



CENTRE FOR RENEWABLE ENERGY SOURCES C.R.E.S.

FUEL CELLS AND THEIR APPLICATION IN BIO-ENERGY

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1. INTRODUCTION

Society will need to progressively reduce the utilisation of fossil fuels and rely on sustainable sources of energy in order to ensure security of supply, protect the environment and unlock itself from geographically limited sources of energy. Renewable energy sources will thus be called to cover a major part of our future energy needs.

To transform the varied types of renewable energy sources into the familiar energy forms used by society – electricity, heat, locomotion – it is best first to convert them to a common energy form: Hydrogen, the most abundant element in nature, whose properties make it the ultimate fuel. Then use the most efficient and clean energy converter available to turn hydrogen into the desired energy form: the Fuel Cell, a device that can convert the chemical energy of a hydrogen-rich fuel into electricity and heat through electrochemical conversion rather than combustion.

The combination of Hydrogen and Fuel Cells that rely on renewables holds the promise for a sustainable future. Fossil fuels will be used in the short and medium term to help establish hydrogen infrastructures and technologies, till the economics become right for renewables to take over.

The European Commission High Level Group for Hydrogen and Fuel Cell Technologies predicted that by the year 2050 our society will have become a “Hydrogen” society with most of the hydrogen being produced by renewables and used in fuel cells.

Biomass, including wastes, is one of the major sources of renewable energy and its energetic use is CO₂ neutral. It can be used as a solid fuel or converted into liquid or gaseous forms for the production of electric power, heat or chemicals, or for use in vehicles. There are a variety of well established methods for the conversion of dry or wet biomass into gaseous or liquid biofuels. Then there are many methods for converting and upgrading biofuels into gases that are suitable for using in fuel cells.

The present study covers the above subjects, focusing on powering fuel cells with biomass derived fuels. A review is initially given of the energetic properties of hydrogen, the methods for its production, storage and use and the international research effort. The principle of operation of fuel cells is presented next followed by a description of the various types of fuel cells and the research work being undertaken in the field. Emphasis then moves to the various types of biofuels and the ways for their production. The methods for transforming these biofuels into fuels useful for fuel cells – a process known as reforming – is presented next. Even these reformed gases however could be contaminated with substances that would degrade the performance of fuel cells and so purification or upgrading techniques are required that are investigated next.

Having covered the technicalities concerning hydrogen, fuel cells and biofuels, the study moves on to review the types of stationary and transport applications of fuel cells, then to presenting the related EC R&D projects plus a few case studies of biofuel driven fuel cells before moving on to a market analysis including a SWOT study of biofuel driven fuel cells. A non-exhaustive list of major fuel cell manufacturers is provided in the annex of the study.



2. THE HYDROGEN ENERGY VECTOR

Environmental concerns and security of supply issues support the transition from a fossil fuel based society to a hydrogen society in order to meet our ever-increasing energy needs in a sustainable manner. Historical trends prove that humanity, once in the industrial age, tends to use fuels whose carbon content keeps on diminishing, with the hydrogen content increasing, rendering hydrogen as the “ultimate” fuel. The combination of hydrogen, biofuels, electricity and fuel cells gives a promise for a sustainable energy future for Europe and the world.

2.1. Hydrogen properties

Hydrogen is the most abundant element in nature but can be found only in compounds due to its high reactivity (e.g. water, hydrocarbons), which on the other hand makes hydrogen such an interesting fuel, suitable for many combustion applications (Table 1). Hydrogen can be produced from a variety of energy sources and if “combusted” in fuel cells the only by-product is water vapour. However hydrogen has its drawbacks: since it does not exist free in nature energy must be consumed to extract it from its compounds. It has a high cost (twice the cost of gasoline per energy content) and is difficult to store, specially in an energy-dense form. The following table compares the properties of various energy carriers.

Energy Carrier	H ₂ (220 bar)	Methane (NG)	LPG	Methanol	Petrol	Lead batteries
Energy density per weight (kWh/kg) ¹	33.3	13.9	12.9	5.6	12.7	0.03
Energy density per volume (kWh/lt)	0.53	2.6	7.5	4.4	8.7	0.09

Table 1 Comparison of energy properties of various energy carriers

Hydrogen combusts in air in a much wider range than methane. Its explosion limits are also much wider; it is these properties after all that render it such an interesting fuel. However, as can be observed in the following table, hydrogen first goes through a combustion range, before going to the explosion range (4-13% volume), meaning that it will most probably combust rather than explode, which is not the case for methane (5-6%). Hydrogen being much lighter than air, disperses quickly and much faster than methane.

	Hydrogen	Methane	Propane
LCV (kWh/Nm ³)	3	9.9	25.9
Density (kg/m ³)	0.09	0.7	2
Concentration for combustion (volume %)	4.1 – 72.5	5.1 – 13.5	2.5 – 9.3
Explosion limits (volume %)	13 – 65	6.3 – 14	-
Dispersion coefficient (cm ³ /s)	0.61	0.15	-

Table 2 Comparison of combustion properties of various energy carriers

¹ the weight of the storage tank for each fuel has not been taken into consideration with the exception of the lead batteries



2.2. Hydrogen production, storage, use

Hydrogen can be produced from water through electrolysis or from fossil fuels through reforming. The energy required by these processes can be obtained from various sources than include fossil fuels, nuclear energy and renewable energy sources, including biofuels. This plurality in terms of energy sources is one of the main advantages of the hydrogen energy vector, since the world economy can disentangle itself from its dependency on oil. If hydrogen is produced through the reforming of fossil fuels, then CO₂ is released. Nuclear energy although CO₂ free, has still to address nuclear waste disposal issues. If hydrogen is produced through water electrolysis, then the emissions related to its production are those associated with the power industry.

Vast quantities of hydrogen as an industrial gas are produced around the world. Total annual production amounts to 500 billion normal cubic meters (Nm³/yr), equivalent to less than 10% of the world oil production in 2002. Almost all of this hydrogen is produced from fossil fuels, as shown in Table 3, while only 5% of this hydrogen is commercially used and distributed – the majority is consumed internally in refineries or chemical plants. Commercial hydrogen sales are expected to increase by over 8% per annum till 2008 [Trogish, 2004].

Feedstock	%
Natural gas	48
Oil	30
Coal	18
Electrolysis	4

Table 3 Feedstock used in the global production of hydrogen [Trogisch, 2004]

Even though electrolysis provides a much more pure form of hydrogen, only a small percent of the global production is obtained in this way in small plants due to the fact that it is much more costly than natural gas reforming, which is three times more energy-efficient than electrolysis if fossil source electricity is used (80% for reforming and 40% x 70%=28% for electricity production and electrolysis). The following table shows indicative costs for hydrogen production.

Method	Cost (\$/GJ)
Natural Gas reforming	5
Coal gasification	11
Biomass gasification	13
Electrolysis with large scale hydro	12
Wind electrolysis	32
PV electrolysis	50-100

Table 4 Hydrogen production costs [Hart, 1997]

The storage of hydrogen is considered as its “Achilles’ heal”. Its storage in an energy dense form is particularly hard to achieve and is currently one of the many areas of research. Hydrogen is commonly stored in gaseous form under pressure. Large storage tanks are under a pressure of 16 bar while in cylinders hydrogen is stored under 200-250 bar. Pressures of 750bar are being experimentally investigated for applications in the transport sector. Hydrogen in liquid form can be



stored in special vacuum tanks, like the ones used in space applications. This type of storage addresses the problem of storing hydrogen at high volume densities, however liquid hydrogen is still four times less “energy dense” per volume as kerosene. Additionally, 40% of the energy contained in gaseous hydrogen needs to be consumed for lowering the temperature of hydrogen down to 14 degrees Kelvin where it liquefies.

Innovative storage methods include bonding hydrogen in metal hydrides that are metal dusts whose atom structure allows for the orderly packing of hydrogen atoms, thus achieving higher volume densities than hydrogen in compressed gaseous form (volume is approx. that of gaseous hydrogen at 300 bar, for a tank pressure of 10 bar). The weight of these materials is however quite significant, where usually only 1.5% of the total weight is the weight of hydrogen. Depending on the properties of the metallic hydride dust, heat must be supplied to the tank for hydrogen to be released while heat must be absorbed for charging the tanks with hydrogen.

The vast quantities of hydrogen produced today are consumed in non-energy related uses that are summarised in the following table.

Usage	%
Ammonia production	50
Refineries	37
Methanol	8
Space	1
Other	4

Table 5 Hydrogen usage [Hart, 1997]

Hydrogen is used in ammonia (NH₃) production that in turn is used for the production of fertilisers. In refineries hydrogen is used for the upgrading of fuels, mostly for the removal of sulphur. Hydrogen is becoming the single most important product of the refinery so that the final products can meet the ever more stringent fuel specifications, however it remains an internally consumed product and rarely exits the refinery. The petrochemical industry uses hydrogen to produce methanol, which as it will be seen later, is sometimes used in fuel cells where it is reformed to release its hydrogen content. Hydrogen is also used in the food industry for the hydrogenation of fats. Some other uses accrue from the physical properties of hydrogen, like lubrication, heat transfer (cooling of power plant generators) or buoyancy (meteorological balloons).

The space programme of the USA has been the only case where hydrogen was used as a fuel. Hydrogen can very well be burned in suitably modified boilers, gas turbines and internal combustion engines. However, it is the development of fuel cells where hydrogen can be combusted with minimal or no emissions that has opened new horizons for the energetic use of hydrogen in transport, mobile, portable and stationary applications, spanning all types of human activities.

2.3. Hydrogen in the research agenda

Driven by recent technical advances in hydrogen and fuel cells technologies and the need for diversified and sustainable technologies OECD governments are intensifying their R&D efforts. Almost 1 billion Euro per year are invested globally for hydrogen and fuel cells research, the three



main players being the US, Japan and Europe. Half of this amount is spent on fuel cells R&D and the rest on technologies to produce, store and use hydrogen in other energy conversion devices like internal combustion engines. The respective investment from the private sector is considerably larger (approx. 3-4 billion Euro a year), including major oil and gas companies, car manufacturers, electrical utilities, power plant component developers and a number of “small” players (SMEs) in the current hydrogen and fuel cell market.

Multi-annual programmes have been announced by the major countries active in the field, including a 1.7 billion \$ over 5 years in the US, 2 billion Euro in the 6th Framework Programme and the Growth Initiative of the EC and 30 billion Yen per fiscal year in Japan. Similarly significant programmes are in place in individual countries like Canada, Germany, Italy and others. These efforts are complimented by three major international co-operation initiatives:

- The International Energy Agency (IEA) has formed in April 2003 the Hydrogen Co-ordination Group to enhance co-ordination among national R&D programmes, building on the IEA co-operation framework, including the Implementing Agreements on Hydrogen, Advanced fuel cells and others
- In November 2003, sixteen countries including non-OECD countries Russia, Brazil, India and China have formed the International Partnership for the Hydrogen Economy (IPHE), following a proposal of the US
- In January 2004, the EC established the European Hydrogen and Fuel cells technology platform (HFP), which is a cluster of public and private initiatives aiming to co-ordinate and promote the development and application of hydrogen energy technologies including fuel cells

A review of the national R&D programmes on hydrogen and fuel cells has recently been published by the IEA, in the context of the previously mentioned Hydrogen Co-ordination Group work, in which the current author was a contributing member covering Greece [IEA, 2004].

2.4. Hydrogen from renewables

Long-term forecasts for hydrogen production show some deficiencies between supply and demand, implying that increased production must be covered from alternative energy sources, including renewables. One should not forget that the production of hydrogen from fossil fuels results to CO₂ emissions, the quantities of which per mole of hydrogen produced depend on the feedstock and production technology used. Natural gas is the fossil fuel with the highest hydrogen to carbon ratio, however hydrogen from electricity producing renewables or from CO₂-neutral biomass are the ways for producing hydrogen in a distributed fashion without any CO₂ emissions. The CO₂ produced through various pathways of H₂ production is discussed in chapter 8.2.

Hydrogen production from nuclear energy is also CO₂-free, however the handling of nuclear wastes is not yet solved while uranium is found in fewer places in the world than oil, meaning that the dependency on few countries possessing raw materials with remain. Also the technologies used are very complicated and only a few countries and companies possess the knowledge for the development of nuclear plants. Hydrogen from renewables has none of these problems since renewables are



indigenous and available around the globe, while RES technologies and hydrogen production and use technologies can be manufactured almost anywhere around the globe.

Hydrogen from fossil fuels can also be CO₂ free if CO₂ sequestration is to be applied. The method has been demonstrated in the North Sea where CO₂ is pumped back into oil wells to enhance the extraction of oil. However this approach would greatly increase the cost of hydrogen and would create a problem of what to do with the large quantities of the produced CO₂.

It is thus predicted that even if fossil and nuclear fuels can be sources of hydrogen in the short to medium term, it is renewables that will be the sources of hydrogen in the long-term. The hydrogen vision compiled by the European Commission High Level Group on Hydrogen and Fuel Cells Technologies demonstrates this trend (blue arrows indicate role of RES in the Hydrogen economy).

