FUEL CELL BASICS

1. Origins and principle

1. Back to the origins: from the gas battery to the fuel cell

The seminal work of **William Grove** on fuel cells in 1839 is well known nowadays but at the time of his invention, the scientist rather called the device a “gas voltaic battery”. Therefore, while year 1839 is unambiguously considered at the birth date of fuel cells, the first official appearance of the term “fuel cell” will only be found in a publication of the Transactions of the Faraday Society almost one century later, in 1922*. Grove’s first invention, a battery called “Grove cell” was used by the American Telegraph Company due to its high current output until 1860. After having started as a lawyer Grove will turn to a professor of physics, and after then switch between a legal and a scientific carrier several times. With probably some help from the German chemist **Christian Schönbein,** a friend and colleague with whom he is exchanging fruitful ideas; he successfully reverses the electrolysis of water that has been discovered in the early 1800s by English chemists **William Nicholson**, **Anthony Carlisle** and experimented by **Humphry Davy**. Grove constructs a cell consisting of two separate sealed compartments, each one having a porous platinum foil electrode dipped in aqueous sulfuric acid and being fed by hydrogen gas and by oxygen gas, respectively. The experiment however, does not generate enough electricity to do useful work. Therefore, Grove combines in series several sets of electrodes and obtains the actual “gas battery”. He shows this way that a constant current can be drawn between electrodes and observes that water and heat are produced as byproducts. Yet, he is unable to quantify the reaction products and study in much more detail the system he has created. The reason is that these questions could not possibly be answered due to the lack of a comprehensive theory and adequate equipment in the 1840s. He is also conscious that the chief issue is to increase the “surface of action” between the components and comes close to the idea of gas electrodes as used in current fuel cells. It really seems that the man was too much ahead of his time!

Unlike batteries such as the Grove cell, the gas battery is left as a scientific curiosity during a large part of the XIXth century. Times were not up to, should we say. Despite continued technological advancements, applications in the real world have not come to the mind of engineers and inventors. Nevertheless, during the same period the debate is lively among scientists trying hard to clarify the basic principles of electrochemical phenomena. Grove’s gas battery becomes a perfect practical illustration of these theoretical discussions. In order to explain the origin of current flow between certain materials, a “contact” theory involving mere physical contact and a “chemical” theory involving a chemical reaction are opposed. Schönbein and Grove are in favour of the chemical theory. The truth is actually in-between, and after a long controversy it is eventually established that in a gas battery the reaction will only occur in the contact zone between reactant, electrode and electrolyte.

None but the main founder of modern physical chemistry, the Russan-German **Friedrich Ostwald** eventually brings a decisive contribution to the theoretical and experimental understanding of fuel cell reactions in the 1880s. By skillfully associating measurements of physical properties and chemical analysis, and thanks to his work on metal catalysis, he succeeds to explain how fuel cells operate: not only the function of the different components (electrodes, electrolyte and gas reactants) but also their thermodynamically- and kinetically-driven interactions at the interface between the electrode and the electrolyte under the presence of a fuel. This breakthrough in the scientific knowledge about gas batteries is the necessary open door for practical attemps to make them become a reality. At the turning point between the XIXth and XXth centuries, the first systems begins to come out from European and US laboratories as researchers are examining the possibility of converting coal or coal gas directly into electricity. As coal is a fuel, Grove's gas battery changes its name into "fuel battery" and finally "fuel cell" as we know today.

In agreement with Grove's request for a higher contact area between fuel cell components, early developments (50 years after Grove's experiments!) are devoted to experimental improvements in the design, e.g., introduction of more efficient platinum black powder as a catalyst coated on the bulk platinum electrodes and addition of a porous diaphragm in order to impregnate the liquid electrolyte. In 1889 German chemist **Ludwig Mond** and his assistant **Charles Langer** build a device running on air and coal gas known as the "Mond gas". At the same time other systems are setup by US and French teams. Typical problems experienced by researchers are due to materials chosen in the different parts or gas leakages between compartments, which prevent from reaching high voltages upon series combination of the unit cells and cause limited durability. It is also observed that only high-cost precious metals such as platinum can make the reaction with a valuable efficiency. This is obviously deleterious for practical applications of the process.

The end of the XIXth century is also the time for a prospective debate about the possible direct production of electricity from inexpensive coal and combustible gasses: such a perspective is asserted by some authors nothing less than a revolution while strongly tempered by others, (e.g., controversy in the Electrical World Journal in 1895). Finally, consensus is made on the fact that gas batteries are complex and costly systems unable to compete with more simple batteries. In the following period batteries undergo continued development for several applications including cars, whereas gas batteries are put away back in the lab for a few more decades. Let us remind that in the first quarter of the XXth century one third of all automobiles were battery-powered electric vehicles. What visionary mind could have predicted at this time that it would require hundred more years or so before gas batteries, now called fuel cells, could come close to being "ready for market"?

It is therefore at the lab level that the next improvements are obtained on fuel cells. The importance of the kinetics in the electrochemical reactions is discovered. At the beginning of the XXth century, new electrolyte materials performing at higher temperatures than aqueous solutions are explored that will lead to the various types of modern fuel cells: melt carbonates, solid oxides, phosphoric acid. Further historic information about practical developments of a specific fuel cell technology will be found in the corresponding pages of this website. For example, **Francis Bacon**'s pioneering work on acid phosphoric fuel cells is reported in the AFC page.

* According to an alternative thesis, the first fuel-cell system builders Lang, Mond and Jacques were also the inventors of the term "fuel cell" around 1890, but the exact birth date remains elusive and unsolved.

2. The basic principle of a fuel cell

Basically, a fuel cell is a device that converts directly the chemical energy stored in gaseous molecules of fuel and oxidant into electrical energy. When the fuel is hydrogen the only by-products are pure water and heat. The overall process is the reverse of water electrolysis. In electrolysis, an electric current applied to water produces hydrogen and oxygen; by reversing the process, hydrogen and oxygen are combined to produce electricity and water (and heat).

A fuel cell can be seen with profit as a “chemical factory” that continuously transforms fuel energy into electricity as long as fuel is supplied. However, unlike internal combustion engines that can be regarded as factories as well, fuel cells rely on a chemical reaction involving the fuel, and not on its combustion.

During combustion, molecular hydrogen and oxygen bonds are broken and electrons reconfigure into molecular water bonds at a picosecond length scale. There is no possible way to “catch up” these free electrons and the net energy difference between molecular bonds in products vs. reactants can only be recovered in the most degraded form of energy, i.e. heat. A Carnot cycle involving the transformation of heat into mechanical and electrical energy is then involved in conventional methods for generating electricity: these successive steps of transformation of energy severely limit the overall efficiency of the process (which is by definition the product of the efficiency of the different steps).

In a fuel cell the direct conversion of the chemical energy of covalent bonds into electrical energy is made possible by the spatial separation of the hydrogen and oxygen reactants by the electrolyte. The electron transfer necessary to complete the bonding reconfiguration into water molecules occurs over a much longer length scale. This allows direct collection of electrons as a current in fuel cells and leads to fuel efficiencies two to three times higher than in internal combustion engines (depending on the fuel cell technology).

Unlike batteries, there is no chemical transformation of any component of the fuel cell device during operation and it can generate power without recharging, as long as it is being fed with fuel.

The unit fuel cell structure called the membrane electrode assembly (MEA) typically consists of an electrolyte in contact on its both sides with two electrodes, one negative electrode (anode) and one positive electrode (cathode). Fuel is continuously fed to the anode side and oxidant is continuously fed to the cathode side.

