEV, known as H2MOVES, was announced in Oslo. It plans to bring seventeen state-of-the-art FCEV from Daimler and Fiat to the city and includes the establishment of a hydrogen refuelling station in the city by H2 Logic. This is a Scandinavian initiative to advance the commercialisation of hydrogen for transport as well as connecting the region with the fuelling infrastructure in neighbouring Germany. The project has a budget of €19.5 million ($28 million), financed by company contributions as well as European Union (EU) and national funding from Norway and Denmark. Ten Mercedes-Benz B-Class F-CELL cars from Daimler (Germany), two Alfa Romeo MiTo fuel cell vehicles from Centro Ricerche Fiat (Italy) and five electric city cars with fuel cell range extenders from H2 Logic (Denmark) are to be provided in 2011 for daily operation.

A hydrogen refuelling station from H2 Logic will be designed and built in Oslo to offer hydrogen with a fully integrated purchase interface. The station will comply with the latest international hydrogen refuelling standard SAE J2601, ensuring safe and fast refuelling in minutes, and will be based on a combination of on-site production and trucked-in hydrogen. Norwegian electricity, of which more than 90% is based on renewable hydro and wind power, will provide the basis for the hydrogen generation.

During 2010 and into 2011, the EU finalised a free trade agreement (FTA) with South Korea, lowering tariffs and import/export duties between the two countries. With a mutual interest in developing fuel cell technologies, this new agreement could open up new

A large demonstration project for FCEV, known as H2MOVES, was announced in Oslo. It plans to bring seventeen state-of-the-art FCEV from Daimler and Fiat to the city and includes the establishment of a hydrogen refuelling station in the city by H2 Logic. This is a Scandinavian initiative to advance the commercialisation of hydrogen for transport as well as connecting the region with the fuelling infrastructure in neighbouring Germany. The project has a budget of €19.5 million ($28 million), financed by company contributions as well as European Union (EU) and national funding from Norway and Denmark. Ten Mercedes-Benz B-Class F-CELL cars from Daimler (Germany), two Alfa Romeo MiTo fuel cell vehicles from Centro Ricerche Fiat (Italy) and five electric city cars with fuel cell range extenders from H2 Logic (Denmark) are to be provided in 2011 for daily operation.

A hydrogen refuelling station from H2 Logic will be designed and built in Oslo to offer hydrogen with a fully integrated purchase interface. The station will comply with the latest international hydrogen refuelling standard SAE J2601, ensuring safe and fast refuelling in minutes, and will be based on a combination of on-site production and trucked-in hydrogen. Norwegian electricity, of which more than 90% is based on renewable hydro and wind power, will provide the basis for the hydrogen generation.

During 2010 and into 2011, the EU finalised a free trade agreement (FTA) with South Korea, lowering tariffs and import/export duties between the two countries. With a mutual interest in developing fuel cell technologies, this new agreement could open up new
business opportunities on both sides with a clear advantage over other countries. Some of the main benefits for EU exporters are the removal of €1.6 billion ($2.3 billion) of customs duties which EU exporters to South Korea face every year. On the first day the agreement enters into force some €850 million ($1.2 billion) will be removed, increasing over time. Potential gains will be even higher as the trade between the EU and South Korea is expected to expand due to the FTA.

Overall, Europe remains a promising region for fuel cell adoption, supported by clear government policies and incentives. The commercial roll-out of stationary and portable fuel cells is helping gain early market adoption and demonstrate the technology to the public in various applications.

**North America**

Towards the end of 2010, the US Fuel Cell Council and the National Hydrogen Association announced they would join forces to accelerate the commercialisation of fuel cell and hydrogen energy technologies. The newly formed Fuel Cell and Hydrogen Energy Association (FCHEA) has spent significant energy since its formation lobbying government for confirmation of funding for fuel cells and hydrogen technologies. FCHEA’s membership represents the entire fuel cell and hydrogen supply chain and the association is headquartered in Washington, DC.