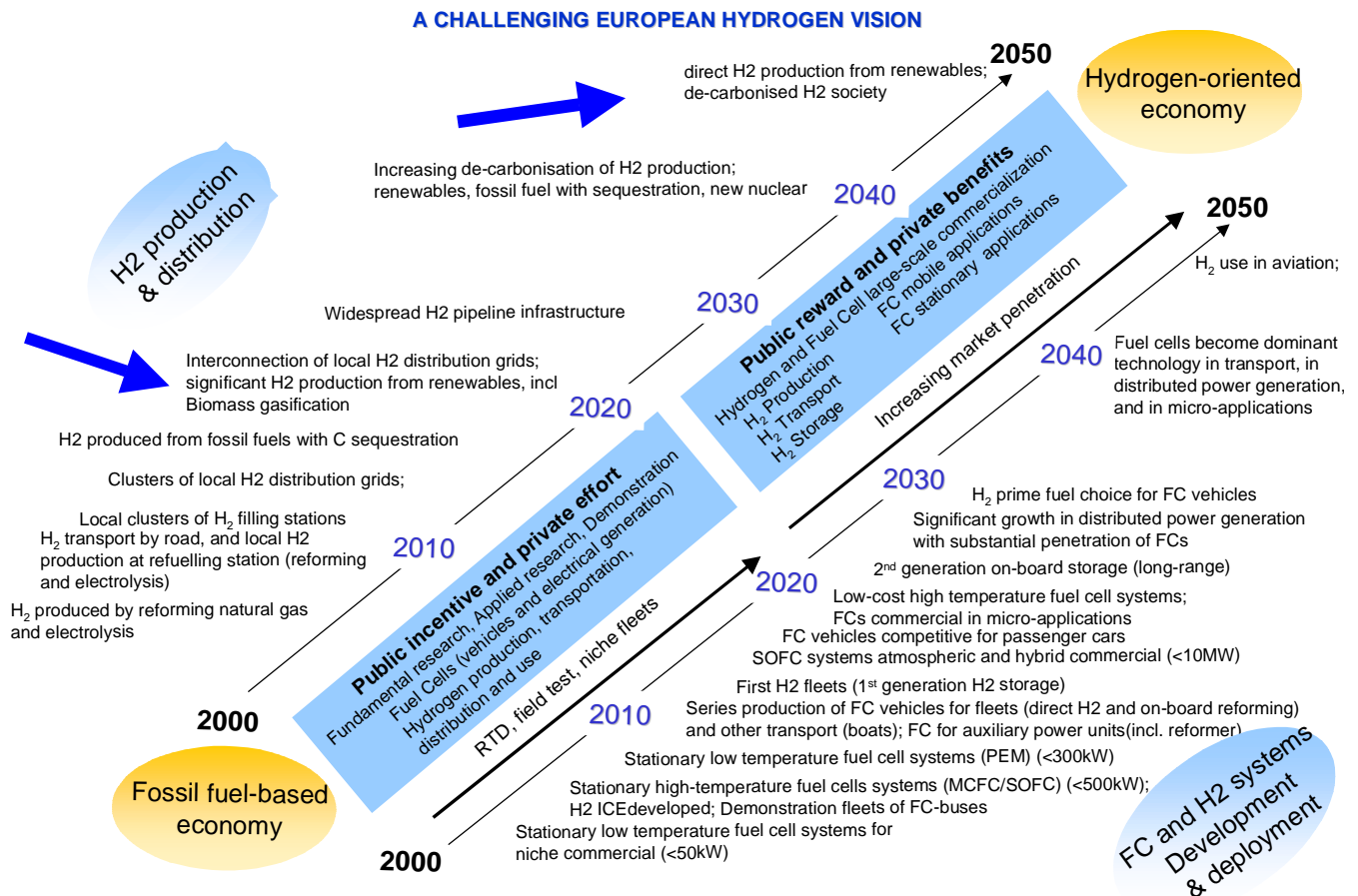


Fig. 1 Role of Renewables in the Hydrogen economy
[High Level Group of Hydrogen and Fuel Cells Technologies]

One should keep in perspective though that other energy outlook studies of the European Commission, like the WETO study [WETO, 2003], do not foresee that hydrogen is to play a major role in the energy scene till 2030, indicating that perhaps the predicted road map is slightly optimistic for hydrogen.



3. THE FUEL CELL ENERGY CONVERTER

3.1. Basic Principles

A fuel cell is an electrochemical device for the direct conversion of the chemical energy of hydrogen into electricity, heat and water vapour. This conversion can be done with very high electrical efficiency (35 – 55%) and with minimum environmental intrusion. These two aspects have rendered fuel cells as the most likely energy conversion devices in the medium to long term, in both transport and stationary applications and for all power ranges. The capability of fuel cells to operate with a variety of fuels is of particular interest to the present study, since this makes them a favourite candidate for the optimal use of biofuels.

The basic operation of a fuel cell is exactly the opposite of electrolysis. In an electrolyser, an electric current is passed through water which is broken into oxygen and hydrogen. In a fuel cell hydrogen and oxygen are combined producing an electric current and water. The principle was demonstrated by Sir W. Grove in 1839 and is shown schematically below.

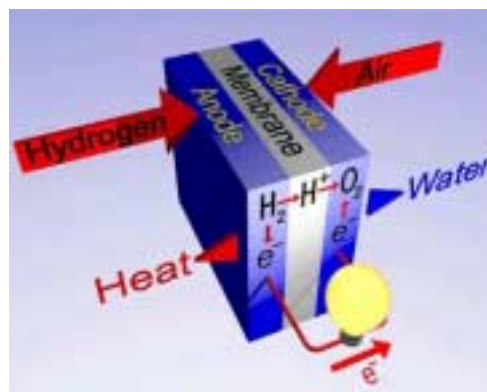
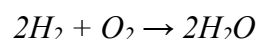


Fig. 2 Working principle of fuel cells [fuelcellworld.org]

Fuel cells operate very much like batteries, the main difference being that in batteries the reactants are stored within the battery itself and are limited by its size, while in a fuel cell they are stored externally and energy can be produced as long as fuel is fed to the anode and an oxidant to the cathode (Fig. 2).

In a fuel cell the hydrogen fuel is consumed (“combusted”) in the anode in the reaction:



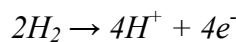
where electrical energy and heat are produced. This electrical energy is proportional to the contact area between the gases, the electrolyte and the electrodes and inversely proportional to the distance between the electrodes. To maximise the electrical energy production of a fuel cell, electrodes are thus usually made flat with a thin layer of solid or liquid electrolyte sandwiched between them. The type of electrolyte defines the type and name of the fuel cell.



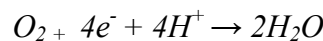
The most common types of fuel cells are:

- polymer electrolyte membrane fuel cells (PEM) where the electrolyte is an ion exchange membrane (described in chapter 4.1)
- alkaline fuel cells (AFC), where the electrolyte is an 80% concentrated solution of KOH (chapter 4.2)
- phosphoric acid fuel cells (PAFC) where the electrolyte is 100% concentrated phosphoric acid (chapter 4.3)
- molten carbonate fuel cells (MCFC) where the electrolyte is alkali carbonates that in the high operating temperatures of this fuel cell form molten salts (chapter 4.4)
- solid oxide fuel cells (SOFC) where the electrolyte is a solid, non-porous metal oxide (chapter 4.5)

The mechanism for the production of an electric current is different at each electrode and this in turn depends on the electrolyte used. In the case of an **acid electrolyte** fuel cell (PEM and PAFC, fig. 3) the hydrogen gas ionises at the anode releasing electrons and creating H^+ ions or protons, a reaction that releases energy (heat)



At the cathode, O_2 reacts with the electrons coming from the anode after passing through an electrical circuit (electrical load) and the H^+ ions passing through the electrolyte to form water.



The electrolyte should have such properties that would allow only the H^+ ions to pass through it and not the electrons, otherwise the electrical load could not be satisfied. The process is shown schematically in the following figure:

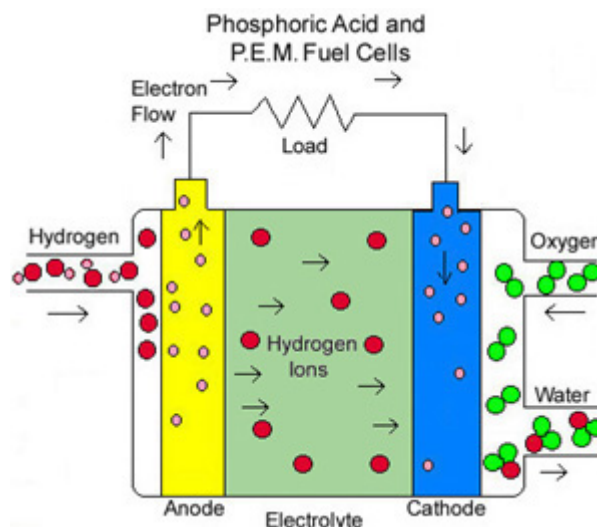
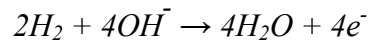


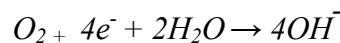
Fig. 3 Schematic operation of fuel cells with an acid electrolyte for PEM & PAFC [Illinois Institute of Technology web site]



In an **alkaline electrolyte** fuel cell (AFC, figure 4) the reactions at each electrode are different. The available hydroxyls (OH^-) react with hydrogen at the anode releasing energy (heat) and electrons and producing water.



At the cathode O_2 reacts with the electrons coming from the anode after passing through an electrical circuit (electrical load) and water in the electrolyte, forming new OH^- ions.



In this case, the electrolyte should allow OH^- ions to pass through but not the electrons. Water is consumed at the cathode but double as much is produced at the anode.

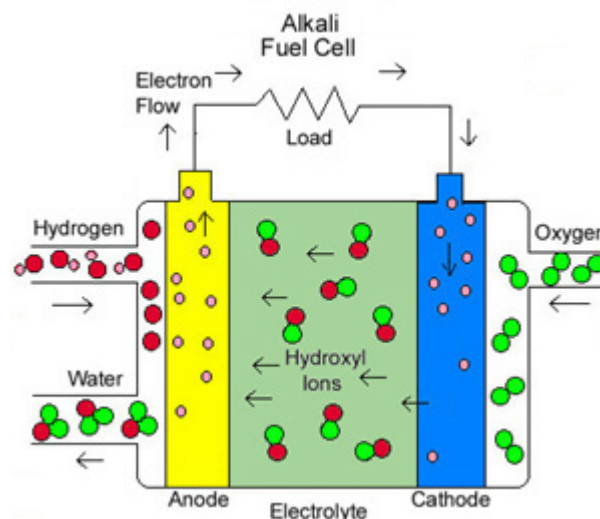
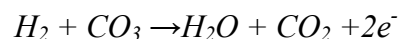
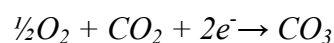


Fig. 4 Schematic operation of fuel cells with an alkaline electrolyte [Illinois Institute of Technology web site]

In a **molten carbonate** fuel cell the electrolyte used is high-temperature compounds of salt (like sodium or magnesium) carbonates (CO_3) that are in molten form due to the high temperatures (650 °C). At the anode the reactions are:



At the cathode the reactions are:



The reaction is shown schematically in figure 5. It is interesting to note here that carbonate ions of the electrolyte are being used up in the reactions and CO_2 needs to be injected. This is important in



case fuels containing CO₂ are to be used, where molten carbonate fuel cells have an advantage compared to other fuel cell types.

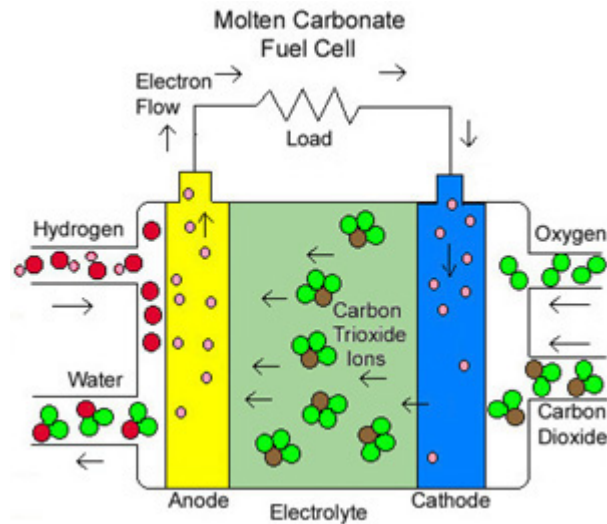


Fig. 5 Schematic operation of fuel cells with a molten carbonate electrolyte [Illinois Institute of Technology web site]

Lastly, a hard, ceramic compound of metal (like calcium or zirconium) oxides (chemically, O₂) is used as electrolyte in **solid oxide** fuel cells that operate at very high temperatures of the order of 1000 °C. Such electrolytes do not suffer by leaks (like the previous ones) but they can crack.

The reactions at the anode of solid oxide fuel cells are: $H_2 + O^- \rightarrow H_2O + 2e^-$ while at the cathode: $\frac{1}{2}O_2 + 2e^- \rightarrow O^-$

The reaction is shown schematically in figure 6.

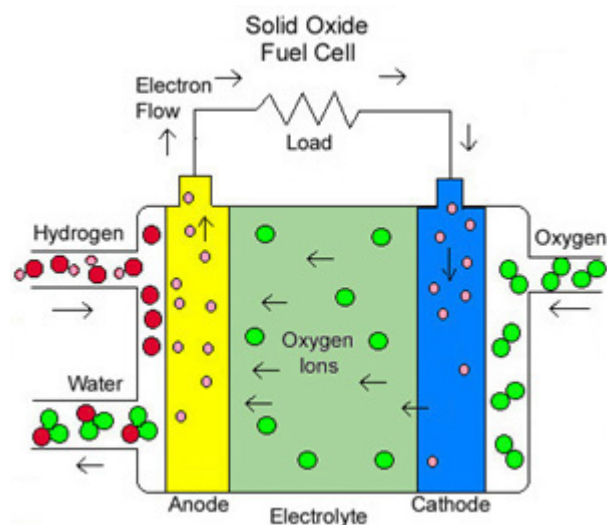


Fig. 6 Schematic operation of fuel cells with a solid oxide electrolyte [Illinois Institute of Tech web]



3.2. Fuel cell efficiency

Efficiency of a system is defined as the energy produced divided by the energy input. For the case of fuel cells the energy produced is electrical energy and the energy input is the chemical energy of the fuel. The latter is usually expressed by Gibbs free energy, thus efficiency is expressed as:

$$\frac{\text{Electrical energy produced}}{\text{Gibbs free energy}}$$

Gibbs free energy is sometimes replaced by the calorific or heating value of a fuel, since a fuel cell is to be compared with combustion or heat engines. One should note that calorific value appears as lower (LCV) or higher (HCV) calorific value, depending on whether the enthalpy of vaporisation of water has been taken into consideration. For hydrogen HCV = -285.84 kJ/mole and LCV=-241.83 kJ/mole. The LCV is most commonly used, since it gives higher values of efficiency.

For the case of combustion engines, efficiency is limited by the Carnot limit, namely $(T_1-T_2)/T_1$ where T_1 is the maximum temperature of the heat engine and T_2 the lower (exit) temperature in degrees Kelvin. The efficiency limit of a heat engine increases with increasing maximum temperature. The opposite happens for fuel cells, as can be observed in figure 7. It can also be observed that contrary to what is commonly believed, heat engines can display higher efficiency limits than fuel cells (at high temperatures). However at such temperatures, the heat available in a fuel cell can be used in CHP or in a bottoming cycle to produce more electricity through a gas turbine.