Fuel cell reactants are classified as fuels and oxidants on the basis on their electron donor and electron acceptor properties. Oxidants mainly include pure oxygen and oxygen-containing gases e.g. air, or halogens e.g. chlorine. Fuels include pure hydrogen and hydrogen-containing gases, e.g. methanol, ethanol, natural gas, gasoline, biogas, diesel, etc.

In the most straightforward case, i.e. the hydrogen fuel cell the combustion of hydrogen into water is split into two electrochemical reactions occurring at the anode and cathode, respectively, which are termed as the two half-cell reactions:

$H_2 = 2\,H^+ + 2\,e^-$
$\frac{1}{2}\,O_2 + 2\,H^+ + 2\,e^- = H_2O$

Combination of the two half-cell reactions gives the overall combustion reaction:

$$H_2 + \frac{1}{2}\,O_2 \rightarrow H_2O$$

In any fuel cell configuration the role of the electrolyte is crucial because it must insulate the two half-cell reactions electrically in a strict sense while allowing the ionic passage of protons produced at the anode to the cathode side where they will combine and form a molecule of water. As a consequence, electrolytes are both good proton conductors and electric insulators. The third requirement for electrolytes is impermeability to gases in order to separate the anodic and the cathodic compartments, and thus prevent parasitic reactions due to gas crossover. Finally, the electrolyte has to be chemically resistant to any reactant or product during the process.

As passage of electrons is hindered through the electrolyte, they are forced to flow another way. To this purpose, electrodes are connected to an external electrical circuit and instead to follow protons the electrons take this second pathway. This allows direct collection of electricity. Depending on the type of fuel cell, the most suitable electrode materials are of various natures: metals or oxides, catalyzed or not. They are described in the section relative to the members of the fuel cell family. The common feature of fuel cell electrodes is a high surface area in order to maximize each half-cell reaction zone; therefore they are relatively porous compounds.

Every type of fuel cell is characterized by its own particular geometry, dimensions, and materials; yet, the core of the device remains the same: it consists of an electrolyte, two electrodes, and two gas backing layers and most often, bipolar plates separating unit cells.

For the gas backings not less than five different requirements must be fulfilled:

1. Good electronic conductivity to transport the electrons from the electrochemical oxidation of hydrogen most efficiently;
2. High gas permeability to allow easy access of the gas reactants from the feeding source to the reaction zone;
3. High porosity to optimize product water management in the system;
4. Good resistance strength to give a mechanical support to the MEA;
5. High corrosion resistance to the acidic environment in the fuel cell.

The bipolar plates are the interconnecting components that collect the electrons and drive them to the external circuit. They are grooved with channels for gas flow input and output and must manage water as well as possible. The design and the geometric dimensions of the channels (in the order of 1 mm) are crucial for obtaining a homogeneous transport of gases on the whole surface of electrodes, evacuate liquid water droplets formed by the fuel cell reaction, thus achieving stable continuous operation. As every component in a fuel cell, they must be corrosion-resistant; but unlike gas backings, the bipolar plates must be gastight.

2. Benefits of the fuel cell technology

1. Stacks and systems

Now moving from the single fuel cell unit to real-world systems, what do we have to add to get them all setup and why?

Similar to all electrical devices the output power of a fuel cell is equal to the current multiplied by the voltage. While the current may be in theory indefinitely increased by increasing the reaction area between hydrogen- and oxygen-containing reactants, the voltage, i.e. the potential difference between the anode and cathode, is thermodynamically limited to a little more than 1 V by the nature of the two half-cell reactions in a fuel cell: hydrogen oxidation reaction (HOR) at the anode and oxygen reduction reaction (ORR) at the cathode. Moreover, losses inevitably occur in a fuel cell due to slow kinetics of the electrode reactions (activation overpotential), intrinsic resistances of the different components and contact resistances between one other (ohmic overpotential), and transport resistances of the reactants (concentration overpotential). Therefore, under operational load the actual voltage of a single fuel cell is in the 0.6-0.7 V range.

Useful voltages are generally achieved by interconnecting multiple unit fuel cells in series. This is the concept of “stacking”. The stack’s final output voltage will depend on the number of cells and the available current will be proportional of the total surface area of the cells. In this configuration, the conductive interconnecting element is in contact with both the anode of one cell and with the cathode of the adjacent cell, hence the name “bipolar plate”. Flow channels are grooved on each side for gas distribution and water removal. Bipolar plate materials are highly impermeable to gases in order to avoid harmful fuel and oxidant mixtures: these materials are mainly graphite, polymer-graphite composites and metals such as stainless steel or aluminum (most often coated with a corrosion-resistant alloy).
Bipolar stacking has been up to now the most simple and the most conventional configuration in most types of fuel cell systems, particularly low-temperature systems. For high-temperature systems such as SOFCs however, sealing issues due to large temperature gradients during operation have driven research toward alternative arrangements, leading to the development of a tubular design.
In tubular stacking, the different elements of the fuel cell unit (anode/electrolyte/cathode) are arranged concentrically forming a hollow cylinder. Fuel is fed on the anode side, either through the inside or along the outside of the cylinder, and oxidant is fed on the cathode side. Series connection is accomplished by vertical addition of the cells (in the height direction) while parallel connection is accomplished by horizontal addition of the cells (in the same plan). The tubular design is well suited for high-temperature applications since it minimizes the number of seals in the fuel cell system thus alleviating problems due to unmatching expansion coefficients.
Planar stacking is a second alternative to the bipolar arrangement, in which cells are connected laterally rather than vertically. Several planar designs have been explored, mostly for small-scale systems: the banded-membrane design, in which the anode of one cell is connected to the cathode of the adjacent cell across the band; and the flip-flop design, in which there is interconnection of unit cells on the same side of the band thanks to alternate

anodes and cathodes. The main advantage of this third arrangement is a better volumetric packaging, yet at the expense of increased resistance losses.

Besides the fuel cell stack, referred to as the fuel cell subsystem, the other subsystems that are needed to keep the whole system running can be classified into three categories:

1. The thermal management (cooling) system
2. The fuel delivery/processing system
3. The power electronics (and safety) system for power regulation and monitoring

The components that draw electrical power from the fuel cell thereby causing parasitic power losses are called ancillaries. For example, an actively cooled fuel cell system will employ an ancillary device like a fan, a blower or a pump for cooling fluid circulation.

1. As fuel cells are usually about 30-60% electrically efficient (depending of the type of fuel cell), the balance of energy is released in the form of heat and this has to be managed by the system in order to maintain the thermal gradients inside the stack at the lowest possible level (within a few °C) and ensure stable operation. A cooling system is required for fuel cells that cannot benefit from natural heat regulation by the ambient, i.e. all systems except small PEMFCs (output power < 100 W). The cooling fluid can be either a gas (air), or a liquid (distilled water or aqueous glycol-based solution) depending on the heat dissipation capacity needs and the other characteristics of the fuel cell system. Given that the heat capacity of liquids is much greater than that of gases; consequently, small liquid-cooled devices will generally be far more efficient than their massive gas-cooled equivalents.

In advanced fuel cell systems, the heat released by the stack can be purposely recovered for internal (1) or external (2) heating. Examples follow:

(1) Heat can be used for conditioning reactant gases = pre-heating + humidification;
(2) Heat can be used for providing space and/or water heating in a house, or passenger compartment warming in a car;

Cogeneration by heat recovery is a powerful means to increase the overall efficiency of fuel cells systems up to 80-85%. It is very advantageous in high temperature fuel cell systems, mainly PAFC and SOFC.

2. Given that almost all practical fuel cells today use hydrogen or compounds containing hydrogen as a fuel, there are two primary options to feed a fuel cell: **(1)** in a direct way by pure hydrogen or (2) by a hydrogen carrier after upstream processing.