Fuel cell systems are also gaining certification across the USA verifying they meet safety, performance and emission standards in the country. Both UTC Power and FuelCell Energy had products ANSI/CSA FC-1 certified during the year, an award assuring customers and insurers that these fuel cell power plants meet all design, construction, quality, safety and operational requirements; it also confirms they can be safely connected to the existing power infrastructure. This certification can help to lower the cost and time for fuel cell installation, facilitate approval by local inspectors, and increase access to clean energy funding, all of which are necessary for the wider commercialisation of fuel cells.

Both companies also received approval from the California Air Resources Board (CARB), which operates the strictest emission standards in the USA. In 2001, CARB adopted a regulation establishing a distributed generation (DG) certification programme requiring manufacturers of electrical generation technologies which are exempt from district permit requirements to certify their technologies to specific emission standards before they can be sold in California. Both the UTC PureCell 400 and FuelCell Energy DFC3000 met the DG Certification Regulation 2007 Fossil Fuel Emission Standard, meeting the following emissions limits:

- Emissions of oxides of nitrogen no greater than 0.07 pounds per megawatt-hour;
- Emissions of carbon monoxide no greater than 0.10 pounds per megawatt-hour;
- Emissions of volatile organic compounds no greater than 0.02 pounds per megawatt-hour.

These fuel cells will remain certified until 2015, as long as no modifications to the technology are made which affect emissions, efficiency or operating conditions.

Other states are also accommodating fuel cells and hydrogen in their permitting, and in South Carolina the Hydrogen Permitting Act was introduced to uniformly permit hydrogen and fuel cells at the state level using internationally recognised codes and standards. This was the result of a collaborative effort between industry and government organisations led by the Office of the State Fire Marshal. The participants wanted to ensure that commercial and industrial businesses seeking to site hydrogen for energy use, or as a transportation fuel cells are gaining certification by meeting safety and emissions standards across North America.
fuel in the state, are given equal treatment and comply with consistent standards. Authority and responsibility for permitting hydrogen and fuel cell facilities in South Carolina lies under the jurisdiction of the Office of the State Fire Marshal; it provides a central source of expertise while the industry grows, without additional cost to taxpayers in the state.

A new bill was also signed into law in California expanding the types of vehicle eligible to use High Occupancy Vehicle (HOV) lanes. This allows up to 40,000 additional motorists to drive alone using fuel efficient cars in HOV lanes, and includes fuel cell as well as battery electric vehicles. With California already hosting trials of fuel cell vehicles and planning to expand its hydrogen infrastructure to accommodate greater numbers of FCEV by 2015, this announcement could further facilitate consumer adoption of the technology in the state.

Asia

In Japan, the Yamanashi Prefectural Government is planning to ease restrictions on the use of hydrogen fuel in the prefecture. In many places around the world, laws can prohibit the storage and use of hydrogen, for example within a certain distance of public highways. The Yamanashi Government is seeking to address this issue. Its aim is to allow fuel cell vehicles to refuel at motorway service stations, which is banned under existing laws. Hurdles like this may not always be apparent but must be overcome in order for fuel cell vehicles to be widely adopted by the general public. The Yamanashi Government plans to install filling stations along the Chuo Expressway, a major roadway connecting Tokyo and Nagoya, and is also engaging in promotional activities in collaboration with Yamanashi University to encourage use of FCEV.

Further to its plans to introduce hydrogen refuelling infrastructure, the Japanese Government is launching a partnership to investigate the use of refinery hydrogen to fuel FCEV. With the 2015 target for commercialisation in mind, Japan’s Ministry of Economy, Trade and Industry is funding 50% of the initiative to supply high purity hydrogen in conjunction with industrial collaborators.

China has the potential to become a world leader in fuel cell technology and announced in August its ten-year blueprint for the nation’s new energy car industry. According to reports, one plan from the blueprint is to increase China’s annual production of electric cars, hybrid vehicles, hydrogen fuel cell cars and solar cars to 15 million units by 2020. These plans are yet to be approved, but with China having emerged as the world’s biggest market for light duty vehicle sales, there is obvious potential for the future.