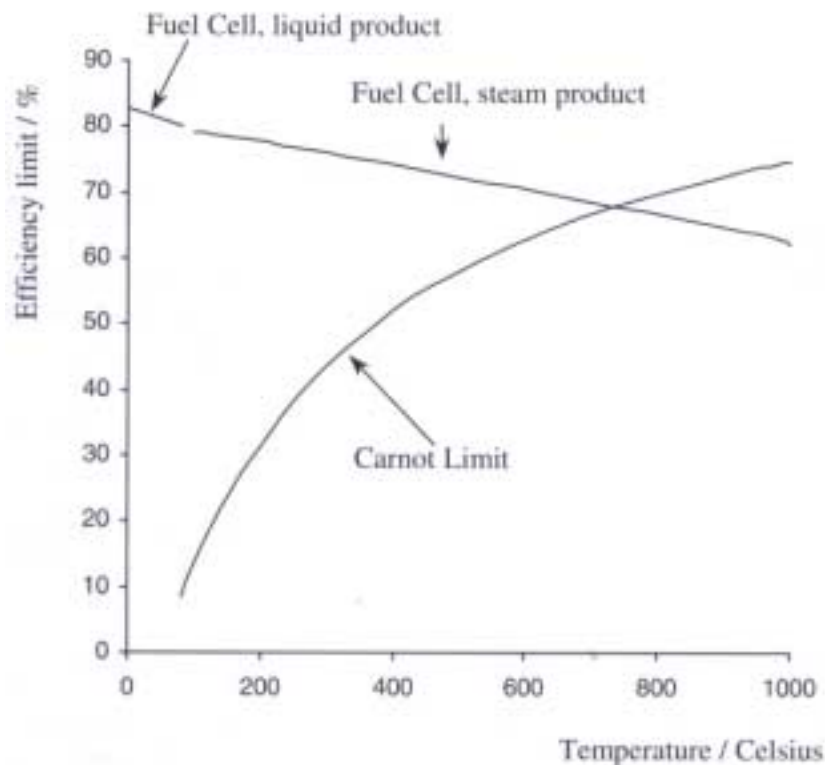


Fig. 7 Efficiency limits vs. temperature plot for a fuel cell and a heat engine [Larminie, 2000]



3.3. Reaction rate

Like in any chemical reaction, the reaction of hydrogen at the anode of a fuel cell requires an “activation energy” in order to start and then proceeds at a given rate of reaction. In order to reduce the activation energy and increase the rate of reaction, three approaches can be followed:

- use of catalysts
- higher temperatures
- increased electrode area

Since reactions take place at the surface of the electrode, the last of the previous three points is important. Electrode area is so vital that performance of a fuel cell is quoted in terms of “current per cm^2 ”. The effective surface area of fuel cells is increased thanks to the fact that electrodes have a microstructure that gives them 2- or 3-orders of magnitude higher surface areas than their planar area.

3.4. Bipolar plates

The voltage across a single cell is typically 0.7 Volts. To produce a useful voltage many cells need to be connected in series, forming a collection of cells known as a “stack”. This could be done by connecting the edge of each anode to the cathode of the next cell, but then electrons would need to travel across the face of each electrode in order to get to the collection points. This method is thus rarely used.

The most common interconnection method is the bipolar plates. Such plates allow connections all over the cathode of one cell and the anode of the next. At the same time, the bipolar plates allow the feeding of the hydrogen carrying gas to the anode and oxygen to the cathode, keeping the two gases tightly separated. This is why bipolar plates are some times referred to as flow field plates. The meander pattern of a typical bipolar plate is shown below:

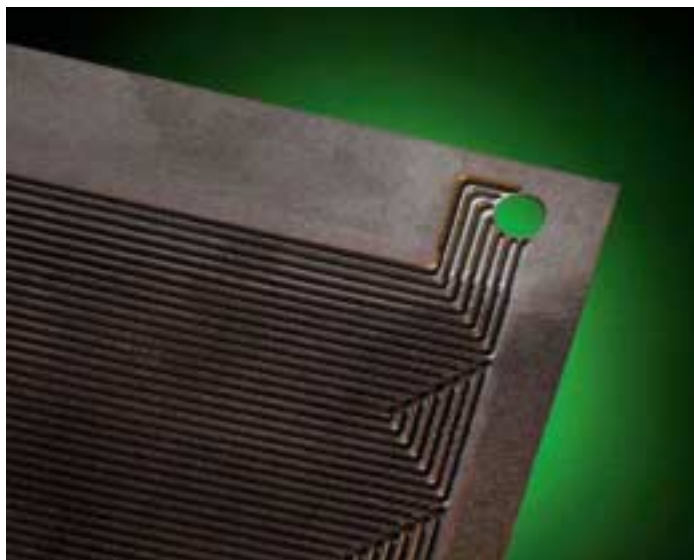


Fig. 8 A carbon – graphite bipolar plate by Porvair Fuel Cell Technology [Fuelcellworld web site]



The basic shape of a bipolar plate is a flat piece whose faces are engraved with channels that allow the flow of the reacting gases. These channels should be made as wide as possible in order not to block the flow of gases. On the other hand they should be made as narrow as possible to allow for contact points to the electrodes to be maximised. The bipolar plate should also be as thin as possible to minimise electrical resistance and limit the space taken by the fuel cell stack. For the case of a proton exchange membrane fuel cell, the anode, electrolyte and cathode are made in one thin piece commonly referred to as the Membrane Electrode Assembly (MEA). In such a fuel cell therefore, the bipolar plates make the majority of the volume of the stack. Bipolar plates are commonly made of graphite and their cost is a major part of the cost of a fuel cells system.

3.5. Balance of Plant

The core of a fuel cell is the stack, consisting of the previously discussed electrodes, electrolytes and bipolar plates. The complete engineering package of the fuel cell however includes many other components commonly referred to as “Balance of Plant”, or BoP. These components depend on the type of fuel cell and it could be the case that they take up a lot more space than the fuel cell itself, specially for the case of Combined Heat and Power (CHP) applications.

The hydrogen carrying fuel and the oxygen need to be circulated using pumps or blowers. Compressors could be used in some cases of larger fuel cells. Additionally, fuel cells produce DC power, which can rarely be exploited for covering an electrical load. Some power conditioning unit is required in the form of a DC/DC converter or a DC/AC inverter, in case electricity is to be fed to the grid or used to drive the various electric motors connected to the pumps or blowers. The processing of hydrogen could require complex hardware in case hydrogen needs to be purified or humidified, or in case pure hydrogen is not available, to reform and purify hydrogen rich gases.

Control valves, pressure regulators and a controller are invariably required in a fuel cells system. The starting up and shutting down of a fuel cell can be a complex procedure that the controller will also need to address.

A cooling system is also required, although in most cases the excess heat could be exploited to cover some demand in heat or to preheat the fuel or to help release hydrogen in the case of hydrogen storage in metal hydride tanks.

3.6. Advantages of fuel cells

The advantages of fuel cells can be summarised as:

- **High efficiency:** fuel cells are capable of converting chemical energy of a fuel directly into electricity through an electrochemical reaction. One step is required compared to the three steps required in conventional installations that involve combustion for the production of thermal energy in the form of steam, expansion of steam through a steam turbine to produce mechanical work and rotation of an electrical generator to produce electricity. Additionally the efficiency of a fuel cell is independent of its size, which is not the case for today’s combustion based power equipment. This however does not hold for the peripheral hardware constituting the balance of plant and its parasitic loads where the load is proportionately higher for smaller sizes. Electrical efficiencies ranging between 35 and 55% can be achieved by fuel cells. If the thermal energy generated by the fuel cell is also converted to electricity



through a turbine cycle then the electrical efficiency can increase even up to 70%. In combined heat and power mode, fuel cells can exhibit efficiencies up to 80%.

- **Size flexibility:** a single cell of a fuel cell produces approximately one volt of potential. Single cells can be stacked to provide the appropriate voltage for any application. Manufacturers produce fuel cells with a power of a few Watts for mobile phones, a few tens of Watts for portable computers, few kW for home systems and a few MWs for power generation applications.
- **High reliability:** fuel cells have no moving parts and thus require minimum maintenance and fewer shut downs. It is common that the hardware comprising the balance of plant (BoP) would fail and cause a fuel cell system break down, especially because the BoP hardware has not been designed specifically for fuel cells. The performance and reliability of some types of fuel cells is affected by the suitability (purity) of the fuel, meaning that the purification equipment has an important role to play in some types of fuel cells.
- **Emissions:** Water vapour is the only by-product in case pure hydrogen is used as fuel. Even in the case of using fossil fuels like natural gas, there are no NO_x, CO or HC emissions. CO₂ is emitted in case fossil fuels are used. This could also be the case if the hydrogen produced comes from fossil fuels reforming or from fossil fuel based electricity in electrolyzers.
- **Ease of installation:** since fuel cells have no moving parts they produce minimal noise and vibrations. This, in combination with the limited emissions, makes their siting straightforward and suitable for applications close or inside buildings, in accordance with the local fuel regulations.
- **Fuel flexibility:** given the appropriate fuel treatment devices including reformers, purifiers, driers, deoxidisers, etc. various types of fuels can be used in fuel cells. Of course one aims to minimise this hardware for reasons of cost, volume and simplicity of operation by choosing the most suitable type of fuel cell for each fuel. Additionally there are types of fuel cells that are more tolerant to impurities or perform internal reforming, meaning that the fuel treatment requirements are inherently minimised. Fuel cells can be adapted to utilise hydrogen, methane, methanol, ethanol, landfill gas, digester gas or oil.

3.7. Disadvantages of fuel cells

The disadvantages of fuel cells on the other hand are listed below:

- **Cost:** fuel cells are expensive to build since demand has not reached the level that would allow mass production, meaning many devices are still build by hand. Additionally, some fuel cells use expensive materials
- **Size & weight:** fuel cells are at present larger and weigh more than internal combustion engines of equivalent rating, their size and weight however is diminishing
- **Start up times:** the start-up times of fuel cells vary from a few minutes to some tens of minutes, which is a major drawback specially for transport applications
- **Reliability:** even though reliability is potentially higher than that of competing technologies, currently the reliability of fuel cells and their operating life is lower, due to the immaturity of the technology
- **Fuel availability:** for many fuel cell types and applications the fuel is not readily available and related fuelling infrastructure needs to be established. In case fossil fuels are used, their reforming produces some pollutants locally



There are additionally some disadvantages that are related to specific types of fuel cells:

- **PEM** fuel cells require expensive catalysts and are susceptible to poisoning due to the low operating temperatures
- **AFCs** require that the fuel and air streams are free from CO₂
- **PAFCs** require platinum catalysts, run on low current and power and have large size and weight relatively to other fuel cell types
- **MCFCs** and **SOFCs** that operate in high temperatures suffer from corrosion and breakdown of cell components



4. TYPES OF FUEL CELLS

4.1. Proton Exchange Membrane Fuel Cells

Proton exchange membrane or polymer electrolyte fuel cells (PEMs or PEFCs), also referred to as solid polymer cells (SPs or SPFCs) were first developed in the 1960s for the NASA space programme. Their electrolyte is a ion conducting polymer membrane, onto the sides of which the anode and cathode are bonded (platinum catalyst), forming membrane electrode assemblies (MEAs). This development campaign led to the Nafion membrane of Dupont, the industry standard till today. PEM fuel cells operate at temperatures around 80°C but efforts are made to increase this temperature to more than 150 °C that will lead to a more tolerant cell to impurities.

Pure hydrogen is the ideal fuel for PEMFCs whereupon they can display a very high efficiency of 50%, however due to the fact that they operate at low temperatures the heat produced cannot be exploited for fuel reforming in case pure hydrogen is not available. In such cases the efficiency could fall to below 40% (some of the fuel would be consumed to provide the heat for reforming). Carbon Monoxide can poison the fuel cell catalyst and therefore additional hardware is needed to limit CO to below 50ppm.

PEMFCs have a high power density, meaning low weight, cost and volume. This has resulted from increases in current density that can be as high as 1 A/cm². Their low temperatures operation allows for shorter start-up times and better load following capabilities. PEM fuel cells are seen as the fuel cell of choice for transport applications but can also be applied in portable and stationary applications, including Combined Heat and Power (CHP).

PEMFCs can be applied to a wide range of power applications, from a few Watts for mobile phones, to a few kW for stranded generating sets to a few tens of kW for cars and buses and a few 100s of kW for industrial CHP systems. All these systems would utilise the same type of electrolyte, electrode structure and catalyst, but would differ in the water management, in the method of cooling, in the bipolar plate design, the operating pressure and the reactants used.

Pictures 9 and 10 show a PEM fuel cell stack and a PEM fuel cell system respectively.



Fig. 9 A 1.5 kW PEM fuel cell stack by IRD Fuel Cells A/S [IRD Fuel Cells web site]



Fig. 10 The Axane 2kW Roller Pack PEM fuel cell system [Axane web site]

4.2. Alkaline Fuel Cells

F. Bacon demonstrated the viable operation of alkaline fuel cells (AFCs) in the 40s and 50s. AFCs were used in the Apollo missions to the moon. AFCs are high-performance fuel cells due to the rate at which chemical reactions take place in the cell. They are also very efficient, reaching efficiencies of 60 percent in space applications. The electrolyte of Alkaline Fuel Cells (AFCs) consists of a potassium solution (35 wt% KOH) for 120°C operating temperature that is more concentrated (85 wt% KOH) for an operating temperature of 260°C. The fact that the electrolyte is a corrosive liquid is considered one of the disadvantages of AFCs.

Another disadvantage is that it is easily poisoned by CO₂. In fact, even the small amount of CO₂ in air can affect the cell's operation, making it necessary to purify both the hydrogen and oxygen used in the cell. This purification process is costly. Susceptibility to poisoning also affects the cell's lifetime, further adding to cost. Cost is less of a factor for remote locations such as space or under the sea. However, to effectively compete in most mainstream commercial markets, these fuel cells will have to become more cost effective. AFC stacks have been shown to maintain sufficiently stable operation for more than 8,000 operating hours. To be economically viable in large-scale utility applications, these fuel cells need to reach operating times exceeding 40,000 hours. This is possibly the most significant obstacle in commercialising this fuel cell technology. A 2 kW AFC is shown in figure 11.



Fig. 11 2kW AFC [Fuel Cell Control Ltd web site]



4.3. Phosphoric Acid Fuel Cells

Operating fuel cells at higher temperatures to PEMs or AFCs has some advantages, including:

- Faster electrochemical reactions due to lower activation losses
- Higher tolerance to contaminants, meaning reduced need for noble metals
- the high temperature allows for the reforming of the fuel used and the “extraction” of hydrogen
- similarly, the heat available at the exit of the fuel cell can be used in applications requiring good quality heat (CHP) or can be used to drive a gas turbine in order to produce more electrical power in fuel cell and turbine hybrid systems

Phosphoric acid fuel cells (PAFC) operate at medium temperatures (up to 200 °C) and are the most well developed of the “hot” fuel cells. Many 200kW PAFC CHP systems have been installed around the world that were built by United Technologies - ONSI (formely International Fuel Cells - IFC). Some of these units have been run on biogas from sewage treatment plants. Since PAFCs operate at medium temperatures they require noble metals catalysts made of platinum and, like PEMs, are poisoned by carbon monoxide, meaning that a complex fuel processing system is required. The electrolyte is concentrated phosphoric acid (H_3PO_4). The electrodes used are of the gas diffusion type like for PEMs consisting of Pt supported on carbon, a solution that has allowed considerable reduction in Pt loading.