(1) In the first case, hydrogen is produced outside the fuel cell system in an industrial process (steam reforming for example), and is ready for direct use. The fuel management subsystem will include a hydrogen reservoir related to the physical state of hydrogen stored: high-pressure gas cylinder (up to 700 bars) for compressed gas, double-walled insulator under cryogenic conditions (22 K) for liquid hydrogen in extreme situations where mass storage capacity is especially important, e.g. space conditions, or low-pressure container for metal hydrid compounds ground into extremely fine powders. The advantages of direct hydrogen feeding include high performance, simplicity, and the elimination of impurity concerns. But the current storage options, mainly in the form of compressed gas or reversible metal hydride, are not optimal yet.

(2) In the second case, the system is more complex. Since hydrogen is not available as is, it must be derived from hydrogen-containing fuels called "hydrogen carriers" that are widely available in the industry, like methane, methanol, diesel or gasoline. Except a few hydrogen carriers that are directly usable in fuel cells systems including methanol in DMFCs and methane in SOFCs of MCFCs, a vast majority of them must be processed before they enter the fuel cell. This is possibly achieved in two different ways:

i. by direct electro-oxidation
ii. by chemical reforming

A further distinction must be made between external reforming whether reforming occurs in a chemical reactor separated from the fuel cell, and internal reforming whether the reaction takes place at the catalyst surface inside the fuel cell.

i. Direct electro-oxidation of the carrier fuel into hydrogen is attractive because it avoids the extra step of reforming it prior to the fuel cell reaction and all chemical reactors associated with it. Direct Methanol Fuel Cells are based on this principle, and other simple compounds like ethanol and formic acid can also be employed. Unfortunately, the overall electrical efficiency of this category of fuel cells is significantly reduced due to the complexity of the reactions. As a result, the energy density gained by the absence of a reformer or a fuel reservoir can be largely offset by the low fuel efficiency and the need for larger stacks.

Direct electro-oxidation is best applied in portable applications, where simple systems, minimal ancillaries, and low power are needed.

ii. External reforming systems are composed of several devices for successively treating chemically or physically the gas reactant (hydrogen carrier) and the products (including hydrogen). Several ways are possible, and the exact conditions will vary with the process and the hydrogen carrier. The most used process is steam reforming: fuel molecules are burned over a catalyst (nickel-, copper oxide- or zinc-based) under the presence of water steam at a few hundred degrees C, according to the reaction:

$$C_xH_y + x\,H_2O_{(g)} \leftrightarrow x\,CO + (1/2y + x)\,H_2 \Rightarrow H_2, CO, CO_2, H_2O$$

The yield of this endothermic reaction can be further increased in the presence of excess water vapor via the water-gas shift reaction involving the product CO:

$$CO + H_2O_{(g)} \leftrightarrow CO_2 + H_2$$

Before reforming, the fuel may have to be desulfurized and heated. After reaction, a hydrogen-containing gas mixture is obtained that in certain cases has to be purified in multi-processing steps. This additional post-treatment is required for removing poisons and be able to feed the fuel cell with a pure hydrogen gas, what is especially important for low-temperature systems.

Internal fuel reforming is possible for high-temperature fuel cells with certain fuels. In this case, the fuel is mixed with steam prior entering the fuel cell anode where it is both reformed into hydrogen and the usual co-products CO and CO_2 and then split into protons in the fuel cell reaction. Under these high-temperature conditions, the presence of carbon oxides is not an issue anymore. These gases are even further processed in situ thus contributing to the fuel cell efficiency. Although the different interplaying parameters are difficult to optimize, internal reforming is a promising solution because it gives an elegant (and economically winning) answer to a complex question.

Fuel reforming is best applied in stationary applications, where fuel flexibility is important and the excess heat can be managed inside or outside the system. However, fuel reforming technology is not a current choice of authorities for transportation applications since the existing technologies do not meet the technical or economic targets, and only marginal improvement is expected in efficiency and emissions between a hybrid vehicle and an FC vehicle equipped with on-board reforming.

For any of the fuel delivery/processing systems considered previously, gas pumps are used to feed the gas reactants in the fuel cell, and a water purge system must also be integrated.

3. Last but not least, it is necessary to manage the direct power output of the fuel cell into usable power. The power electronics subsystem consists of:

(1) Power regulation;
(2) Power inversion;
(3) Power monitoring and control;
(4) Power supply management.

Power conditioning corresponds to regulation and inversion of the fuel cell power output.

(1) Regulation allows delivery of power at a voltage level that is stable over time from a fuel cell output power that most often is not. Fuel cell power is generally regulated by DC/DC converters, which transform the fluctuating Direct Current (DC) voltage input into a fixed, stable DC voltage output. A DC/DC converter is generally 85-98% efficient.

(2) Inversion means converting the DC power provided by the fuel cell into Alternative Current (AC) power consumed by most electronic devices, electric motors, and the electrical grid. This task is performed by a DC/AC converter. Similar to DC/DC converters, DC/AC converters are 85-97% efficient. Consequently, these devices taken together yield a 5-20% decrease in fuel cell electrical efficiency, which is far from negligible. Selections of optimal options for a given fuel cell stack technology, geometry and size in a given environment is therefore an essential point.

(3) Power monitoring and control includes system monitoring by gauges, sensors, etc. that measure the conditions of the fuel cell, system actuation by valves, pumps, switches, fans, etc. that regulate them, and a central control unit that mediates the interaction between sensors and actuators. Most control systems are based on feedback algorithms to maintain stable fuel cell operation, i.e. different sets of feedback loops are implemented between stack monitoring elements and ensuing corrective actions by actuators.

(4) Power supply management is the part of the power electronics subsystem that adapts the electrical power output of the fuel cell to the load requirements. Depending on the application, the demand may be driven be toward short-time and/or large-scale load changes that the fuel cell alone is not able to answer due to lag times in system ancillary components such as compressors and pumps. The dynamic response of the fuel cell can be enhanced by energy storage buffers like batteries or capacitors. The response time will be reduced from seconds or even hundreds of seconds to milliseconds. In the case of stationary fuel cell applications, the power supply management subsystems must also incorporate a special control device for interacting with the local grid, allowing for example shutdown or disconnection during a power outage.

The target application ultimately dictates the fuel cell system design and the choice of fuel delivery. In portable systems for instance, there is a strong incentive to minimize the size of components and avoid the use of ancillaries. Direct or reformed methanol fuel systems may provide energy density improvements compared to direct hydrogen storage solutions. A delicate trade-off is necessary between the size of the fuel cell unit and the size of the fuel reservoir. In utility-scale stationary power generation, durability and efficiency are of prime importance. Reformed natural gas and biogas are the leading fuel solutions due to their wide availability and low cost.

2. Advantages

- Efficiency

Fuel cells combine many of the advantages of both internal combustion engines (ICE) and batteries. Thanks to the direct conversion of chemical energy into electrical energy, fuel cells are 2-3 times as efficient as ICEs for vehicle propulsion: the net electrical efficiency of a PEMFC ranges between 40 and above 50% in a driving schedule, which is favorably compared to the 21-24% efficiency range of ICEs “from well to wheel”, i.e. accounting for the type of fuel used and its entire life cycle. Now if we add in the calculations the reforming process of gasoline and methanol or the use of compressed hydrogen in the calculations the efficiencies are 33, 38, and about 50%, respectively.

Interestingly, the fuel cell efficiency does not drop for small systems because it does not depend on its size: unlike gas turbines for example that suffer from scale effects, small fuel cell devices are quite as efficient as larger ones. Accounting for energy losses in ancillaries the efficiency is somewhat lowered but is in any case higher than conventional systems.