The National Assembly of the Republic of Korea announced the successor to its feed-in tariff programme, which ends in 2011, the Renewable Portfolio Standard (RPS). The new standard will come into force in 2012 and mandates 350 MW of additional renewable power capacity per year through 2016, and 700 MW per year through 2022. The RPS affects electricity producers with an annual capacity greater than 500 MW. From 2012, they will be required to generate 2% of their electricity using new and renewable energy (NRE) sources; this percentage will increase by between 0.5% and 1% per year.
year to reach 10% by 2022. Different NRE generation types were ranked in order to calculate the price per kilowatt hour for the energy generated. Higher weightings are better, meaning a higher price will be paid for the electricity generated. Fuel cells received the highest weighted value of 2.0, in recognition of their high capacity factor and environmental advantages. Electricity producers will be paid based on actual energy generated, meaning fuel cells are highly valued in comparison to more intermittent renewable power sources such as solar and wind.

**Rest of the World**

In the Rest of World region, South Africa has shown significant interest in the development of fuel cells during the past year. According to Platinum 2011, published by Johnson Matthey, the country produces more than 75% of the world’s platinum, a key catalytic element used on the electrodes of PEMFC, DMFC and PAFC. This dominance in the platinum industry is driving South Africa’s desire to grow its contribution to the fuel cell industry and, in doing so, add value to one of its key domestic resources.

In August 2010, Altergy Systems announced that it, Anglo American Platinum’s Platinum Growth Metals Development Fund (PGM) and the Government of South Africa, through its Department of Science and Technology (DST), had formed Clean Energy Investments, a company headquartered in South Africa whose principal objective is to manufacture and market Altergy fuel cell systems in South Africa and other sub-Saharan countries. PGM and DST each invested undisclosed amounts in Clean Energy Investments, which will be jointly owned by Altergy, PGM and the South African Government.

This collaboration marked the launch of the South African Government’s Hydrogen South Africa (HySA) strategy to develop a hydrogen economy, expanding uses for the country’s national resources including platinum. Anglo American Platinum is the world’s largest producer of platinum group metals and, according to its website, accounts for 40% of the world’s newly mined platinum.

Altergy’s fuel cells provide backup power for mobile telecommunications sites around the world as an alternative to batteries or diesel generators. Clean Energy Investments initially intends to establish a distribution network for Altergy’s Freedom Power range of fuel cell products throughout the sub-Saharan region. If successful, Clean Energy will then establish a manufacturing and assembly plant in South Africa under licence from Altergy.

This is a significant development: Africa has one of the fastest growing telecommunications markets in the world and has a poor grid infrastructure, therefore there is a genuine opportunity for fuel cells here. According to the Ernst and Young report: Africa Connected: A telecommunications growth story, from 2002 to 2008 it grew at a compound annual rate of 49.3%. Despite the global economic downturn, it is expected that this growth will continue at a faster rate than any other region over the next few years.

Involvement by the South African Government in development projects, such as that with Altergy, continues the work of the National Hydrogen and Fuel Cell Technologies Research, Development and Innovation strategy which began in 2008 and is now known as HySA. Three Centres of Competence (CoC) were established to implement the HySA strategy, and have targets to supply 25% of global platinum group metal fuel cell catalyst demand by 2020; a point reiterated by Science and Technology Minister Naledi Pandor, speaking at the opening of a laboratory in the HySA Systems CoC in September 2010. The HySA centres are developing three main areas: CHP; portable power systems; and hydrogen-fuelled vehicles, and have developed collaborations with industry and academia both at home and abroad.
Elsewhere, in February 2011, the Indian Government announced its budget for 2011-2012 which provided concessions for fuel cell vehicles. The Government is proposing a 10% reduction in excise duty for vehicles based upon fuel cell technology.

At the end of 2010, an interesting collaborative project emerged between Russia and Japan to determine the feasibility of providing Japan with hydrogen generated using wind power on the neighbouring island of Sakhalin. Demand for hydrogen is expected to rise in Japan with the widespread adoption of fuel cells for transportation and household energy. If the feasibility study is successful, the project plans to store the hydrogen as an organic liquid (methyl cyclohexane) and, after transportation, extract the hydrogen for use and return the organic carrier, now toluene, for reuse.