The stack consists of a repeated arrangement of a bipolar plate, the anode, the electrolyte and the cathode, like in a PEM FC. Provision must be made for cooling of the cells using air or liquids, the later requiring less space between cells. Some indicative performance figures of the most advanced cells produced by IFC were 0.323 W.cm^{-2} in cells operating at 645 mA.cm^{-2} and 0.66 Volts per cell. Degradation rates of $4\text{mV}/1000$ hours of operation have been achieved but these have been surpassed by Mitsubishi Electric with $2\text{mV}/1000$ hours for 10,000 hours of operation at 200 to 250mA.cm^{-2} .

A number of PAFC fuel cells (more than 65 MW) have been installed and been operated for many years and have shown very good reliability of the stack and power quality. This means that such systems have been chosen in “premium power” applications such as banks, hospitals or computing facilities. Most plants are of 200 kW but some plants go up to 5MW. A unit built by International Fuel Cells and Toshiba has a power of 11MW. Figure 10 shows 5x200kW PAFC units in Alaska.

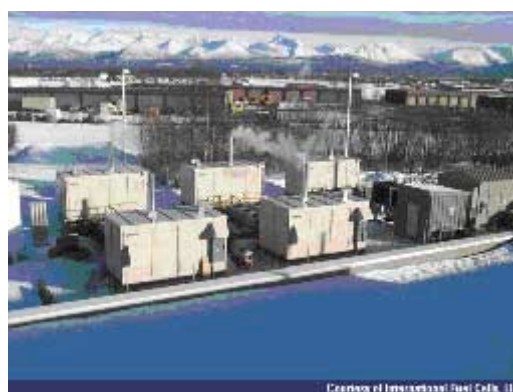


Fig. 12 Five 200kW PAFC units operating in Alaska [Bellona web site]



4.4. Molten Carbonate Fuel Cells

MCFCs are high-temperature fuel cells that use a molten carbonate salt mixture electrolyte suspended in a porous, chemically inert ceramic LiAlO_2 matrix. Since they operate at extremely high temperatures of 650°C and above, non-precious metals can be used as catalysts at the anode and cathode, reducing costs. Molten carbonate fuel cells (MCFCs) are currently being developed for natural gas fuelled stationary application of few MWs rating for power plants for electrical utility and industrial applications.

Molten carbonate fuel cells can reach efficiencies approaching 60 percent, considerably higher than the 40% efficiencies of a phosphoric acid fuel cell plant. When the waste heat can be exploited, overall fuel efficiencies can be as high as 85 percent.

Unlike the fuel cells operating at low or medium temperatures, MCFCs don't require an external reformer to convert more energy-dense fuels to hydrogen. Due to the high temperatures at which they operate, these fuels are converted to hydrogen within the fuel cell itself by a process called internal reforming, which also reduces cost.

MCFCs are not prone to carbon monoxide or carbon dioxide "poisoning" – they can even use carbon oxides as fuel – making them more attractive for fuelling with gases produced from coal. This makes them particularly suitable for using landfill gas or anaerobic digester gas produced at waste water treatment plants where CO_2 can be as much as 40% of the produced gas.

Although they are more resistant to impurities than other fuel cell types, scientists are looking for ways to make MCFCs resistant enough to impurities from coal, such as sulphur and particulates.

The primary disadvantage of current MCFC technology is durability. The high temperatures at which these cells operate and the corrosive electrolyte used accelerate component breakdown and corrosion, decreasing cell life. Scientists are currently exploring corrosion-resistant materials for components as well as fuel cell designs that increase cell life without decreasing performance. Figure 13 shows a 1-MW plant based on MCFC technology. [IEA, 2004]



Fig. 13 A 1-MW MCFC of FuelCell Energy [Fuelcell Energy Inc. web site]



4.5. Solid Oxide Fuel Cells

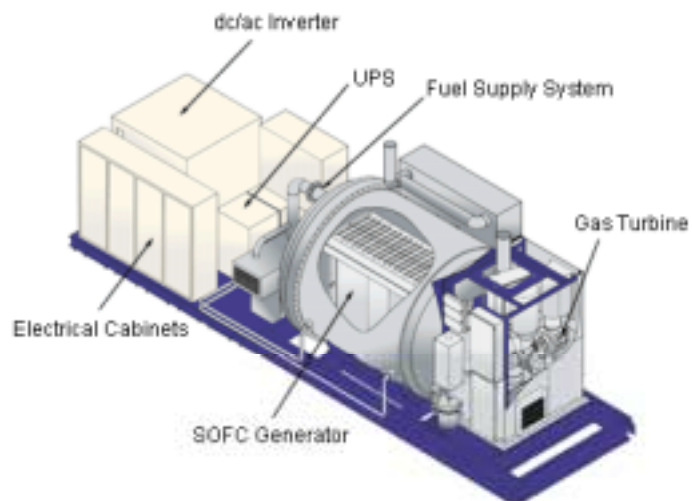
Solid oxide fuel cells (SOFCs) use a hard ceramic compound as the electrolyte. Since the electrolyte is a solid, the cells do not have to be constructed in the plate-like configuration typical of other fuel cell types and cylindrical cells are the norm. SOFCs are around 50-60 percent efficient at converting fuel to electricity. In Combined Heat and Power applications overall fuel use efficiencies could top 80%.

Solid oxide fuel cells operate at very high temperatures (around 1,000°C) that removes the need for precious-metal catalyst, thereby reducing cost. It also allows SOFCs to reform fuels internally, which enables the use of a variety of fuels and reduces the cost associated with adding a reformer to the system. SOFCs are also the most sulphur-resistant fuel cell type; they can tolerate several orders of magnitude more sulphur than other cell types. In addition, they are not poisoned by carbon monoxide (CO), which can even be used as fuel. This allows SOFCs to use gases made from coal.

High-temperature operation however has disadvantages. Long start-up times are encountered (making them unsuitable for transport applications) plus significant thermal shielding is required to retain heat and protect personnel. The high operating temperatures also place stringent durability requirements on materials. The development of low-cost materials with high durability at cell operating temperatures is the key technical challenge facing this technology.

Areas of current research are development of lower-temperature SOFCs operating at or below 800°C that have fewer durability problems and cost less. Lower-temperature SOFCs produce less electrical power, however, and stack materials that will function in this lower temperature range have not been identified.

SOFC-based home CHP units have been developed in Europe and beta-models are being tested in the context of demonstration campaigns. SOFCs are ideal to be hybridised with gas turbines thanks to the high operating temperatures. Such a model is shown below.

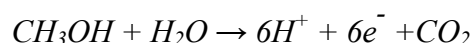


*Fig. 14 The Siemens Westinghouse 220kW SOFC-gas turbine hybrid
[Siemens web site]*



4.6. Direct Methanol Fuel Cells

The Direct Methanol Fuel Cell (DMFC) converts methanol and oxygen electrochemically into electrical power, heat, carbon dioxide and water. This type of fuel cell is in contrast with one that uses hydrogen that has been produced from the reforming of methanol, which can be termed “indirect methanol fuel cell”. A DMFC works in the same way as a PEMFC with the difference that, at the anode (negative electrode), the methanol is first split into hydrogen and carbon dioxide before the same catalyst splits the hydrogen into protons and electrons. The reaction at the anode is shown below:



Methanol needs to be mixed with water. The reactions involved are rather slow and require a special platinum/ruthenium catalyst on a carbon substrate to improve reaction rates. Similarly the cathode reaction is catalysed by platinum particles on a carbon substrate. The major drawback of DMFCs is their low efficiency that is quoted as 4% due to the slow rates of reaction. For improved rates of reaction through the catalysts mentioned previously, electrical efficiencies of the order of 30% have been quoted [IRD Fuel Cells web site]



Fig 15 A 700W DMFC of IRD Fuel Cells A/S [IRD Fuel Cells web site]

4.7. Direct Ethanol Fuel Cells

The previously described direct methanol fuel cells technology has been investigated for a number of years, leading to commercial products. The direct use of ethanol, or other small organic compounds such as formic acid or formaldehyde, in PEM fuel cells is still in an early investigation stage, with experiments being performed with single cell fuel cells. Such fuels are being investigated in order to identify fuels that are largely available or renewable, inexpensive, non-toxic and with a high reactivity at low temperatures.

The main problem of direct ethanol (sometimes referred to as direct alcohol) fuel cells is their low efficiency, resulting from the poor performance of the electro-catalysts and the severe fuel cross over from anode to cathode. Research is being undertaken to increase the reaction rate at the anode that will increase efficiency and reduce fuel permeation, the latter caused by reduced fuel concentration at the anode as the fuel is consumed more exhaustively. {Zhou 2003, Zhou, 2004}



4.8. Fuel cells research

A number of countries are undertaking major efforts for the development of fuel cells [IEA, 2004]. Japan has arguably the biggest national programme that in a period of twenty years has spanned high and low temperature fuel cells, for stationary or transport applications. Current research focus is on PEM fuel cells for embedded generation in buildings (domestic and office).

Canada has a similarly long and important involvement in fuel cell development and has the industry to prove of its success. Effort has been based on low temperature fuel cells for stationary, transport and stand-alone applications. Canada has indeed been a pioneer in the development of PEMFCs with Ballard being one of the most successful commercial fuel developers. Besides developing and commercialising fuel cells, the national efforts focus on the development of standards for hydrogen and fuel cell technologies in view of their wider application.

In the US, R&D efforts are lead by the Department of Energy (DOE) and focus on the development of reliable, low-cost, high-performance fuel cell system components for transportation and stationary applications. The available budget is of the order of 40million Euros per year, some of which are allocated towards the Vision 21 projects for the development of clean central station generation technologies and the rest to embedded generation technologies. A major US activity is the Solid State Energy Conversion Alliance (SECA), a partnership between DOE, the National Laboratories, and industry to develop and demonstrate planar solid oxide fuel cells for embedded generation. DOE also develops fuel cell technologies with an emphasis on the PEM fuel cell for both stationary and transportation applications. PEM fuel cells for transport applications are being developed in the context of the FreedomCAR partnership between DOE and the major car manufacturers of the US. The DOE also has the responsibility for developing PEM fuel cells for portable and distributed generation applications as well as the technologies required for the hydrogen energy infrastructure that is important in the long-term for large scale use of PEM fuel cells.

Europe has been a leader in hydrogen technologies and especially in hydrogen production technologies through pressurised electrolysis. In the last 20 years its research agenda in the field expanded to include fuel cells.

Considerable R&D on fuel cells has been conducted in Germany in the last 15 years, Germany being a leader in hydrogen technologies. Efforts have concentrated on new materials, improved components and system integration. The national fuel cell program has received strong national and regional funding and has made notable progress in a number of key areas including development of high temperature fuel cells (MCFC, SOFC) for stationary applications, including the 200kW Hot Module MCFC of MTU and the 1kW Hexis SOFC of Sulzer for home applications. Public funding for fuel cell activities amounts to €10 million annually and an equal amount is provided by the private sector.

In Italy, established heavy industries as well as young SMEs have been involved in R&D activities in areas of fuel cell development since the early 1980s. Currently, they are focused on the development and demonstration of PEMs for stationary and automotive applications and MCFCs for on-site and distributed generation. Research activities on materials and components for SOFCs are also being carried out. A national programme of 30MEuro annual budget supports R&D efforts in the field.



5. TYPES OF BIOFUELS

Raw biomass can be used directly as fuel, however in many cases it is processed prior to usage in order to be converted to a form more suitable to various energy technologies. The various biomass conversion technologies are briefly outlined in this section along with the compatibility of the produced biofuels to fuel cells.

The average cost of various fuels is compared with that of gaseous biofuels in the following table.

Fuel Cost	(Euro per mmBtu)
Reformed H ₂	17
Natural Gas	6
Fuel Gas from Biomass Gasification (BG)	>40
Biogas from Anaerobic Digestion of Biomass (ADG)	1.2
Landfill Gas (LFG)	1.6 to 2.5
Ethanol	10 (sugar-based) 12-15 (cellulosic)

Table 13 Average cost of gaseous fuels [Baron, 2004]

5.1. Fuel gas from biomass gasification

Biomass gasification is a well established technology for the production of combustible gas from various biomass feedstocks including wood, wood chips, forest waste, agricultural and even municipal waste. Gasification is a two step endothermic process during which a solid fuel is converted into a combustible gas. In the first step, components of the fuel are pyrolysed, whereupon volatile components are vaporised at temperatures around 600°C. The resulting vapour contains hydrocarbons, hydrogen, carbon monoxide, carbon dioxide, tar and water vapour. In the second step char (that had not vaporised in the first step) is gasified through reactions with oxygen, steam and hydrogen. The end product is a fuel gas that can be upgraded to synthesis gas after purification and removal of pollutants and particulates. Some of the unburned char is combusted to provide heat to the endothermic reactions.

In case these gasification systems are integrated in CHP plants that use conventional gas-fired engines or turbines, then overall efficiencies of 25 to 35% can be achieved [Xenergy, 2002]. For larger scale systems like IGCC, efficiencies of up to 40-45% can be achieved. Such values can be achieved with fuel cells even for smaller scales of the order of a few kW.

The composition of the fuel gas produced depends on the original composition of the feedstock as well as the process parameters. The gas composition is usually, hydrogen (30-40%), CO (20-30%), CH₄(10-15%), water (6%), N (1%). However a lot of contaminants are also present in this fuel gas that need to be removed through purification if this is to be used in fuel cells. Again the purification process varies according to the gasification technology and the type of fuel cell. Diluents and



contaminants like tar, particulates, sulphur and alkali metals need to be removed. The steps usually followed are reforming, where CH_4 is converted to CO_2 and H_2 and clean-up, which could be one of the following:

- Leaching: removal of soluble organics and alkali compounds by “washing” biomass prior to gasification
- Activated carbon: adsorption of contaminants following gasification
- Cold sulphur removal: use of a fluidised-bed tar cracker followed by scrubbing
- Hot gas clean-up: use of a cracking process to convert tars and unreacted char to H_2 , CO and light hydrocarbons

These methods are well established, however their application at the scale of small (a few kW) fuel cells is still to be proven from a practical and economic point of view. Indeed there is no consensus in scientific literature whether a fuel cell or a gas turbine would be more suitable and tolerant to use the gas produced from biomass gasification, specially if for the case of combined heat and power applications.