In co-generation mode with simultaneous use of electricity and heat, a global efficiency has to be considered. This explains that stationary systems like fuel cell power plants can attain energy efficiencies of 85%. Thanks to the thermal yield the global efficiency is roughly doubled with respect to the use of electrical yield only. This is a huge improvement!

- Reduced emissions

Because fuel cells are electrochemical systems and do not rely on combustion, they are the cleanest fuel-consuming energy technology, with near-zero smog-causing emissions. They produce benefits in all applications: power generation, industrial equipment, transportation, military power and consumer electronics.

The emissions produced by a fuel cell system strongly depend on the fuel used and its origin. For example, a FC vehicle produces only water if it is fed by compressed hydrogen, some CO, CO_2 and CH_4 if it is fed with ethanol, and additional SO_2 if it is fed with gasoline. Under fuel cell operation, undesirable products such as carbon monoxide CO, sulfur oxides SO_x or nitrogen oxides NO_x, ashes and carbon particulate emissions are virtually zero.

Best results are achieved with a fuel cell system running on hydrogen, the hydrogen being produced by water electrolysis from renewable electricity. Emissions of pollutants are increased for electricity from the grid, i.e. a mixture of thermic, nuclear and renewable sources.

- **Reliability, low maintenance and quietness**

Fuel cells can help provide stability and continuity to the electric grid since they can maintain a continuous base power in parallel with or independent of the grid. Fuel cells provide high quality power without any risk of power outage. They have more predictable performance over wider operating temperature ranges than lead acid batteries.

Fuel cells can be recharged everywhere within a few minutes by refueling while batteries have to be plugged in for time-consuming recharge (and eventually replaced). They operate at constant peak performance from fuel replenishment to depletion. Therefore operation time is well-known and directly proportional to the amount of fuel supplied.

Fuel cells systems have practically no rotating or even moving parts. Certain types of fuel cells (PEMFC, SOFC) are all solid state thus close to mechanically ideal. This means less noise and potentially reduced maintenance work (and related costs) besides refueling. Stationary fuel cells require only minimal maintenance (once every one to three years) compared to monthly or quaterly site visits to lead acid battery-based installations.

Fuel cells are relatively silent systems making them suitable for residential areas. The only parts that are liable to cause moderate noise are the pieces of ancillary equipment like fans, compressors and pumps. Noise levels measured on stationary systems are typically as low as 50-60 dB.

- **Sustainability**

Fuel cells are powered by hydrogen, the most abundant element in the Universe. Hydrogen can be produced from a variety of sources including fossil fuels, natural gas, methanol, and various renewable energy sources: wind, photovoltaic, geothermic, waves, etc. This is a keypoint asset from the perspective of greenhouse gas reduction and follow-on process of the Kyoto Conference.

Fuel cells are essential to achieving carbon reduction goals, with CO_2 reduction ranging from 40% or better using conventional fuels to nearly 100% using renewable derived hydrogen, as compared to conventional power sources. Fuel cells can contribute to the world's end of dependence on hydrocarbons. They can greatly simplify the sequestration of CO_2 from hydrocarbon fuels, enabling the use of domestically-produced fuels including coal, biomass and hydrogen.

Due to their low environmental footprint, fuel cells are a realistic option in several fields concerned by the climate change debate: automotive, residential, industrial.

- **Compactness**

Fuel cells offer higher energy density and higher storage capacity compared to batteries, and thus good compactness, which is an interesting feature especially for portable applications.

- **Modularity and flexibility**

Fuel cells allow independent scaling between power (determined by the fuel cell size) and capacity (determined by the fuel reservoir size). The fuel cell size can be adapted by simply changing the number of elementary cells and the active area. Scale up is therefore very easy, from the W range of a cell phone to the MW range of a power utility plant. For miniaturized systems techniques derived from microelectronics are being developed.

Fuel cells are the ideal solution when space is limited or weight is a concern, offering clean and quiet operation in a wide range of installation conditions. For example, the reduced footprint requirements for normal rooftop loading limits, and zero-emission combined with silent operation make them highly suitable for indoor/outdoor, urban/rural applications.

In addition, they can be fueled by a variety of fuels including intermittent renewable energy.

3. Issues

There are three main barriers remaining to widespread adoption of the fuel cell technology:

- **Cost**

- **Durability**

- **Lack of hydrogen infrastructure**

The lack of hydrogen infrastructure has long been considered the biggest obstacle in particular for introduction of fuel cell vehicles, although this question resembles the classic chicken-and-egg problem (there are no FCVs because there are no hydrogen fueling stations, but there are no hydrogen fueling stations because there is no demand for hydrogen as fuel for FCVs…). Establishing the necessary infrastructure for hydrogen production, transport and distribution would require significant capital investment, but there is no absolute impediment, since hundreds of hydrogen refueling stations already exist in the U.S.A., Japan, and Europe. Obviously, legislation and standards are however still missing. In a recent paper published by General Motors, it is projected that consumers will not have to pay significantly more for hydrogen than gasoline in the longer term and also that the key challenge remains matching scale and timing of hydrogen investment with actual hydrogen demand.

We should add to the list the public acceptance of a daily use of hydrogen.

3. Applications of fuel cells

1. Automotive applications (50-250 kW)

This section is limited to the application of fuel cells for **light-duty vehicle** and bus propulsion. The other related application as an **auxiliary power unit** onboard the vehicle will be treated in the next section named “Niche transport applications”.

a. Light-duty vehicles (50 kW)

Almost all major car manufacturers have demonstrated prototype fuel cell vehicles and have announced plans for production and commercialization in the near to midterm future (5-10 years). The race to develop a viable fuel cell vehicle and bring it to market began during the 1990s and continues today. The big drivers for the development of automotive fuel cell technology are its efficiency, low or zero emissions, and fuel that could be produced from local sources rather than imported. The main obstacles for fuel cell commercialization in automobiles are the cost of components and the availability of hydrogen.

The only fuel cell technology satisfying to both temperature and time response criteria for vehicle propulsion is the PEMFC. The low operating temperature combined with good durability and range makes it ideal for use in light duty vehicle. Power range is about 50 kW.

PEMFCs meet the 4000 h lifetime target for automotive applications at the laboratory scale. The effect of real-life conditions on the fuel cell system (repeated startups and shutdowns, impurities in fuel and air, low and high temperatures) has to be assessed more thoroughly.
Startup and steady operation in extremely cold climates (-40°C) require specific water management controls, whereas the heat rejection system must be sized for hot weather conditions (+40°C). Water balance is a prerequisite in a PEMFC for optimal operation; this results also in an additional cooling system.

Four configurations are possible in a Fuel Cell Vehicle (FCV):

- The fuel cell is sized to provide all the power needed. Due to the slower response of fuel processors (reformers), this configuration only applies for fast dynamic hydrogen-fed vehicles. A small battery may be present but for startup only.
- In the parallel hybrid configuration, the fuel cell is sized to provide the base load, but the peak power for startup and acceleration is provided by a battery. The battery allows rapid startup without preheating of the fuel processor and recapturing of the braking energy, resulting in a more efficient system.

- In the serial hybrid configuration, the fuel cell is sized to recharge the battery and the battery drives the electric motor. The relative sizes of the battery and the fuel cell are tied up: a smaller battery will have to be recharged faster and will result in a larger fuel cell.
- Fuel cell serves only as an auxiliary power unit, that is, not for propulsion. This configuration is attractive for idling trucks requiring operation of air-conditioning or refrigeration systems.