Developments by Electrolyte

The chemistry of each different fuel cell type varies depending on the fuel, operating temperature, nature of the membrane and the composition of its electrolyte. Fuel Cell Today currently considers six main fuel cell types: PEMFC (including HT PEMFC), DMFC, MCFC, PAFC, SOFC and AFC. In terms of commercial success, the leader by far in terms of unit shipments is the PEMFC. This technology serves the biggest number of individual markets and is found throughout the portable, stationary and transport sectors. DMFC is the second most significant type by unit shipments and is mainly found in the portable sector, apart from some niche transport applications. Fuel Cell Today reports shipment numbers to the nearest 100 units, so while all fuel cell types are establishing markets for themselves, some unit shipments are currently too small to appear in our figures.

In megawatt terms the story is very different. The significance of MCFC, SOFC and PAFC in the large stationary sector makes their contribution much more obvious. With PEMFC expected to be the electrolyte of choice for the automotive industry, its dominance in terms of shipments is likely to continue, but the contribution of other electrolytes to the megawatt total will undoubtedly grow as they are used in more prime power, micro-CHP, large CHP and UPS installations.
Proton Exchange Membrane Fuel Cells

Data compiled by the US DoE demonstrate that platinum loading on PEMFC has decreased by more than 80% between 2005 and 2010. The chart shows this DoE data, also including targets set by the DoE for reductions in platinum loadings for fuel cell catalysts by 2015. It is widely expected that these targets are feasible, and Fuel Cell Today believes they are essential to achieving the necessary cost reductions to enable the widespread use of fuel cells in both new and existing applications. However, in PEMFC, DMFC and PAFC, platinum offers superior performance compared to other catalyst materials in terms of the balance between power density, durability, activity and cost, and is unlikely to be fully removed from fuel cells for these reasons. Research focused on reducing fuel cell platinum content but maintaining catalytic activity should be encouraged in order to ensure fuel cells are successful in the future.

A variant of PEMFC which operates at higher temperatures is emerging in the stationary sector where it is finding application in both micro-CHP and UPS. Running at temperatures up to 200°C, HT PEMFC use different materials, such as polybenzimidazole, in their membranes and are more tolerant to impurities in the fuel streams. When fuelled by methane or other hydrocarbons, the higher stack operating temperature means the stack is more tolerant to the impurity carbon monoxide in the reformed fuel. As a result, the fuel processing system can be much simpler. The additional by-product heat produced by HT PEMFC can also be used as part of an integrated installation, increasing the overall efficiency of these units.

Direct Methanol Fuel Cells

DMFC technology is similar to PEMFC in terms of operating temperature, but the manner in which it processes fuel produces carbon monoxide; this compound is particularly bad for the activity of platinum catalysts. This is not a major problem since adding a small quantity of ruthenium (another metal from the platinum group) to the catalyst ensures the activity of platinum can be maintained. Similar to PEMFC, much research is focusing on methods of reducing the precious metal content of these systems, including the use of alloys and advanced ways of influencing the structure of catalyst particles to incorporate lower cost materials, known as core–shell technology. This takes advantage of a core of less active, cheaper material surrounded by the more active, and costly, metal. Technology advancements like these have the potential to lower costs, but much more development and optimisation is needed to guarantee the necessary levels of activity and lifetimes.

Other Fuel Cells

Other types of fuel cells are finding increasing demand for certain applications. As described in the Introduction chapter, MCFC, SOFC and PAFC are all increasingly popular choices for large stationary units, a trend which is set to continue. SOFC units have also been developed for the small stationary market and there are plans to introduce them into the Ene-Farm scheme in 2011. AFC technology is likely to remain a niche technology, with none of the current large-scale projects planning to include it as an option.
Fuel Cells have for many years been labelled as a technology for the future. In this Review, Fuel Cell Today argues that this is no longer a correct view: fuel cells are commercially available today, and in all regions globally. They fulfill the world’s ever-increasing demand for energy across a more diverse range of applications than any other technology, and our analysis shows this trend continuing. To gain a better understanding of the potential for growth in fuel cell shipments, we will discuss the three main application sectors in turn, each comprising a number of sub-divisions, subject to different drivers and barriers.