Considering the various types of fuel cells, high temperature fuel cells like SOFC and MCFC are considered as more appropriate to use syngas, since at the temperatures they operate CO is a fuel rather than a contaminant. Tars and sulphur need to be removed from the gas stream. Low temperature fuel cells on the other hand do not integrate well with biomass gasification due to their lower tolerance to contaminants, meaning that the purification sections would be more complex and costly.

5.2. Biogas

The anaerobic digestion of biomass produces methane. Such facilities are commonly used by agricultural facilities, agro-food industries, animal farms and waste water treatment plants as a waste treatment methodology that promotes nutrient recycling and odour control. Bacteria are used to promote biological reactions that convert approx. 40% of the solid input into a methane-rich gas.

Biogas from anaerobic digestion (ADG) typically contains 55-65% methane, 30-40% carbon dioxide, 1-10% nitrogen, small amounts of oxygen and traces of substances that can poison fuel cells like hydrogen sulphide, halogen compounds and non-methane organic compounds. There are two basic types of digesters:

- **batch type digesters** that break up one batch of material at a time. They are loaded with waste and then capped. Common types are the covered lagoon and the complete mix digesters. Waste decomposition produces heat but adding heat will accelerate the process. Mixing is used to keep the solids (2-10%) in suspension.
- **continuous digesters** where waste is fed continuously or at regular intervals. A common type is the plug flow digesters. Wastes with 11 – 13% solids can be processed.

In addition to the feeding mode of operation of a digester there are two basic principles of digester operation, the liquid phase fermentation in which the solid phase is rather low and usually in the range of 4-10 wt% and the solid state fermentation where the solid phase is in the range of 30-35 wt%. The latter type can be considered as an intensification process since it has significantly higher biogas productivity per day per unit reactor volume (by a factor of 5-7).



Temperature is the single most significant factor in both digestion processes. Bacteria are most productive in the range 36 – 54°C and their operation can be either mesophilic (30-38 °C) or thermophilic (50-70 °C). This fact shows that there is potential for CHP applications at such installations, exploiting the ADG produced which is either released, or flared. Some IC engines have been installed but these are rather noisy and with considerable emissions so fuel cells could prove an interesting alternative.

Anaerobic digester gas can be used in distributed power and heat applications, like for the case of fuel cells mentioned below. However it can also be upgraded and injected to the natural gas network to be used in more conventional applications. The process of upgrading before injection to the NG grid involves CO₂ and hydrogen sulphide removal so as to increase the methane concentration by about 30%, increase the heating value by from 7.5 to 11 kWh/ Nm³, reduce CO₂ by 30% and reduce the H₂S from 500 ppm down to 3ppm. Such a project is being undertaken in Pucking, Austria where 10Nm³/hr of ADG is processed and about 6Nm³/hr are fed to the natural gas grid [Dorniger, 2005]. The project will cost 1.1 MEuro. A similar example is that of the city of Tilburg The Netherlands where biogas is produced from source separated waste and garden waste and is purified to natural gas quality and subsequently fed into a natural gas pipeline of the local network. Another attractive biogas application is in the transport sector where biogas is upgraded to natural gas quality and is compressed for use in buses as transport fuel as is in the cities of Lille and Stockholm.

For a fuel cell application running on waste water treatment plant biogas the contaminant limits are shown in table 14, as presented in a study by the EPA in the US [Spiegel, 2000].

Biogas contaminant	PAFC requirements	Issue / concern
Hydrogen Sulphide (H ₂ S)	<4 ppmv	Poison to fuel processor reforming catalyst
Halogens (F, Cl, Br)	<4 ppmv	Corrosion of fuel processor components
Non Methane Organic Compounds	<0.5% olefins	Poison to fuel processor shift catalysts
O ₂	<4%	Over-temperature of fuel processor beds due to excessive oxidation
NH ₃	<1 ppmv	Fuel cell stack performance
H ₂ O	Remove moisture and condensate	Damage to fuel control valves. Transport of bacterial phosphates
Bacteria & solids	Remove all bacteria & solids	Fouling of fuel processor piping & beds

Table 14 List of biogas contaminants that need to be removed prior to use in fuel cells

To remove the various contaminants for the above mentioned case, a filter was installed prior to the pre-treatment facilities to remove solids, liquids and bacteria. The pre-treatment facilities consisted of a non-regenerable desulphuriser bed in conjunction with a coal bed and were used to remove hydrogen sulphide with an efficiency of 98%. Halide levels were sufficiently low for them to be handled in a halogen guard bed available at the fuel cell processor itself. The previous treatment was considered as adequate to offer a 5 year life span to the fuel cell's catalyst.



Since fuel cells suitable for such applications are commonly manufactured to operate on natural gas, some alterations need to be made to allow for the handling of larger quantities of lower calorific value gases, since ADG contains around 35-45 % diluents (mostly CO₂). These modifications included resizing pipework and valves to allow for increased flow capacity and pressure. The actual operation showed lower values of efficiency than the respective fuel cell running on natural gas, however, given that the price of fuel is much lower than that of natural gas, this can compensate for the loss of efficiency. A more significant drawback however is the fact that the methane content of biogas can vary between +/- 10%. As a result the fuel cell needs to be operated at power outputs lower than the nominal capacity in order to avoid shut down related to any decrease in CH₄ content.

Biogas is compatible with PAFCs, MCFCs and SOFCs. Most demonstration projects have used PAFCs but some demonstrators are planned with MCFCs.

5.3. Landfill gas

Methane is generated in landfills by the natural degradation of municipal solid waste by anaerobic micro-organisms. A pipe grid system can be used to collect this gas and lead it to a flare or to a CHP system, preventing the release of methane to the atmosphere (20 times more potent greenhouse gas than CO₂) as well as controlling odour.

Landfill gas or LFG is composed of 50-60% methane, 40% CO₂ and small quantities of nitrogen, hydrogen, oxygen and H₂S. Many other compounds are found as traces, like alkalenes, aromatics, chlorocarbons, hydrocarbons, oxygenated compounds and sulphur compounds. Due to the complexity of its composition, four or five separate steps are required for the pre-treatment of landfill gas before it can be used in fuel cells. The gas entering the fuel cells must be essentially clean of contaminants like sulphur and halogens and consist primarily of methane, nitrogen, oxygen and carbon dioxide. Besides the obvious factors affecting the gas pre-treatment steps that are the composition of the landfill gas and the requirements of the fuel cell, a third factor is that the composition of the LFG can vary periodically in the context of seasons or years. The treatment steps for cleaning LFG for subsequent use in fuel cells should be:

- hydrogen sulphide (H₂S) removal at ambient temperature
- cooling
- condensation
- drying
- additional cooling
- hydrocarbon removal
- filtration

However a simple desulphurisation step proved effective in the experimental running of a small SOFC (3cm² single cell) with LFG [Staniforth, 2000], where after running the fuel cell for 6 hours its power was reduced to only 70%. Further improvements were achieved by mixing the LFG with air in order to augment the inherent carbon dioxide reforming with partial oxidation.

Most of the projects that have demonstrated the use of LFG with fuel cells have relied on PAFCs, which were the first fuel cells that were commercially available and at significant capacities. PAFCs will most probably be the fuel cell of choice in the near term but will be replaced in the long term by



SOFCs and MCFCs that require fewer pre-treatment steps, once these units become commercially available. PEMFCs are not that suitable for using LFG.

5.4. Ethanol

Ethanol is produced in large quantities around the globe and is used as a petrol additive or replacement in the transport sector. In the first case conventional internal combustion engines can be used provided the amount of ethanol does not exceed 5%, while in the second case, the IC engine must have separate specifications. Ethanol can well be used in fuel cells. Ethanol can be produced in two ways.

- through technologies that **convert starch or sugar-based** raw material
- through technologies that **convert cellulosic biomass** into ethanol. In this case, sugars must be formed from the cellulosic material, which subsequently can be fermented and distilled into ethanol

Due to the high purity of the resulting ethanol, there is minimal pre-treatment that needs to be done to the fuel for its use in fuel cells, compared to other biofuels. A reforming process is certainly necessary in order to produce hydrogen, that can be either steam reforming or partial oxidation. For stationary applications, steam reforming is more suitable for the case of dilute ethanol and water mixtures (55% ethanol and 45% water by volume, resulting from partial distillation) while partial oxidation is preferable for more pure ethanol mixtures [Ioannides, 2000].

Ethanol is considered as a better fuel than natural gas in terms of energy density, cell voltages and electrical power density (W/cm^2) that a fuel cell would provide. However, ethanol is more expensive on a €/kWh basis compared to natural gas.

High temperature fuel cells like MCFCs and SOFCs are capable of internally reforming ethanol. For lower temperature fuel cells, an external reformer is required that will operate at high enough temperatures (higher than those of the fuel cell) in order to turn ethanol into a viable fuel that will not cause poisoning of the fuel cells.

Ethanol can well be used in fuel cells for transport applications. Indeed it has a number of advantages in terms of safety and storage requirements in comparison to pure hydrogen or gaseous biofuels. However its cost is again the main drawback for its application. It is expected that this cost could fall to 15c€ per litre by 2010 [Xenergy, 2002]. The present high cost means that there are today very few demonstration facilities.

Besides the previous use of ethanol in fuel cells that involves a reforming step, there do exist fuel cells that can use ethanol directly, commonly referred to as direct ethanol fuel cells or DEFCs.

5.5. Pyrolysis Oil

Pyrolysis oil is produced through a pyrolytic process where biomass material (commonly forest or agricultural waste) is rapidly heated to 500°C in the absence of oxygen and then vaporised and condensed to a liquid oil. Due to the complexity of pyrolysis oil in terms of the different compounds encountered, little research work has been done with respect to its use in fuel cells. However some studies have been made that consider that reforming of pyrolysis oil is technically



feasible. The potential “coking” of the catalysts could prove to be a major obstacle however. Another approach currently investigated is catalytic reforming that would convert pyrolysis oil into gases, mostly hydrogen and CO (at a 2:1 ratio), some methane (2 – 4%) and CO₂ (15%).

Pyrolysis oil is expected to be able to achieve lower prices than ethanol, however the complexity of the reforming process means that a higher temperature reformer would be required, meaning in turn that more energy would be required in that step. Pyrolysis oil is currently being demonstrated as fuel in more conventional combustion engines like gas turbines or ICEs. Its use, compared to conventional fuels, would result to a carbon-neutral cycle and lower SO_x emissions plus ½ NO_x emissions compared to a diesel engine.

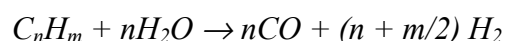


6. FUEL REFORMING

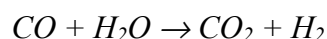
Reforming is the generic term used for converting hydrocarbons into hydrogen and CO₂. There are three basic reforming techniques, steam reforming (endothermic), partial-oxidation (exothermic) and autothermal reforming (combination of the previous two; close to thermal equilibrium). The reforming process consumes between 20-30 % of the energy contained in the fuel to be reformed.

6.1. Steam reforming

Steam reforming (SR) is currently the most wide spread method for producing hydrogen from light hydrocarbons thanks to the relative simplicity of the method. Fuel is mixed with superheated steam at 1,100°C under pressure and in the presence of a nickel based catalyst. Carbon in the fuel is oxidised producing carbon monoxide while hydrogen is released:



The CO is then subjected to a further reaction at 400 – 500 °C, known as water gas shift reaction in which it is reacted with water to produce more hydrogen and CO₂.



The temperature regime of the reactions and the catalyst used depends on the fuel to be reformed. If for example methanol is the feedstock, then this process takes place at 300 °C, making the process suitable even for transport applications. The range of feedstocks is limited to final boiling point and aromatic content. Methane (as in natural gas or biogas) can be reformed as well as propane and butane, but higher hydrocarbons need to go through a pre-reforming process producing hydrogen, methane and carbon oxides.

Steam reforming is most efficient at large scales but less effective at a scale as that suitable for use inside a car, where the energy spent would be almost 40%. At the same time steam reformers are rather bulky and since high temperatures are required, they are slow to respond to start-ups or transients in general.

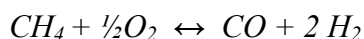
6.2. Partial Oxidation

As the name implies, partial oxidation or POX is the partial or incomplete combustion of a fuel, resulting from the use of a substoichiometric amount of oxygen (air). The process is highly exothermic and self sustaining, however for small-scale applications a catalyst could be used to increase reaction rates at lower reaction temperatures. The process is mostly used for liquid fuels.

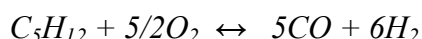
During partial oxidation the incomplete burning of hydrocarbons produces char, vapours and oils. These are quenched through the introduction of superheated steam which promotes the water-gas shift reaction (described previously under steam reforming) necessary to reduce CO and increase H₂ production.



For the case of methane:



While for pentane:



Non catalytic POX reactions can require temperatures as high as 1,000°C for the case of petrol, which implies the use of special materials. The reduction of temperatures through nickel-based catalysts means that standard materials can be used and that the amounts of CO are reduced, meaning a smaller shift reactor is required. Overall efficiency is also improved.

For heavier hydrocarbons, reaction temperatures can range from 870°C for catalytic POX up to 1,400°C for non-catalytic POX. For diesel fuel with high sulphur concentrations, reaction temperatures are 925°C for catalytic POX and 1,175°C for non-catalytic POX.

Usually POX reactors have better efficiencies than steam reformers and are more compact since no external heat transfer is required, thus more suitable for transport applications. However the high temperatures involved result to low H₂ and CO₂ selectivity and construction materials constraints, while in the case of steam reforming, the H₂ and CO₂ selectivity is higher. Designers choose among the two processes depending on the particular application.

6.3. Autothermal reforming

The autothermal reformer or ATR is a hybrid between the steam reformer and the partial oxidiser. In such a reactor heat is internally exchanged between the endothermic steam reforming reaction and the exothermic partial oxidation reaction. A catalyst is required to determine the relative extents of each reaction. Maximum temperatures are limited by the fact that the SR reaction absorbs heat from the POX reaction. Autothermal reforming provides a fuel processor compromise that operates at a lower temperature than the POX, is smaller, quicker starting, and quicker responding than the SR and results in good H₂ concentration and high efficiency that is equal or better than that of a steam reformer.

6.4. Reformers developers

Some companies active in the development of small scale reformers are listed below. Large units like those applied to refineries are considered a mature technology.

Johnson Matthey is developing an autothermal reformer called Hot-Spot aimed to be used for methanol reforming on board vehicles. The reformer starts using a POX reaction. Once water is fed in, H₂ output increases by 50% and the reaction becomes autothermal. Apparently 100% of the CH₃OH is converted leaving CO to be cleaned prior to use in a fuel cell.