A hydrogen fuel cell vehicle does not generate any pollution and is qualified as Zero Emission Vehicle (ZEV). If another fuel is used and reformed onboard, the propulsion system has some emissions generated during the reforming process, but those emissions are in general still much lower than the emissions from an **internal combustion engine (ICE)**; therefore the fuel cell vehicles using a fuel reformer are typically qualified as Ultra Low Emission Vehicles (ULEV). Fuel cell-powered vehicles also generate significantly less greenhouses gases than the comparable gasoline-, diesel-, or methanol-powered ICEs.

Hydrogen is the only fuel that results in a zero-emission vehicle, particularly if hydrogen is produced from renewable sources. Use of hydrogen as transportation fuel could reduce dependency on imported oil. A fuel cell system that runs on pure hydrogen is relatively simple, has the best performance, runs more efficiently, and has the longest stack life. Hydrogen is nontoxic and, despite its reputation, has some very safe features.

One of the biggest problems related to hydrogen use in passenger cars is its onboard storage. Hydrogen can be stored as compressed gas, as cryogenic liquid, or in metal hydrides. Tanks for gaseous hydrogen are bulky, and the amount to be stored depends on the fuel efficiency and the required range (typically 300 miles or 500 km). In order to achieve a better match between the storage capacity of the tank, the fuel efficiency of the car and its range, further improvements in vehicle design, introduction of new lightweight composite materials, and compression of hydrogen at 700 bar are mandatory.

The difficulty of storing hydrogen onboard a vehicle, as well as lack of hydrogen infrastructure has forced car manufacturers to consider other, more conveniently supplied fuels. In that case the fuel cell must be integrated with a fuel processor that produces hydrogen from gasoline or methanol. However, apart from being a non zero-emission process, onboard reforming is not easy and raises numerous engineering issues:

- Onboard reforming reduces the overall efficiency of the propulsion system, which leads to upgrade the fuel cell size;
- Onboard reforming enhances complexity, size, weight, and cost of the propulsion system;
- Startup time of fuel processors is too long in practice: this issue may be avoided in hybrid configurations;
- Durability issues of the PEMFC due to impurities in the reformate hydrogen have been evidenced.

Many car manufacturers are perfecting their proprietary PEM units for use in their vehicles, e.g. Honda with the FCX Clarity, General Motors with fuel cell-powered Chevrolet Volt and Equinox models, and Volkswagen with fuel cell-powered Touran and Tiguan models. While the first one is based on a specific fuel cell design, all the others are derived from standard ICEs, with mere replacement of the propulsion engine by a fuel cell system. Alone amongst the major automakers, BMW is developping an SOFC-based **auxiliary power unit** for its 7-series luxury car model.

Fuel cell vehicles, because they are still an immature technology and thus are manufactured on a prototype level, are far more expensive than mass-produced ICEs. However, forecast studies conducted by car manufacturers have shown that cost-competitivity could be achieved accounting for mass production manufacturing techniques. The main high-cost components in the fuel cell stack are the catalyst precious metal Pt, or Pt-based alloy, the ionomer membrane, Nafion or fluoropolymer, and the graphite bipolar plates. The cost target for fuel cell vehicles, similar to the current production cost of ICEs, i.e. \$35-\$50 per kW, demands large economies of scale during manufacturing of the stacks and performance improvements in terms of Watts per unit active area.

The future remains positive, since major manufacturers worldwide are about to release fleets of hundreds of fuel cell vehicles as Honda did in 2008 in California, and the prospect of thousands of vehicles available to individual consumers after 2012 is strong.

b. Buses (250 kW)

Buses for city and regional transport are considered the most likely type of vehicles for an early market introduction of the PEMFC technology. Most of the issues discussed in the previous section, Light Duty Vehicles, also apply for the fuel cell applications in buses. The major differences are in power requirements, operating conditions and resulting lifetime, space available for hydrogen storage, and refueling sites.

Buses require typically 250 kW under high demanding, intermittent conditions, with frequent starts and stops. Compared to their diesel engine equivalent the efficiency gain is about 15%.

Buses are almost always operated as a fleet and refueled in a central facility. Storage of large quantities of hydrogen onboard (the roof location is very safe for a gas lighter than air) is not a concern. These two characteristics make use of hydrogen much easier.

Thanks to use of hydrogen, fuel cell buses are Zero Emission Vehicles (ZEVs), which is a big advantage over diesel buses in densely populated regions. Demonstration programs funded from local to international level have seen several fleets of fuel cell buses deployed in European cities (Clean Urban Transport for Europe program), in the U.S.A. (Sunline Transit Authority in Palm Springs), and in large cities worlwide (United Nations Development Program, Global Environment Facility).

The main obstacles for commercialization of fuel cell buses are their cost and durability. Because the production series for buses are smaller than for passenger cars, their cost per kW is somewhat higher, as is the expected lifetime. Together with the intermittent operating regime, this could eventually challenge the current fuel cell technology.

2. Niche transport applications (1-10 kW)

Small mobile fuel cell systems are designed to produce 1 to 10 kW of electrical power with low to zero emissions. This application is not as demanding as passenger cars or buses. The possible applications are very diverse and include:

- Utility and leisure vehicles, material handling industrial vehicles, e.g. forklifts, tow trucks, bicycles, scooters, motorbikes, golf carts; and wheelchairs for mobility assistance;
- Aircraft and aerospace applications;
- Marine and submarine applications;
- **Auxiliary power units (APUs)** for on-board power supply.

An auxiliary power unit is composed of a small fuel cell system (a stack in the KW power range and a balance of plant part, with or without a reformer), which is associated to a prime driver engine i.e., internal combustion engine or electric motor, in order to supply additional power not related to the propulsion of the vehicle: air-conditioning, multimedia playing or other comfort features. The fuel cell technology allows power generation without engine operation and enhances the run time of batteries. This is especially a good point at the time where anti-idling regulations are setting place in a number of countries. Hence fuel cell-based APUs improve the power flexibility of the vehicle without a complete replacement of the existing technology, which could foster an early market uptake of these “secondary” power sources. Moreover, the continuous increase in electrical demand for leisure vehicles and equipments is now accompanied by a desire for environmentally friendly on-board conveniences. The growth in this sector is being driven by the need for clean, quiet, efficient power with extended run-time particularly in the high end of the campervan and luxury boating markets. In a market largely insulated against recession, consumers are willing to pay a premium for the advantages that fuel cells have over batteries and generators. Campervan manufacturers have understood this very well and are now offering fuel cell-based APUs at least as optional extra and even standard equipment.

Fuel cells for these applications are of the PEMFC or DMFC type, with a small number of SOFC-based units essentially for APU applications. PEMFC-based units are largely dominant in the aerospace, aircraft and materials handling markets while DMFC-based units are more often found for leisure, marine and mobility assistance vehicles. DMFC-based APUs run on methanol without a reformer. SOFC- and PEM-based APUs usually incorporate a fuel reformer built into the unit so that the system can run on alternatives to hydrogen. In a peculiar market approach, the selection of fuel determines the type of fuel cell stack and the reformer technology. The reason for this fuel diversification is the desire to design the fuel cell APU to run on a fuel that is readily available to the end user. The choice of the same fuel for the fuel cell-based APU as the main engine is a specific requirement of this application. Today this means gasoline or diesel, and development efforts are currently geared towards efficient reformers in order to make this eco-friendly option available for use in commercial trucks shortly.