**Portable**

The market for portable fuel cells offers potential for growth in both the short and long term. Near-term potential lies with toys, educational units and APU. Sales of PEMFC and DMFC units in this sector have outpaced all other fuel cell shipments for the past five years, and are likely to continue to do so for the near future, with 2011 shipments expected to grow by 25% compared to 2010. The military continues to show a keen interest in the sector and will be a leading driver of developments in portable fuel cells.

Ultimately, one of the biggest opportunities for fuel cells is in consumer electronics and a number of companies are poised to commercially release external charging devices in 2011. While these units will undoubtedly find success providing off-grid power in remote locations, significant improvements in power density are required to enable the miniaturisation necessary for fuel cells to be integrated directly into consumer electronics; only then are they likely to become part of our everyday lives in mobile phones and laptops. If these advances can be realised and costs reduced, it would open up opportunities in a market expected to exceed $950 billion in 2011, according to the Consumer Electronics Association.

**Stationary**

Growth in unit shipments for stationary fuel cells is expected to be led by the micro-CHP market for residential use with total stationary shipments in 2011 growing by 35% on the previous year. The Japanese Ene-Farm project has shown impressive growth since 2005, and currently boasts more than 13,000 installations across Japan; Fuel Cell Today expects this project to continue growing. Amid concerns over the provision of electricity in Japan, with nuclear power falling out of favour, fuel cell micro-CHP units offer some degree of independence from the national power grid. In other countries such as Korea, Denmark, Germany and the USA, micro-CHP projects are at various stages of testing and introduction. If we apply the known growth rate from the Japanese deployment to just four of these additional projects worldwide, we can reasonably expect to see more than 20,000 units sold globally each year by 2014, and 100,000 units installed cumulatively by 2015.

Deployment of UPS systems is expected to grow, predominantly due to interest from the rapidly expanding global telecommunications industry. All regions have shown significant interest in the technology with thousands of units currently installed. Energy security and grid independence are topics of increasing importance and with the potential for sales in India and Africa only beginning to be realised, we expect the UPS sector to show impressive growth during the next three to five years.

The deployment of large stationary fuel cells for prime power is likely to be led by Asia, specifically Korea, where the Government’s RPS is to be implemented from 2012. Fuel cells are awarded the highest weighting of all renewables in the RPS and, with the requirement for electricity producers to generate 10% of their output using new and renewable technologies by 2022, this is a significant driver for adoption of fuel cells.
According to the US Energy Information Administration, Korea ranked eleventh highest in the world in terms of global electricity production capacity in 2007 with a total of 66,200 MW. Our calculations show that by 2022 a total of 5,950 MW of new and renewable capacity must be installed in order to conform to the RPS (not accounting for growth in overall energy production). POSCO Power recently completed the construction of a 100 MW BoP plant near Seoul, and if this produced at maximum capacity for the duration of the RPS, it would still only be able to service 20% of the requirement. We therefore see potential for further expansion of manufacturing capacity in Korea and for the continued adoption of prime power fuel cells in that country.

**Transport**

Fuel Cell Today does not expect to see overall growth in the transport sector in 2011 due to a lack of orders anticipated for the light duty vehicle and bus markets, compared with previous years. Fuel cell buses tend to be bought in batches for specific fleet projects and as such less activity is expected this year. The light duty vehicle sector has completed its product development and testing and is now focusing on 2015 to commercialise the technology. The materials handling industry has been a key adopter of fuel cells, and continues to be an area of growth in 2011, with confidence in the technology having grown to the point at which customers are deploying fuel cell powered forklift trucks as the sole power source on site, with no contingency of the old, battery powered technology. There is further scope for growth in North America, where adoption of these units has been spurred on by funding programmes, but expanding the deployment to other regions will be vital. Cumulative shipments exceeding ten thousand units are easily achievable during the next five years, with the business case succeeding without the need for subsidies.