The **Argonne National Laboratory** is another autothermal reformer developer, aiming for a compact, quick starting reformer. Catalysts have been developed for a variety of fossil and renewable fuels including methane, methanol, ethanol, petrol and diesel. The catalysts have shown a tolerance



for up to 30ppm sulphur containing fuels. The fabrication of catalysts in the form of micro-channels has lead to a 3-5 times reduction in the size of the reformer. Designs have been made for 5-10 kW units (refers to the power of a fuel cell that can be driven from the gas of these reformers).

Ceramic Fuel Cells Ltd, is developing a pre-reformer fuel processor that will convert hydrocarbon fuels to a methane and hydrogen-rich reformat. This reformat will be directly used in an SOFC where it will be internally reformed.

Helbio S.A. is a Greek company (spin-off from the University of Patras) that is active in the development and commercialisation of hydrogen and energy production systems from renewable sources integrated with fuel cells. The main hydrogen carriers utilised include bio-fuels such as bio-ethanol, bio-gas and bio-oil. Other sources of hydrogen, such as fossil fuels (natural gas, gasoline and diesel) are also being examined. [Helbio web site]

Hexion is a Dutch company developing hydrogen generators for industrial processes, automotive fuelling and residential fuel cell applications. Its hydrogen generating equipment is based on different modules that can be combined to generate different qualities of hydrogen from different fuels covering pure hydrogen generators for industrial process applications, pure hydrogen generators for automotive fuelling stations and hydrogen generators for residential applications with fuel cells [Hexion web site]

Honeywell is developing an POX fuel processor for JP8 and diesel fuels, to be used in military applications. The reaction takes place at high temperatures and is very fast with residence times of the order of milliseconds. Fuels with a sulphur content as high as 500 ppm were utilised. The system is optimised to produce high yields of H₂ and CO and little carbon deposits.

Nuvera Fuel Cells, besides developing fuel cells is also active in the development of reformers of various types like catalytic partial oxidation, autothermal reforming and steam reforming. The ATR is used for the reformation of a variety of fuels including natural gas, petrol (85% efficiency) or diesel. The largest unit produced was for a 200kW fuel cell.

French company **N-GHY** is developing a high temperature non catalytic HSR whose Generation 1 prototype of 20kW showed multi fuel potential, with a conversion rate of more than 99%. The reformer has been tried with diesel fuel, ethanol, rapeseed oil, rapeseed oil methyl ester (ROME) and a mixture of diesel and ROME. The unit has been developed in the context of French Fuel cell network "reseau PACo".



7. BIO-FUELS COMPATIBILITY WITH FUEL CELLS

7.1. Gas cleanup

Gas cleanup allows for the removal of contaminants and generally the improvement of the available fuel. Harmful substances for the case of fuel cells are:

- particulates
- water that clogs passages
- Ammonia
- Carbon dioxide that dilutes the biogas
- Hydrogen sulphide
- Halogenated hydrocarbons
- Siloxanes

The methods for the removal of these substances are summarised in the following table and are described in more detail in the text that follows [Schmack, 2004, Trogisch, 2004].

	Particulates	H ₂ O	NH ₃	CO ₂	H ₂ S	Hal. H _y C _z	Siloxanes
Biol. Desulph.					X	X	
Activated carbon			X		X	X	X
Iron Oxide					X		
Tenside scrubbing				X	X		
Amine process				X	X	X	
Glycol Dehydration		X					
Selexol		X		X	X		
PSA		X		X			
Water scrubbing				X	X	X	
Membrane separation	X	X	X	X	X	X	
Gas cooling		X					X
Filters, absorbents	X						X

Table 15 Methods for the removal of various substances from gaseous fuel streams

Particulates and **water** removal can be performed in simple steps through filters or absorbent material respectively.

Ammonia (NH₃) concentration in biogas is relatively low, ranging between 0 and 600 ppm. Ammonia can be harmful to PEMFCs and PAFCs. Ammonia is potentially a fuel for high temperature fuel cells, however it would be inefficient to consume hydrogen for the production of ammonia only to produce it again through decomposition of ammonia, since hydrogen could be used directly in a fuel cell. The main method for the removal of ammonia is adsorption using activated carbon or zeolites, absorption using acid water or through membrane separation.

The **Carbon dioxide** (CO₂) content of biogas can vary between 30 – 60%. At such large quantities, it acts as a diluent for most fuel cells and needs to be removed to increase the energy value of the gas.



For the case of MCFCs it actually takes part in the reactions and helps efficiency increase by 2% (paragraph 3.1), for AFCs however it is harmful. Carbon dioxide removal from biogas is very important if this biogas is to be mixed with natural gas and distributed with the natural gas network. In such cases CO₂ levels should be reduced to 1-3 %.

The removal of CO₂ is done through absorption, adsorption, membrane separation or cryogenic separation. *Absorption* or scrubbing is a physical way of removing CO₂ through its transfer from a gas phase to a liquid phase, by solving it to water or polyethelene glycol. The CO₂ carrying gas is pumped through a packed column where the solvent is also pumped in a counter current direction. The solvent can be collected, regenerated and re-circulated to the column. *Adsorption* or pressure swing process involves the capturing of CO₂ on the surface of special porous solid adsorbents which are either activated carbon or molecular sieves. There are four steps in the process, high pressure adsorption, depressurisation to ambient pressure, vacuum stripping and re-pressurisation (hense the term “swing”). This is an efficient process universally used in refineries for the purification of hydrogen, however it is rather expensive for small scale systems of a few kW. *Membrane separation* is based on the different permeability of gases through polymer membranes. There are two types of membranes, the high pressure types (35 bar) with gas phase on both sides and the low pressure membranes with a liquid absorbent on one side, that allows for atmospheric pressure operation and lower cost construction. *Cryogenic separation* involves cooling of the gas down to a temperature of -70°C and a pressure of 50 bar whereupon CO₂ liquefies and can be separated.

Hydrogen Sulphide (H₂S) is commonly found in biogases in concentrations that can be as high as 4,000 ppm. It is produced through the reduction of sulphate under anaerobic conditions by micro-organisms. H₂S is one of the most problematic contaminants of biogases because it is toxic and corrosive to most equipment, while its combustion leads to SO_x emissions that are harmful to the environment. It is recommended to remove H₂S as early as possible to protect downstream equipment. The tolerance of various energy conversion technologies is summarised in the following table [Trogisch, 2004]:

Technology	H ₂ S tolerance (ppm)
Boilers and Stirling engines	<1,000
Cooking stoves	<10
ICEs	<1,000
Microturbines	<70,000 ²
PEMFCs	<1
PAFCs	<20
MCFCs	<10
SOFCs	<1

Table 16 H₂S tolerance of various energy technologies

² It should be noted that for the case of microturbines, the H₂S limits specified by microturbine manufacturers are rather lower than the figure quoted in the previous table and is of the range of 25 to 45 ppm [Lymberopoulos, 2004]



There are physical-chemical and biotechnological processes that have been developed and are widely used for the removal of hydrogen sulphide from gases. The physical chemical methods are the ones traditionally used and commonly consist of adding iron chloride to the digester slurry, that prevents the stripping of hydrogen sulphide to the biogas, keeping H₂S levels down to 100ppm. To get to lower values one needs to revert to techniques like membranes (expensive), condensation (high cost due to need for cooling and compression), adsorption or absorption that are the methods most commonly used, having efficiencies of 99%.

Biotechnological methods are based on using micro organisms to degrade pollutants. For the case of H₂S, the most suitable micro organism for its degradation belongs to the genus *Thiobacillus*. This is a common aerobic bacterium commonly found near sulphur substrates. Such micro organisms are used in biofilters, bioscrubbers or biotrickling filters and successfully remove H₂S in odour control applications and can well be used to do the same in biogas applications. These methods are cheaper than physical-chemical methods with equal or higher efficiencies. For a 100Nm³/hr of biogas application, the cost of H₂S removal using iron oxide adsorption would be 3c€/Nm³ while for a biotrickling filter it would be 2c€/Nm³, for a total cost of biogas upgrading of 10 to 20 c€/Nm³.

Halogenated hydrocarbons are commonly found in landfill and sewage gas, following the chemical reactions or microbial degradation of dumped chemicals, coolants, propellants and chlorinated solvents. Common compounds are chloro- and fluoro-compounds with concentrations ranging from 5-500 mg/Nm³ and chlorine (25-500 mg/Nm³) and fluorine (10-35 mg/Nm³). Such compounds need to be controlled due to the fact that they contribute to the destruction of the ozone layer and the greenhouse effect, plus they cause corrosion and dioxin formation during biogas utilisation.

Similarly to H₂S, physical-chemical and biotechnological technologies are used for the elimination of halogenated hydrocarbons. Adsorption is again the most favoured of the physical-chemical techniques with a 95% efficiency but has a rather high capital investment and operating cost. Biotechnological methods are cheaper but in this case their applicability is limited due to selective destruction and sluggishness, meaning that more research is required in this field. Due to the low tolerance of fuel cells in halogenated hydrocarbons and the fact that a variety of these substances is found in biogas, a combination of adsorption and biological filtration seems necessary.

Siloxanes in biogas cause silicate deposits in heat and power applications. Siloxanes in LFG can range from 0.5 to 12 mg/Nm³ while in ADG it can range from 0.02 to 6 mg/Nm³. During combustion of siloxane containing biogases, silicon is released and can combine with free oxygen forming deposits that can become a few millimetres thick and are difficult to remove by mechanical or chemical means (Fig. 16). These deposits result in poor heat transfer in heat exchangers or reduced efficiency in combustion engines. Abrasion of blades can be observed in turbomachinery, while the activity of catalytic systems is reduced.



Fig. 16 Silicate deposits [Accettola, 2005]

No standard method exists for the removal of siloxanes from biogas. Treatment systems are usually physical. An example is the unit used for a 200kW PAFC plant running on ADG in Cologne in Germany. There the process gas is chilled to -30°C and condensation and ice formation occurs, with siloxanes being absorbed in ice. The gas then passes through an active carbon filter. The purification unit cost 107,000 \$US. Another technology used is polymorphous porous graphite sieves that are very selective to siloxanes and whose material can be regenerated. The cost for a $50\text{ Nm}^3/\text{hr}$ system was reported at \$US 22,000. Other sites use liquid absorption, using the SELEXOL glycol (rather costly but can be regenerated), while research is being performed on adsorption on activated charcoal, absorption in hydrocarbon oil and biofiltration. The latter method shows promise for achieving reduced costs, lower maintenance requirements and tolerance to fluctuations [Accettola, 2005].

7.2. Fuel cell tolerance to contaminants

The following table summarises the different types and properties of fuel cells, as presented in chapter 4.

Fuel cell type	Electrolyte	Charge carrier	Anode reaction	Cathode reaction	Operating temperature
PEM	Solid polymer (such as Nafion)	H^+	$\text{H}_2 = 2\text{H}^+ + 2\text{e}^-$	$\frac{1}{2}\text{O}_2 + 2\text{H}^+ + 2\text{e}^- = \text{H}_2\text{O}$	$50\text{-}100^{\circ}\text{C}$
AFC	KOH	OH^-	$\text{H}_2 + 2\text{OH}^- = 2\text{H}_2\text{O} + 2\text{e}^-$	$\frac{1}{2}\text{O}_2 + \text{H}_2\text{O} + 2\text{e}^- = 2\text{OH}^-$	$60\text{-}120^{\circ}\text{C}$
PAFC	Phosphoric acid	H^+	$\text{H}_2 = 2\text{H}^+ + 2\text{e}^-$	$\frac{1}{2}\text{O}_2 + 2\text{H}^+ + 2\text{e}^- = \text{H}_2\text{O}$	$\sim 220^{\circ}\text{C}$
MCFC	Lithium and potassium carbonate	CO_3^{2-}	$\text{H}_2 + \text{CO}_3^{2-} = \text{H}_2\text{O} + \text{CO}_2 + 2\text{e}^-$	$\frac{1}{2}\text{O}_2 + \text{CO}_2 + 2\text{e}^- = \text{CO}_3^{2-}$	$\sim 650^{\circ}\text{C}$
SOFC	Solid oxide (yttria-stabilized zirconia, YSZ)	O^{2-}	$\text{H}_2 + \text{O}^{2-} = \text{H}_2\text{O} + 2\text{e}^-$	$\frac{1}{2}\text{O}_2 + 2\text{e}^- = \text{O}^{2-}$	$\sim 1000^{\circ}\text{C}$

Table 17 Fuel cell types, electrolytes and electrode reactions [cospp web site]

The tolerance of the various types of fuel cells to various substances was previously discussed. In short it could be said that the operating temperature of a fuel cell determines the need or not of a reformer in case the fuel is not pure hydrogen but a hydrogen-rich gas like methane. Since methane



reforms (in the presence of a catalyst) at ~750°C, the fuel cells that operate at “low” temperatures require an external reformer, while for the “high” temperature fuel cells internal reforming can be achieved. The following table indicates the impact of various gases on the fuel cell types.

Fuel cell type	Hydrogen	CO	CH ₄	CO ₂ / H ₂ O	H ₂ S
PEM	Fuel	Poison (<50 ppm)	Diluent	Diluent	Poison (<1ppm)
AFC	Fuel	Poison	Poison	Poison	Poison
PAFC	Fuel	Poison (<0.5%)	Diluent	Poison	Poison (<50ppm)
MCFC	Fuel	Fuel	Fuel or Diluent	Fuel / Diluent	Poison (<0.5 ppm)
SOFC	Fuel	Fuel	Fuel	Fuel / Diluent	Poison (<1ppm)

Table 18 Impact of fuel constituents on fuel cells [FC Handbook, 2000]

Table 19 summarises the average composition of various biofuels that would in a way indicate the suitability of biofuels and fuel cell types.

Biofuel	H ₂	CO	CH ₄	CO ₂	H ₂ S	N ₂	O ₂	other
Landfill gas (LFG)	0.2%	-	57%	42%	traces	0.5%	0.2%	alkanes aromatics
Biogas	0-1%	-	57-70%	30-40%	3,000 ppm	1-10%	traces	halogens
Biomass gasifier (BG)	10-15%	22-27%	2-3%	10-15%	- ppm	40-50%	-	particulate s

Table 19 Biofuel composition [Baron, 2004]

Combining the information of tables 16&17, one can attempt to draw a table showing the suitability of fuel cell types and biofuels, as shown below, where “++” indicates “very suitable” and “--” indicates “highly unsuitable” for the case of limited pre-treatment. A “/” is sometimes used to indicate suitability before reforming (left of the “/”) and after reforming (right of the “/”).