Like the portable sector, the materials handling sector is one where a real value proposition is now available to warehouse professionals because fuel cell-powered materials handling vehicles operate near silently, with no or few emissions, and offer faster refuelling (1-3 minutes) as well as longer run-time than lead acid batteries and conventional internal combustions engines. Compared with battery-powered equipment, fuel cell systems have also the advantage of not requiring lengthy and floor space-hungry recharges. Moreover, capital investment is less since a single fuel cell will operate continuouly while from a logistic point of view, two or even three batteries are needed per battery-powered vehicle. Fuel cell-based two- and three-wheeled vehicles basically combine clean and efficient indoor operation with lower downtime, rapid refuelling, extended range and no operational degradation over time: since power provided by the fuel cell is constant throughout each shift, there is no performance loss of the vehicle.

Altogether, lower lifetime running costs are expected from fuel cell-based systems than from their equivalents. This explains why an increasing number of manufacturers are developing and selling fuel cell-powered bikes and three-wheelers. A worlwide potential market exists for example in national postal services that use thousands of bikes and delivery trolleys. In the materials handling market, fuel cells seem to be still some way off being a serious competitor to long-used ICEs and acid-lead batteries, but some early niche markets are being actively explored and experience is currently gained in warehouse environments before large scale deployments. Ballard, Plug Power, Nuvera Fuel Cells and Hydrogenics are main players in the materials handling sector who are currently testing products on-site. Finally, mobility assistance vehicles are an interesting niche market for light fuel cell systems, which offer an extended range but none of the inconveniences of battery recharging. SFC Smart Fuel Cells from Germany and Ajusa from Spain have shipped tens of units for impaired customers in 2008.

In the aerospace and aircraft sectors, successful test flights have been reported in recent years, as well as a continued development of fuel cells for auxiliary power units on board larger aircrafts. Due to their silentness and long run time, unmanned aerial vehicles (UAVs) are especially attractive in the defense and aerospace fields for handling military reconnaissance, surveillance missions, or remote communications in strict secrecy. Other civilian applications are studied like remote scientific data collection under harsh conditions, disaster relief missions… It is unlikely that fuel cells will be used as a primary source of power for commercial aircrafts any time soon, but demonstration is being made that they are able to operate under extreme conditions: low temperatures and pressures, and unusual spatial orientations; hence they could provide efficient energy for on-board electrical systems in-flight or under ground operation: heating/cooling, entertainment devices, and even essential controls in the aircraft, thereby reducing fuel consumption. Here a fuel cell APU may offer better efficiency than turbine APUs used today in spite of the necessary kerosene reformer. As a further advantage, in-flight production of water is under investigation by several aircraft companies, e.g. Airbus.

In the marine sector, legislation is likely to act as a key driver for the adoption of fuel cells. New restricting policies requiring low or zero emission for vessels in certain rivers, lakes and inland waterways in China and Europe, as well as growing pressure on regulating pollutant emissions in harbours, in coastal waters and on the high seas, are a favorable ground for the uptake of fuel cells as APUs on board vessels to reduce overall emissions and also for development of fuel cells as main means of propulsion. This has already caused a doubling of unit shipments in 2008 (mainly in Europe) and the trend will supposedly accelerate in the forthcoming years. Proton Motor’s Zero EMission Ship is the first fuel cell propulsed boat: as a demonstration project it has carried passengers since July 2008 in Hamburg's harbour. Other proof-of-concept projects of low-emission and low-noise fuel cell-powered or battery hybrid systems are under development for integration in canal barges, tug or river boats. Silent operation is of utmost importance for certain applications like scientific studies of sea animals. National governements and the International Maritime Organisation are in the process of voting further reductions of pollutant and noise emissions and new laws will certainly follow. Clearly, there is a great opportunity for fuel cells at the time of regulation in the marine environment.

On the naval undersea side, a number of programs are ongoing to develop fuel cell systems for ships and underwater applications. They are funded at their most part by the national navies, and split into primary propulsion for Unmanned Underwater Vehicles (UUVs) and on-board electrical power generation for larger vessels. Like the commercial sector, the key issue is developing fuel reforming technologies that will allow fuel cells to run on a specific range of fuels, including marine diesel and bunker fuels. Powering an UUV by a fuel cell has many advantages in terms of silent and autonomous operation, quick refueling and steady energy output.

Europe is leading the development of fuel cell APU products for recreational vehicles. There are two companies having products available for this niche market, SFC Smart Fuel Cells in Germany and Voller Energy in UK. Unlike most fuel cell manufacturers, who are in still in the research and development phase or run demonstration projects, SFC has shipped in October 2008 a total of 10000 EFOY (Energy FOr You) DMFC-based systems to industrial and private end users, and has created its own fuel cartridge supply infrastructure. Delphi and Cummins Power Generation are working on projects to demonstrate SOFC technology on commercial vehicles, funded by the U.S. Solid State Energy Conversion Alliance. The EU is also funding a project to validate renewable methanol as fuel for SOFC-based commercial vessels and quantify its environmental impact in comparison with conventional systems. The leisure sector will probably remain a leading application for fuel cell-based APUs, but improvements in battery technology could challenge the market growth. This requires continued investment in better products. To consolidate success as an early market for fuel cells, APU systems with output powers in the 1-10 kW range need to be realised at a level of cost, size and durability suitable for commercial use, and sulphur-tolerant reformers for diesel-fuelled systems must be produced that are compatible with future fuel specifications in major markets.

3. Portable applications (0.1-100 W)

In the portable sector, industrial interest for fuel cells in the W power range is great because of recurrent issues inherent to battery technologies (Nickel-Metal Hydrure, Lithium-Ion or Lithium-Polymer). Significative improvements are possibly brought by fuel cells in this field:

- Fuel cells have a higher energy density than batteries, i.e. they provide more energy per unit of weight, up to 5 times more. This allows longer run time before refueling.
- Portable fuel cell systems including the fuel storage container can be designed smaller and lighter than a battery of equivalent power.

- Continuous operation of fuel cells (as long as fuel is supplied) means also longer standby time (depending on the fuel reservoir volume), no time-consuming recharge and associated logistics (e.g., need for several units for battery exchange), and less degradation of the components.

Micro power applications of fuel cells are typically the same as batteries, i.e. all electronic devices for nomad use like mobile phones, laptop computers, personal digital assistants, cameras, and music or multimedia players. Other applications are found in portable military, healthcare or camping tools. In these applications fuel cells are expected to replace batteries thanks mainly to their higher storage capacity. Conversion efficiencies are of less importance as long as they do not restrict autonomy.

Micro fuel cells are of the DMFC or the PEMFC type; they run at low temperatures on liquid methanol, formic acid, or hydrogen stored in low pressure hydride containers. The operation temperature should not exceed 50 to 60°C, which excludes the use of a reformer. Further, it is important that the fuel storage must achieve a high level of security. Use of liquid high-pressure hydrogen is of course excluded as well. In this field PEMFCs with chemical hydrogen storage are competing with DMFCs. While PEMFCs have a higher power density than DMFCs, chemical hydride solutions are not ready for market yet. Portable DMFC-based micro fuel cells have been first demonstrated by Toshiba, Smart Fuel Cell and MTI Micro Fuel Cells. An increasing number of companies are also developing DMFC-based fuel cell cartridges, either as stand-alone products (BIC, Gillette; Neah Power) or for powering their own consumer electronics portfolio (Motorola, Hitachi, Panasonic, Sony). Motorola expects its fuel cells to run about 10 times longer than today’s batteries before needing to be recharged.

Smart Fuel Cell is selling a wide range of DMFC-based products; from 50 W-units targeted to the recreational market, to portable docking stations for laptop computers.