Fuel cell light duty vehicles have for many years been an area of interest to the general public. On the positive side, the message that fuel cell technology can meet the same daily needs as incumbent technologies in the transport sector is understood, but the seemingly perpetual delays in commercialisation have been negative for the technology. This changed in 2009 with eight of the world’s major automakers committing to produce large numbers of FCEV by 2015. This date has remained fixed since that time, and discussions Fuel Cell Today has held with individual automakers have confirmed that commercial deployments would equate to tens of thousands of vehicles. Initial deployments will be limited to regions where hydrogen refuelling infrastructure is available, and projects to build the necessary stations are underway in Europe, Japan and the USA. Development of fuel cell vehicles has progressed to the point at which they offer comparable performance and longevity to existing ICE vehicles, vital to ensuring a smooth transition. By 2015, if only three of the major automakers achieve their intentions, twenty to thirty thousand vehicles could be introduced globally. While this is tiny in comparison to the 75 million light duty vehicles produced annually worldwide, it would be very significant in terms of fuel cell shipments.

**Conclusion**

In conclusion, the outlook for fuel cells has improved in the last few years. Fuel cells are selling without subsidies in many markets and more than 700,000 fuel cells were sold cumulatively between 2005 and 2011. Portable, stationary and transport applications are all exhibiting growth, with the different electrolytes establishing their roles in the various sectors. By 2015, conservative estimates see upwards of 25,000 units sold per year in each of the stationary and transport sectors, with clear potential for significant growth beyond this.
Throughout the five-year period, portable shipments have been underpinned by sales of fuel cell APU into the leisure segment. Portable unit shipments accelerated rapidly in 2009 with high consumer sales of fuel cell toys and education kits. To a lesser extent, shipments were augmented by the launch of portable consumer electronics devices in that year. Shipments of stationary fuel cells have ramped up steadily since 2007 with deployments of micro-CHP particularly in Asia, as well as UPS in North America. In the transport sector, hundreds of fuel cell materials handling vehicles have been shipped, particularly since the start of large-scale demonstration programmes from 2008/2009.

Since 2009, Europe has been the dominant region of fuel cell adoption. This reflects the large number of portable fuel cells that have been deployed in APU and toys. North America has seen strong growth since 2009 with the roll-out of FCEV and materials handling demonstration fleets, sales of portable fuel cells, stationary prime power and UPS shipments. Asia saw strong growth in adoption in 2008/2009 as the commercial deployment of Japanese fuel cell micro-CHP products took place.

Until 2008, DMFC was the leading type of technology due to its use in APU. Since then, applications which use PEMFC have grown rapidly. PEMFC technology dominates fuel cell shipments due to its widespread use in toys, small stationary, and transport applications. Due to the relatively small number of PAFC, AFC and MCFC units shipped and the impact of rounding, no values appear in the table above.
In terms of megawatt shipments, stationary power remains one of the largest sectors, indicating the importance of large stationary installations as well as the high number of micro-CHP units being shipped to Asia. The impact of materials handling and FCEV demonstration programmes can be seen from 2009 onwards when there was a rapid increase in megawatts shipped in the transport sector. Although portable fuel cells are important in terms of unit shipments, due to their small size they are the least important in terms of shipments by megawatt.

Over the last five years, North America and Asia have competed for position as the leading region of adoption by megawatt. This is largely explained by the role of large stationary prime power and CHP/UPS in those regions. The USA and South Korea have been leading the adoption of large, multi-megawatt stationary units in recent years.

PEMFC technology is used in a range of application segments, for instance in transport and stationary applications, and has a power range up to hundreds of kilowatts. Therefore PEMFC has dominated the shipments by megawatt since 2008. Due to the large size of many PAFC, MCFC and SOFC units, the megawatt shipments appear disproportionate to the number of units shipped.
Table Notes