Fuel cell type	LFG	ADG	BG	Ethanol	Methanol
PEM	-	-/+	--	+	+
AFC	--	--	--	?	?
PAFC	-/+	-/+	-	++	++
MCFC	++	++	+	++	++
SOFC	++	++	+	++	++

Table 20 Suitability of fuel cells to biofuels [Baron, 2004]



7.3. Fuel cell poisoning reversibility

PEM fuel cells are the most sensitive to traces of contaminants in the fuel. Investigations have been performed as to the reversibility of the poisoning process [Ferreira, 2004].

For the case of CO, if this is introduced at levels below 100ppm, then the poisoning can be reversed, as can be observed in the following diagram of FC performance (green line) in relation to the presence of CO (red line). It can be observed that once CO is removed from the gas stream and the fuel cell is fed with pure hydrogen, the performance of the fuel cell is restored.

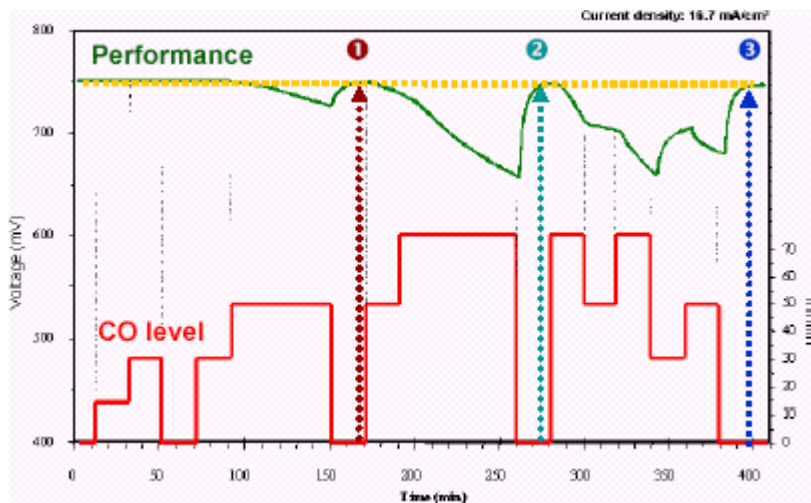


Fig. 17 PEM performance reversibility for traces of CO

Poisoning with H₂S however is an irreversible process if pure hydrogen is used, as can be observed in the following figure (diagram at left). However if oxygen is used then the performance of the fuel cell is restored since Oxygen allowed the removal of Sulphur from Platinum.

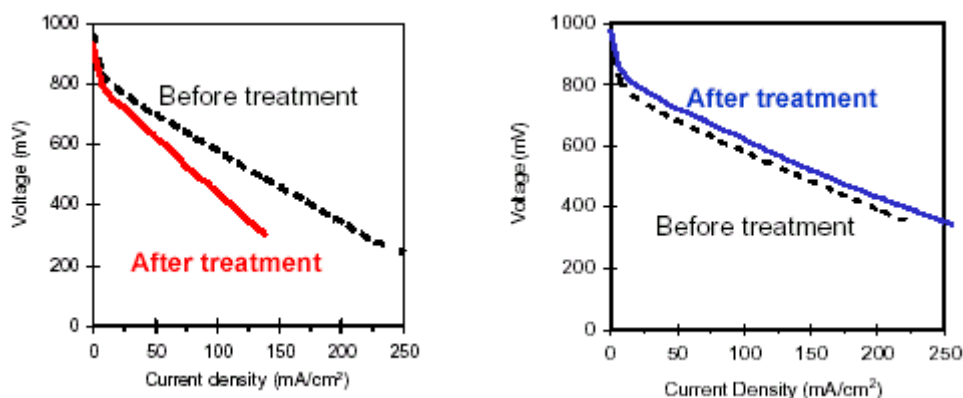


Fig. 18 Poisoning irreversibility of PEM fuel cells to H₂S in case of H₂ treatment (left) and complete gain of performance in the case of oxygen treatment (right)

The poisoning of PEM fuel cells by ammonia however is a completely irreversible process that can not be reversed through either hydrogen or oxygen treatment since ammonia even at the level of 90ppm reduces the conductivity of the Nafion membrane. Traces of linear and cyclic siloxanes also lead to irreversible loss of performance.

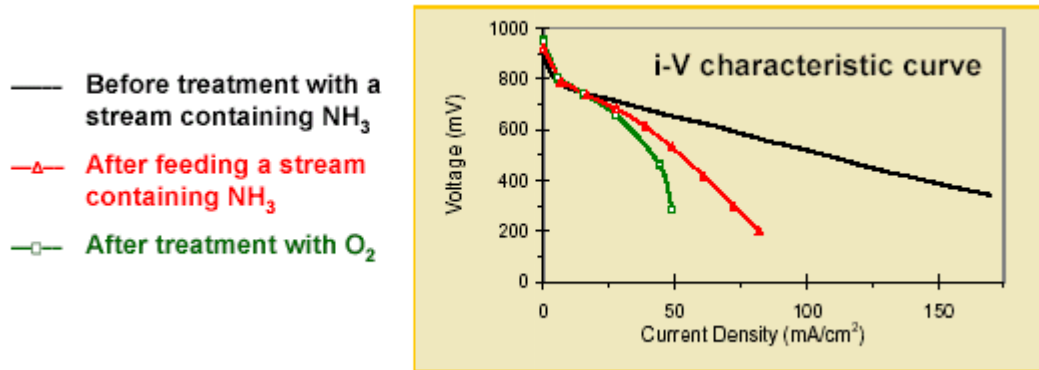


Fig. 19 Irreversible loss of performance after ammonia poisoning

The higher tolerance of high temperature fuel cells to contaminants compared to PEMFCs, in combination with the simpler reformers and purification systems required are the reasons why high temperature fuel cells are better suited for using biomass derived gaseous fuels.

Once the biogas has been upgraded and purified to levels suitable for particular types of fuel cells, then hardware developed for other energy conversion technologies can be utilised. For sites with low pressure in the feed gas, which is often the case for biogas applications, microturbine manufacturer Capstone has developed and is marketing a fuel gas booster that is suitable for their microturbines but also for ICEs or FCs. This is a variable flow scroll compressor capable of compressing up to 60Nm³/hr of gaseous fuel at an inlet pressure of 0.1 bar, to a delivery pressure of 8 bar, consuming 4-6 kW. The compressor has a design life of over 20,000 hours and never requires an overhaul. Annual maintenance consists of replacing second stage oil separator, adding oil and cleaning the heat exchanger. Some limits as to the characteristics / limits of the fuel are:

- H₂S maximum content45 ppm
- Water vapour maximum150 ppm
- CO₂ maximum content.....2.5%
- Inlet temperature50°C maximum
- Discharge gas temperature ... 65°C maximum



8. STATIONARY AND TRANSPORT APPLICATIONS OF FUEL CELLS

Fuel cells are a suitable energy conversion device for both stationary and transport applications. Low temperature fuel cells seem at present more suitable for the transport sector due to their lower operating temperatures that mean short start-up times. On the other hand PEMs require hydrogen of high purity meaning that it would be preferable for a vehicle to carry pure hydrogen rather than a hydrogen rich fuel that would need a heavy and space-occupying reformer and purifying unit. High temperature fuel cells are more suitable for stationary applications, specially for the case where the heat generated can be utilised (CHP). Their long start-up times are not a problem for continuously running applications while their capability to tolerate contaminants or perform internal reforming is an advantage in case an existing fuel distribution infrastructure exists.

Biofuels can be used in such stationary and transport applications, as described below.

8.1. Stationary applications – Distributed generation

Stationary applications of fuel cells for the production of electricity and heat fall under the term Distributed Generation. A number of parameters that include the liberalisation of the energy market, environmental concerns and security of supply have increased the interest in this concept in contrast to centralised generation. This interest has been boosted by the spreading of the Natural Gas networks and by the fact that power transmission losses are avoided if power is produced locally. The possibility to exploit on-site the heat produced in combined heat and power installations further increases the benefits of the DG concept. Suitable technologies have been developed for such distributed generation CHP applications including:

- advanced internal combustion engine based CHP systems
- micro-turbines
- Stirling engines
- fuel cells

The strengths of DG can be summed up as:

- low investment costs
- high efficiency, that can be up to 80% for CHP
- small times for installation
- installation close to load, avoiding transmission losses and power line refurbishment or extension
- low emissions
- capability to utilise a variety of fuels

While weaknesses of DG can be considered the:

- relatively high cost of kWh, depending on fuel used
- need for attention on electrical issues like control of voltage, frequency, reactive power
- non-technical issues for connecting to the electricity grid
- installation cost can be high for the case of existing buildings that need a retrofit



Densely populated areas that, for the case of Europe accommodate 80% of the population, offer major opportunities for the development of such distributed small-scale cogeneration schemes since the demand for power and heat concentrates there. The ideal fuel for these applications would be city gas or natural gas. However rural areas also constitute an interesting market [Loffler 2002]. In such rural areas the benefits of reduced transmission losses become more obvious, while the investment in electricity transportation infrastructure is avoided. Such systems would allow commercial activities to take place, contributing in rural development programmes.

Fuel cells would offer a number of potential advantages compared to other distributed generation technologies, including improved electrical efficiency, low noise, minimal emissions, small number of moving parts (found only in the peripheral systems). The following table compares typical emission values for fuel cells and other distributed generation technologies utilising Natural Gas, when used for power production only [Lymberopoulos, 2004]

Technology	Rating	NO_x	CO	HC
Micro turbines	30-100 kW	9-25 ppm	25-200 ppm	9-25 ppm
Gas turbines	0.8-10MW	6-140 ppm	1-460 ppm	6-560 ppm
IC engines	35kW	30-450 ppm	240-380 ppm	-
IC engines	0.17-1.5 MW	30-3200 ppm	320-830 ppm	2750 ppm
PAFC	200kW	1 ppm	2 ppm	-

Fuel cells have however some drawbacks, that still need to be addressed. These are the high cost of fuel cells and of the upstream fuel pre-treatment and purification hardware and the still limited operating life. The fact that the existing electricity distribution networks are unsuitable for accommodating large numbers of small generation plants, will not help in the penetration of distributed generation technologies, including fuel cells.

8.2. Transport applications

Biofuels have a role to play in the European Commission's Green Paper on security of energy supply and in the White Paper on a common transport policy, where by the year 2020 a target of 20% of alternative fuels in road transport has been set. The most important of these alternative fuels are:

- natural gas
- biofuels
- hydrogen.

According to EC directive 2003/30, biofuels are to cover 2% of the transport fuel market by the year 2005 and 5.75% by the year 2010.

The power trains that are expected to cover the transport market in the future are:

- Spark ignition (petrol) ICEs with port or direct injection
- Compression ignition (diesel) ICEs with direct injection
- Fuel Cells

All these power trains can be combined with batteries for intermediate power storage and regenerative braking capability, leading to hybrid configurations.



Well-to-wheel analyses of the various fuels and power train configurations like the one compiled by the Alternative Fuels Contact Group set up by the European Commission [AFCG, 2003] indicate that it is only liquid biofuels that will be considered as viable options in the transport market. Biofuels considered are methanol, dimethylether (DME) and bio-diesel. Both bio-diesel and DME/methanol are considered as significant fuel options for the car industry to replace diesel and petrol. Initially these will be blended with fossil fuels (5% to 10% blends) without any need for engine alterations. Bio-diesel has an 85% greenhouse avoidance potential, compared to crude oil based diesel. There are similar benefits for other regulated emissions.

A similar study conducted by LBST investigated well-to-tank (WTT) and tank-to-wheel (TTW) fuel chain efficiencies, before concluding on well-to-wheel (WTW) efficiencies [LBST, 2002] for a variety of fuels, including biomass-derived fuels. The bar chart of figure 20 thus shows the WTT energy requirements for crude oil based fuels (first two bars from top), Natural Gas based fuels (next three bars down), electricity based hydrogen production (next four bars down) and biomass based fuels (remaining 7 bars). Energy requirement is presented as the ratio of the total energy consumption (that is equal to the energy content of the fuel plus the energy for its production) in relation to the energy content of the fuel.

It can be observed that the energy use value for petroleum derived fuels is the lowest and just over 1, which is also the case for NG. Biofuels tend to have relatively high values of WTT energy requirement. Compressed methane obtained from anaerobic digestion falls below 1.5 but other options can have values as high as 3, like for the case of ethanol obtained from poplar plantation. One should also refer however to the colour code of the bars, indicating the percent of renewable or non-renewable energy utilised for the production of each fuel.

This helps explain the following figure (Fig. 21) where the estimated WTT Greenhouse gas (CO₂, NH₄, N₂O) emissions related to the production of the same fuels is presented. Since only the well to tank part of the chain is examined, biomass pathways show negative values of WTT greenhouse gas emissions due to the sequestration effect of carbon during plant growth.

For the TTW analysis, internal combustion engines and fuel cells in simple or hybrid combinations were used as powertrain options, for the case of a family vehicle of General Motors capable of 180km/h sustained travel. Considering the biomass derived fuels, Fischer Tropsch diesel was considered as fuel to ICEs only, ethanol and methanol to fuel cell powered vehicles only and hydrogen as fuel to both types of powertrains.

The TTW energy consumption estimated for the various fuels and powertrains is presented in figure 22. Values can be compared to the leftmost bar indicating a conventional vehicle running on gasoline. It can be observed that ICE hybrid vehicles show a potential for 15-25% fuel savings. ICE hybrids actually show better energy consumption figures than FC powered vehicles where fuel needs to be reformed on board. It is only vehicles with pure hydrogen storage and FCs that can offer a potential for 50% reduction of energy consumption compared to conventional solutions. The respective TTW greenhouse gas emissions are shown in the following figure 23. It is only vehicles with on-board pure hydrogen storage that enjoy local zero emission of greenhouse gases, irrespective of the powertrain.