The real challenge is the miniaturization of the system, which may consist of either scaling down the different components of larger existing stacks or developing a specific architecture based for instance on silicone-supported thin films derived from microelectronics. Each of these solutions implies a specific management of the various fluxes in the fuel cell: flux of reactant gases, flux of products water and heat. The crucial point for the micro fuel cell is to handle a power surge upon switching the device from idle to active.

The current trend for portable devices is an ever growing power demand in conjunction with their increasing number of Internet functionalities. Therefore, the advantages of fuel cells of storing more power in the same volume, for longer time while being able to refuel the product quickly instead of recharging will be hopefully seen by most consumers as another area for freedom and lead to a progressive decay of the battery-based today technology. Furthermore, standard batteries on use today like lithium-ion batteries are quite expensive themselves so that the cost barrier for the introduction to fuel cells to the portable market is lower than in other applications.

4. Wireless applications (0.1-1 kW)

Portable soldier power

Wireless tools

5. Stationary applications (1 kW-5 MW)

Among fuel cell applications, stationary applications are the most diversified category. This is due to a wide power range from one kW to multi MW, and many possible end users (civilian/military, industrial/utility services, private individuals…) with different objectives, specifications, and budgets. Requirements on size and weight are less critical and modularity is definitely an advantage: several types of fuel cells are eligible and a large spectrum of fuels is available.

PAFCs were the first fuel cells to be tested on-site and 200 kW modules have been commercialized by UTC Fuel Cells in Japan, USA and Europe since the 1990s. Developments are limited today; nevertheless, these fuel cells are the only ones to be really competitive on the market, and have allowed gaining experience in the integration of cogeneration systems, increasing reliability, and improving management controls. Other types of fuel cells are now under late stage development in the stationary sector:

- High temperature fuel cells SOFCs and MCFCs for applications from residential to industry, and from cogeneration to centralized electricity production;
- Low temperature fuel cells PEMFCs below 80°C essentially for domestic and off-grid applications.

Each type has its own advantages and drawbacks, and there seems to be room for market share, depending on specific needs and relative degree of development of each technology. For example, PEMFC appears more ready for market than SOFC but in the longer term, could be supplanted for certain applications. Another big difference is the possible use of various fuels and of internal reforming in high temperature systems, whereas the choice of the fuel is much more restricted and external reforming in a separate reactor is the only option for low temperature fuel cells. In the short term, natural gas will be preferred due to an existing infrastructure and a positive feedback from the population.

In most stationary applications, heat in addition to electricity is demanded. The temperature at which heat is needed will depend on the application: for residential heating purposes temperatures below 80-90°C are more than enough and PEMFCs can fit (yet sometimes hardly), while for industrial applications where heat is usually recovered to process steam temperatures well above 200°C are required, which is a future market for SOFCs and MCFCs.

The small stationary fuel cell market (<10 kW) is shared between **Uninterruptible Power Supply (UPS)** and **Combined Heat and Power (CHP)** units: UPS systems provide only electrical power with more than 40% efficiency whereas CHP systems based on cogeneration provide power and heat with up to 85% conversion efficiency. PEMFC technology represents today 90% of the total units shipped in 2007 with SOFC taking under 10% and AFC less than 1%. Derived from the CHP, the **Combined Cooling and Power (CCP)** integrates an absorption chiller besides the heat recovery reactor. A set of fuel cell manufacturers working on localized stationary power generation will include for instance Idatech, CellFraft, Nuvera Fuel

Cells and Plug Power with UPS and CHP units on the PEMFC technology side, Ceres Power and Ceramic Fuel Cells with CHP units on the SOFC technology side.

The large stationary fuel cell market (>10 kW) is represented by units operating either tied to the grid or off-grid as CHPs, CCPs or electricity generators. Over the last five years MCFC and PAFC have become commercial and represented 40 and 35% of the total units shipped in 2008 while SOFC technology is starting to take off after intense R&D efforts, with a percentage of 15%. PEMFC technology seems on decay with less than 10%. The current trend observed for commercial shipments is a general increase of the average unit size to the MW level and above and the continued development of key markets such as California and Connecticut in the U.S.A. where two-thirds of the (few) large stack manufacturers are located.

An important distinction to be made is between localized production of small power with (residential applications) or without cogeneration (backup applications), cogeneration of medium power (remote, institutional applications + backup), and centralized production of electricity without heat recovery. The first category is referred to as “localized stationary power” and the second one to “distributed generation”.

a. Localized stationary power

CHP fuel cells are currently developed in sizes appropriate for use in single or multi-family residential applications (3-50 kW) in order to provide clean, quiet and efficient primary or backup power. They can either operate in parallel to the electric grid or off-grid in case of power outage. Like a boiler, they can be installed in the home basement and thanks to the reformer unit; they are able to extract hydrogen from traditional fuel sources such as natural gas and propane. The integration of a fuel cell for home power more than doubles the amount of low-impact electricity that is delivered to the grid, and the non-combustion heat eliminates the need for a boiler. Residential fuel cell cogeneration systems reduce CO_2 emissions by up to 40% compared to conventional energy generation and hot water systems.

Small stationary CHP fuel cell power plants (0.1-5 MW) are a good alternative in such remote locations where grid lines are expensive and/or difficult to install: islands, mountainous areas, sparsely populated regions, etc. They offer a competitive energy solution to many communities that are not currently connected to the electric grid without the need to build a heavy infrastructure. The low maintenance and fuel transport associated costs, and a very limited environmental footprint make fuel cell remote power plants close-to-ideal for this application. Use of propane fuel is strongly considered as an early-adopter target market for rural residential areas and small businesses in remote sites. Alternatively, hydrogen could be produced by renewable energy sources (wind, hydro or solar) and used for local transport. Clearly, there is an avenue for market growth of decentralized power by fuel cells in an increasingly sustainable world.

As compared to lead-acid battery and diesel-powered generators traditionally used by communication centers, fuel cell-powered UPS (0.5-200 kW) offer a greater reliability and more predictable performance over a wide range of operating conditions including harsher (colder/warmer) climates. They are well suited for powering networks for extended periods of time in data centers, banks, and other sensible government or commercial buildings where power interruption must be absolutely avoided. Backup power systems are being deployed across government agencies to demonstrate the increased security brought by fuel cells.

Larger stationary CHP fuel cell units (250-400 kW) can also be installed on the premises of an institutional building, e.g. school, hospital, industrial facility, and provide heat and primary power in addition to backup power. With combined efficiency of 70-80% cogeneration systems reduce primary energy consumption by 20 to 30%. Energy costs would be reduced especially during periods of peak demand. Moreover, along with high reliability, voltage output delivered by fuel cells is steadier than that coming from the electric grid. Voltage fluctuations, which are highly deleterious to computer systems, would be less than an issue upon fuel cell powering.

Last but not least, a new potential application has to be mentioned in the stationary fuel cell market: CHP fuel cell power plants (>1 MW) could be used as CCP in data centers and server farms, providing both power and air-conditioning to the exploding number of servers housed together for electronic data storage (over one million in Google’s server farms, for example).

As the price of residential fuel cell units remains today largely prohibitive for individual consumers without proper incentives, a variety of ownership and leasing options is being progressively made available to them. First adopters will also be able to sell excess power produced by the fuel cell unit back to the electric utility at an advantageous fare and get medium to long-term payback of their investment this way. This is how manufacturers expect to make the shift from technology to market in the residential sector.