- Our 2011 figures are a forecast for the full year.
- The regional numbers represent system shipments by region of adoption.
- Unit numbers are rounded to the nearest 100 units.
- Megawatt numbers are rounded to the nearest 0.1 MW.
- Portable fuel cells refer to fuel cell units designed to be moved. They include fuel cell toys, APU, and consumer electronics.
- Stationary fuel cells refer to fuel cell units designed to provide power at a fixed location. They include small and large stationary prime power, backup / uninterruptible power supplies, combined heat and power, and combined cooling and power.
- Transport fuel cells refer to fuel cell units that provide propulsive power or range extender function to vehicles, including UAV, cars, buses, and materials handling vehicles.
- Our geographical regions are broken down as follows: Asia includes all Asian countries including Japan; Europe comprises all eastern and western European countries, including Iceland; North America comprises Canada and the United States; the Rest of the World region includes all other countries.
- Shipments by fuel cell type refer to the electrolyte. The six main electrolyte types are included here; high temperature PEMFC and conventional PEMFC are shown together as PEMFC. Other types of fuel cell such as microbial fuel cells are not included in our numbers as these are generally still at the R&D stage.
- The data presented here are based on interviews between Fuel Cell Today and key industry players, publicly available sources such as company statements or stock market filings, and planned demonstration programmes by companies and governments.
- The data presented here may differ from those previously published by Fuel Cell Today: Fuel Cell Today’s applications have been redefined to include APU in the portable sector; shipment figures are based on region of system adoption; and the dataset has been updated in the light of new information.
GLOSSARY

AFC – Alkaline Fuel Cell.
AOCA – Automotive Oil Change Association.
APU – Auxiliary Power Unit.
BoP – Balance of Plant.
Capacity Factor – for power plants this is defined as the ratio of the actual output over a period of time to the output had it operated at full nameplate capacity for the same period.
CARB – California Air Resources Board.
CCP – Combined Cooling and Power.
CE – Conformité Européenne.
CHIC – Clean Hydrogen In European Cities.
CHP – Combined Heat and Power.
CO₂ – Carbon Dioxide.
CoC – Centre of Competence.
CUTE – Clean Urban Transport for Europe.
DG – Distributed Generation.
DMFC – Direct Methanol Fuel Cell.
DoE – Department of Energy (USA).
DST – Department of Science and Technology (South Africa).
EU – European Union.
FCHEA – Fuel Cell and Hydrogen Energy Association (USA).
FTA – Free Trade Agreement.
Gas Appliance Directive – European legislation intended to remove technical barriers to trade and establish a single market for safe gas appliances, providing protection for consumers across the European Union.
HKM – Hyundai-Kia Motors.
HOST – Hydrogen On-Site Trial.
HOV – High Occupancy Vehicle.
HT PEMFC – High Temperature Proton Exchange Membrane Fuel Cell.
HySA – Hydrogen South Africa programme.
ICE – Internal Combustion Engine.
kW – Kilowatt.
kWh – Kilowatt-hour.
MCFC – Molten Carbonate Fuel Cell.
MEA – Membrane Electrode Assembly.
MoU – Memorandum of Understanding.
MW – Megawatt.
MPa – Megapascal.
NASA – National Aeronautics and Space Administration (USA).
Nm³ – Normal cubic metres.
NRE – New and Renewable Energy.
OPEC – Organisation of Petroleum Exporting Countries.
PAFC – Phosphoric Acid Fuel Cell.
PEMFC – Proton Exchange Membrane Fuel Cell.
PGM – Platinum Growth Metals Development Fund.
R&D – Research and Development.
RD&D – Research, Development and Demonstration.
RoW – Rest of the World.
RPS – Renewable Portfolio Standard (South Korea).
SOFC – Solid Oxide Fuel Cell.
TfL – Transport for London.
TSB – Technology Strategy Board (UK).
UAV – Unmanned Aerial Vehicle.
UPS – Uninterruptible Power Supply.
USB – Universal Serial Bus.
V – Volt.
W – Watt.
Wh – Watt-hour.
WVTA – Whole Vehicle Type Approval.

Note on currencies:

Unless stated otherwise, all currencies are quoted in US Dollars ($). The following exchange rates, based on average exchange rates from 1st January 2010 to 1st July 2011, have been used:

$1 = €0.6970
$1 = ¥81.5118
$1 = £0.6140