Besides commercially-driven developments, the market growth of this sector is induced by a strong demand pull from governments, e.g. in Japan with the Japanese Large Residential Fuel Cell Programme, or in Germany with the Hydrogen and Fuel Cell Technology Innovation Programme including a 2020 vision to produce 72,000 residential units per year. In the U.S.A after the hurricane Katrina, a special panel order has stated in 2007 that backup power units with an extended run time ought to be implemented in the 30,000 telecommunication base stations registered in the country. Thanks to their modularity, long operation time and low maintenance costs, this is a big potential market for fuel cell systems especially in remote regions where gasoline supply chains for conventional diesel generators are at higher risk to be disrupted anytime. Over ten major telecom companies have tested fuel cell-powered UPS systems worldwide with a general positive feedback, giving rise to a number of distribution deals between stack manufacturers and integrators, among which the big commercial agreement in late 2008 between Idatech and Acme Telepower for telecom backup and uninterruptible power in India. Recent city and national legislations on greening of new buildings, like the London Plan to cut carbon emissions by 20% and the Executive Order 111 in New York City to produce 20% of the electricity in state office buidings by renewable energies by 2010, as well as an increased awareness of the benefits of decentralised power generation also push the technology forward.

b. Distributed generation

Fuel cell power plants in the MW range are well suited for the distributed generation of electricity at locations near demand thanks to their modularity and quietness under operation. The energy produced is of high quality, and there are fewer transport losses. This means fewer distribution lines and low environmental impact. Because the installations are smaller than typical central generation power plants, they are easier to site, permit, and finance.

Among the different types of fuel cells, only high temperature technologies, SOFCs and MCFCs, can be used for distributed generation in conjunction with a steam and/or gas turbine to produce high efficiency electricity >70% compared to similar sized fossil fuel power plants that achieve only 30 to 40% efficiency. They deliver cleaner power for each unit of fuel used, substantially reducing power costs and CO_2 emissions. Like cogeneration systems, these fuel cell units can operate off-grid in some situations for decentralized power generation.

Ongoing developments are focused toward larger units. In the near future however, fuel cell power plants are not intended to replace conventional power plants for primary power generation, but will more likely be used in parallel with the electric grid to increase reliability by getting rid of power blackouts during outages. Utility companies may also utilize them as additional power to relieve grid congestion during peak hours, thereby reducing overall energy costs for end users. Lastly they could reduce the need for new central generation, transmission and distribution, and its associated cost.

Recent market developments have seen an increased interest on distributed generation by legislators and business planners alike with an increased number of units being sold into office blocks and schools. The most active country in the sector has been the U.S.A since the beginning of the 2000's. Through its Self Generation Initiative Programme (SPIG), California has been subsidying the installation of fuel cells and other renewable technologies producing up to 5 MW of power, whose direct effect was the fastest growth for large stationary fuel cells in the world. Connecticut has also issued a Renewable Portfolio and is developing fuel cell-based distributed generation with FuelCell Energy, the world leading company in stationary fuel cell power plants.

6. Members of the hydrogen fuel cell family

All the devices that we call fuel cells can be included in a single family of technologies: each one is differentiated by the type of electrolyte used and thus, by the operating temperature allowing proper proton transport. They all rely on the direct electrochemical conversion of the chemical energy contained in the fuel into electrical energy without an intermediate heat cycle. Even though the electrode half-cell reactions may differ from one type to another due to a different fuel or "hydrogen carrier", the overall reaction remains the same:

$$H_2 + \frac{1}{2} O_2 \rightarrow H_2O$$

Plus, the basic configuration of a single fuel cell is always composed of an ionic conductor separating two electronic conductors, whatever the specific materials constituting these different parts and the exact running conditions. The fuel is always oxidized at the anode and simultaneously, the oxidant is always reduced at the cathode leading to the formation of water and heat side-product without other emissions (when hydrogen is the fuel source). The operating temperature is determined by the temperature range at which the conductivity of the electrolyte used is sufficient for the transport of protons without losses, and its mechanical resistance is at its best. Low temperature fuel cells typically operate below 200°C and high temperature fuel cells above 600°C. In the intermediate temperature range no fuel cells systems do yet exist due to a lack of suitable electrolytes.

Let us now examine the different members of the family with their technical characteristics, forces and weaknesses, specific fields of applications, ordered from low to high temperature fuel cells.

1. The Proton Exchange Membrane Fuel Cell

a. How does a PEMFC work?
b. A short history of PEMFC
c. PEMFC applications and perspectives

2. The Direct Methanol Fuel Cell

a. How does a DMFC work?
b. A short history of DMFC
c. DMFC applications and perspectives

3. The Alkaline Fuel Cell

a. How does an AFC work?
b. A short history of AFC
c. AFC applications and perspectives

4. The Phosphoric Acid Fuel Cell

a. How does a PAFC work?
b. A short history of PAFC
c. PAFC applications and perspectives

5. The Molten Carbonate Fuel Cell

a. How does an MCFC work?
b. A short history of MCFC
c. MCFC applications and perspectives

6. The Solid Oxide Fuel Cell

a. How does a SOFC work?

b. A Short history of SOFC
c. SOFC applications and perspectives

7. Glossary

Anode:

Auxiliary Power Unit (APU): power generation system on a vehicle whose purpose is to deliver electrical energy independently from the main engine and for functions other than propulsion. Different types of APU are found on aircraft, marine vessels as well as on some large ground vehicles. Where the elimination of exhaust emissions or noise is particularly important (such as yachts, camper vans) fuel cells or photovoltaic devices are used as APUs for electricity generation.

Cathode:

Combined Heat and Power (CHP): Family of energy conversion processes involving the simultaneous generation of usable heat and power (usually electricity) in a single process. CHP is a highly efficient way to use both fossil and renewable fuels. In its simplest form, it employs a gas turbine, or a steam engine to drive an alternator, and the resulting electricity can be used either wholly or partially on-site. In a sustainable version of the CHP the engine is replaced by a fuel cell stack. The heat produced during power generation is recovered in a boiler and can be used to raise steam for a number of industrial processes, to provide hot water for space heating, or even cooling. Because CHP systems make extensive use of the heat produced during the electricity generation process, they can achieve overall efficiencies in excess of 70% at the point of use. Unlike conventional power plants, CHP units are sited close to where their energy output is to be used. In the home, a microCHP unit resembling a gas-fired boiler will provide both heat for space and water heating, as does a boiler, but also electricity to power domestic lights and appliances.

Electrode:

Electrolyte: Material that allows passage of ions (charged atoms) but not electrons

Electron:

Ion:

Internal Combustion Engine (ICE): Engine in which the combustion of the fuel occurs in a chamber placed inside and integral to the engine. It is the volume expansion of the high-temperature and pressurized gases produced by the combustion process that creates the mechanical force necessary to drive the movable component of the engine (piston, turbine blade…).

Light duty vehicle: In the U.S. legislation, the light duty vehicle (LDV) category includes all vehicles of less then 8,500 lbs (3859 kg), and is further divided into passenger cars and light-duty trucks. In Europe, vehicles of less than 3500 kg belong to the light sector and vehicles with more than 3500 kg are referred to as heavy duty vehicles (HDV). The light duty vehicle technology is derived from passenger car developments, though the higher vehicle weight requires more engine power.

Reformer:

Uninterruptible Power Supply (UPS): Backup system that provides emergency power power from a separate source when utility power is not available. Unlike an auxiliary power unit, it provides instant protection from a momentary power interruption. A UPS can be used to provide uninterrupted power to equipment, typically for 5-15 minutes until an auxiliary power supply can be turned on or utility power is restored. While not limited to safeguarding any particular type of equipment, a UPS is typically used to protect electrical equipment, telecommunication and data centers, hospitals, etc. where a power outage could cause injuries, fatalities, serious business disruption or data loss. UPS units come in sizes ranging from units which will backup a single computer to units which will power data centers or buildings (several megawatts).