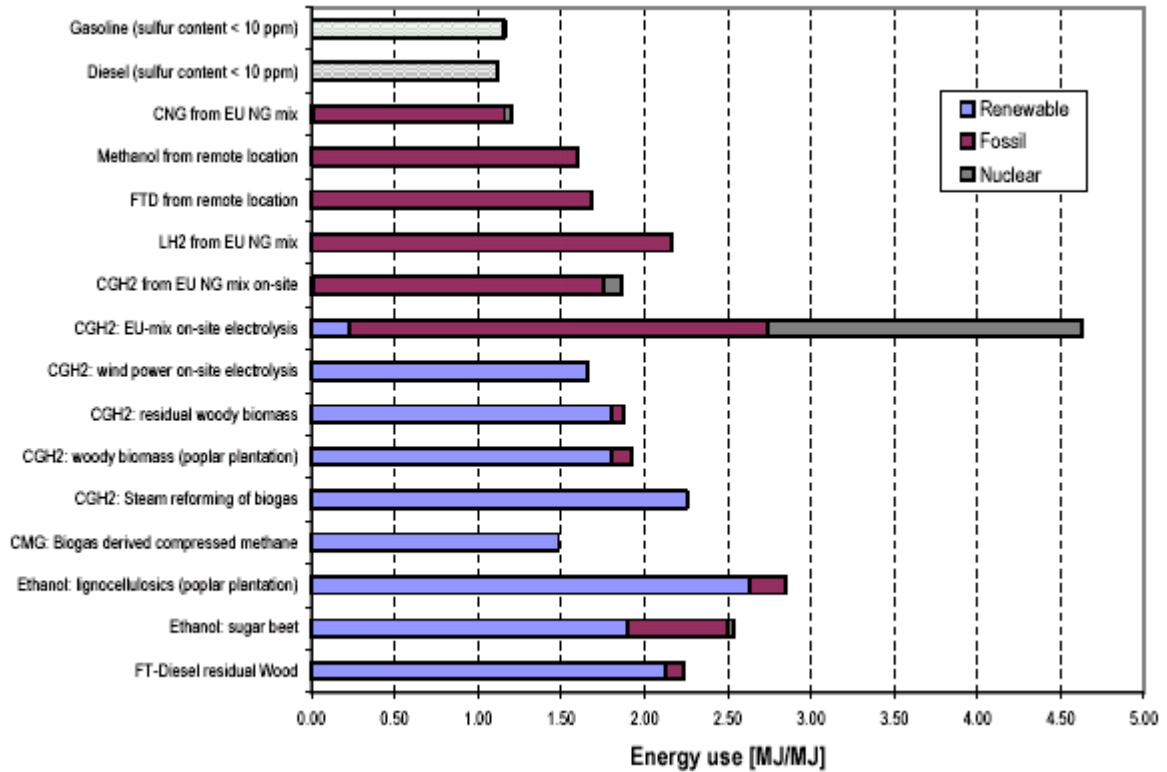


Fig. 20 Well to Tank Energy use for various types of fuels³

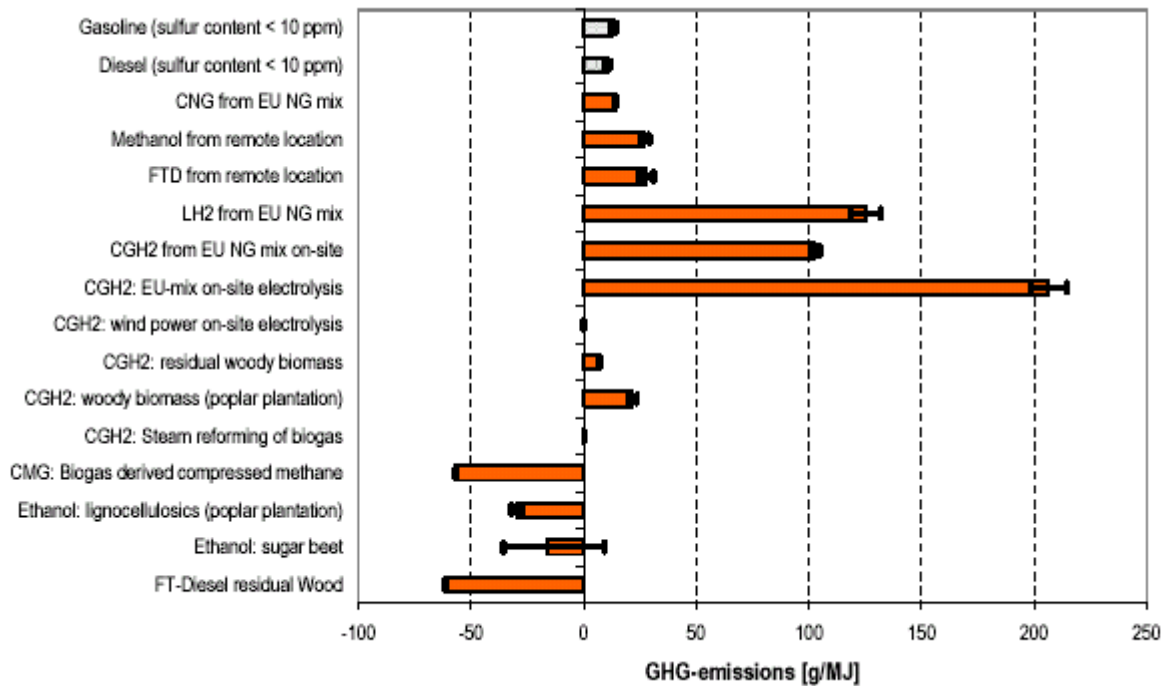


Fig. 21 Well to Tank Greenhouse gas emissions for various fuels

³ Abbreviations CNG: Compressed Natural Gas, CGH2: Compressed gaseous hydrogen, LH2: Liquefied hydrogen, FTD: Fischer Topsch Diesel, CMG: Compressed methane gas

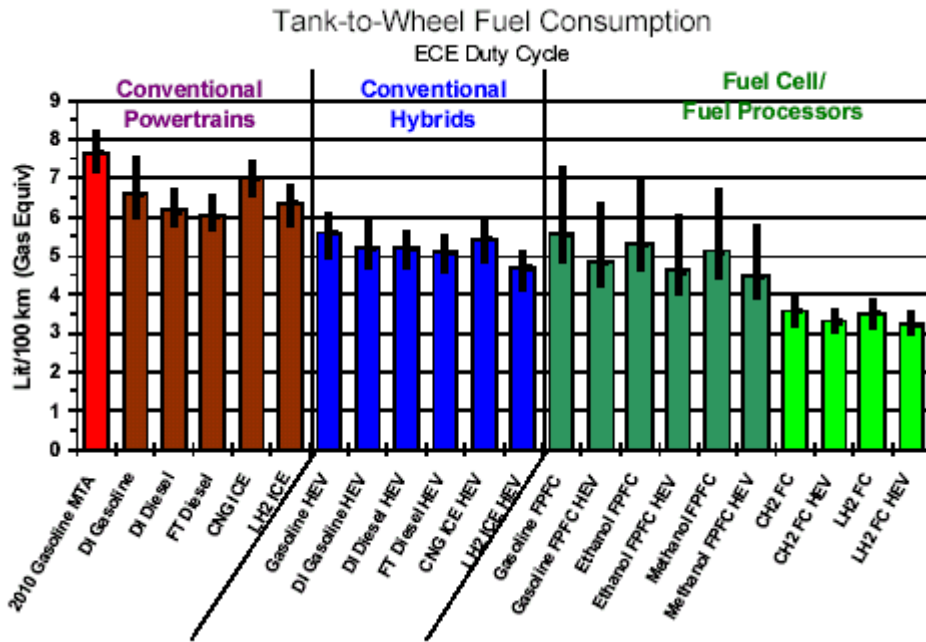


Fig. 22 Tank to Wheel fuel consumption for various fuels and power trains⁴

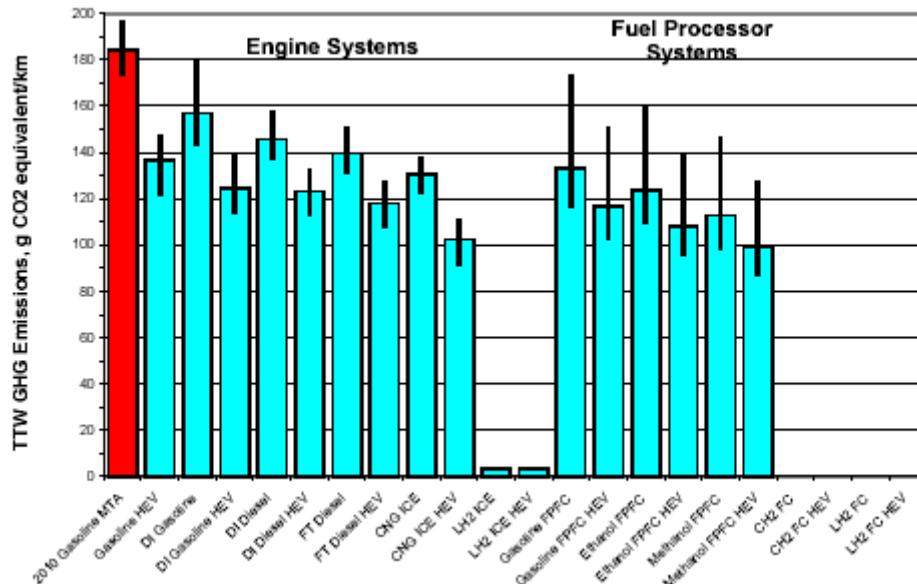


Fig. 23 TTW Greenhouse gas emission for the European driving cycle

Moving on to the complete WTW analysis, figure 24 shows the energy consumed for various selected fuels and power train types. It can be observed that for the case of biomass derived fuels, the pathway displaying the lowest WTW energy consumption is the one where biomass is used to

⁴ MTA: Manual Transmission Automated, FPFC: Fuel Processor Fuel Cell, HEV: Hybrid Electric Vehicle



produce pure hydrogen that is used in FC powered vehicles, which is the conclusion that is of most relevance to the current study.

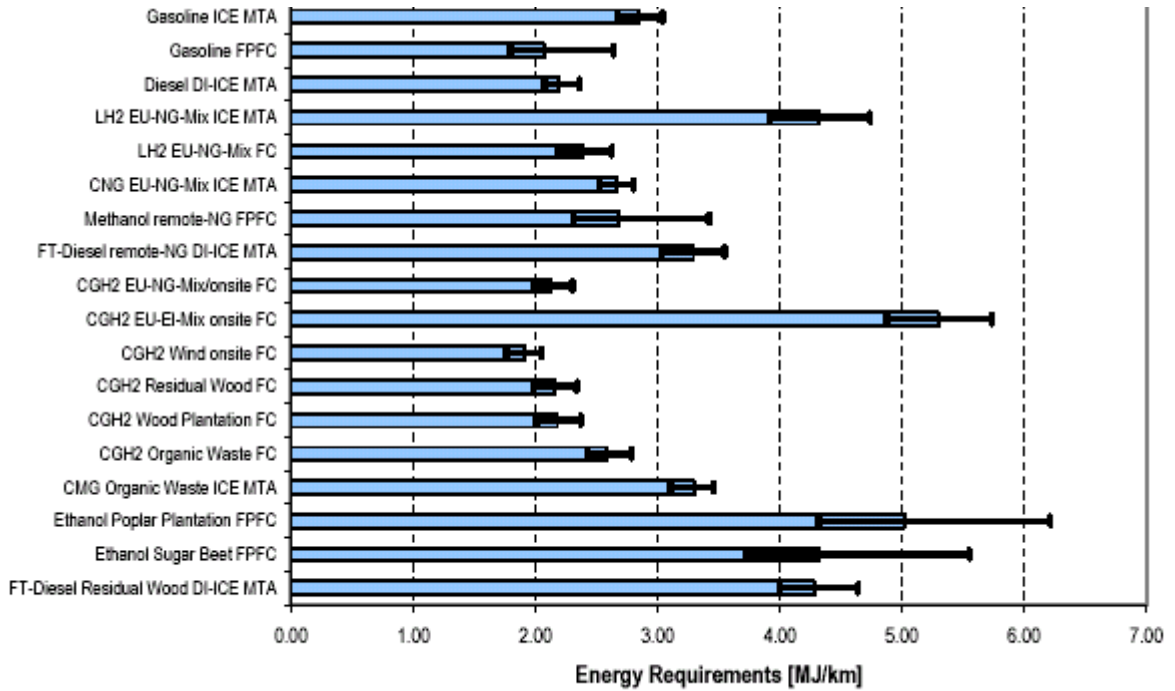


Fig. 24 WTW energy consumption



9. RELATED EC R&D PROJECTS

Hydrogen and fuel cells enjoy considerable political support at the European Union level that has led to respective R&D funds in the 5th and 6th Framework Programmes. The interest is so great that the EC initiated the Hydrogen and Fuel Cells Technology Platform for co-ordinating activities, which could potentially develop into a Joint Technology Initiative Plan. The planned HYCOM and HYPOGEN parts of the GROWTH Initiative aim to establish the first hydrogen communities in Europe.

Among the variety of projects related to hydrogen and fuel cells, a number have been related to the production of hydrogen or hydrogen-rich fuels from biomass, using biogas in fuel cells, gasifier or reformer development, etc. A list of related projects is presented below, while some selected projects are presented in somewhat more detail.

AER-GAS, ENK5-CT-2001-00545 (on-going)

The aim was to develop a reformer (AER – Absorption Enhanced Reformer) that would allow the production of a gas with 80% Vol Hydrogen and a tar content of < 300mg/m³. A CO₂-absorbent was included in the reactor bed to remove CO₂ from the product gas but also shift the chemical equilibrium towards H₂, away from CO, hydrocarbons, soot and tar.

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ZSW

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EC scientific officer: G. Guiu Exteberria

AMONCO, ENK6-CT-2001-00518 (completed)

The aim of this project was to control the biogas production process in order to avoid potential fuel cell contaminants in the biogas stream.

Coordinator: Marianne HABERBAUER

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Fax +43-725-884244

Project web site: http://www.eva.ac.at/projekte/biogas_fuelcell.htm

BIOCELLUS, SE6-CT-2004-502759

This project investigates the effect of pollutants on fuel cell performance. The project has just been initiated.

“Biomass Fuel Cell Utility system”

Coordinator Dr. J. Karl

Institute for Thermal Power Plant System, Technische Universitaet Muenchen

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Phone: +49 89 28916269

project web site: www.biocellus.net



BIO-ELECTRICITY, ENK5-CT-2002-00634 (on-going)

The project aimed to develop and demonstrate the efficient production of hydrogen and electricity from fast pyrolysis bio-oil with the integration in stationary electric power and heat production plants in remote, non-grid connected applications (500 kWe) using Molten Carbonate Fuel Cells (MCFC). For the purposes of the project, each component of the process (fast pyrolysis of biomass, steam reforming of bio-oil, water-gas shift reaction, hydrogen-rich gas upgrading, fuel cell testing), will be considered separately and to a scale of a 5kW fuel cell.

Coordinator: Marinus VAN DE GRAAF

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EC scientific officer: E. Naegele

project web site: <http://www.bio-electricity.tnw.utwente.nl/index.php>

BIO-H2, ERK6-CT-1999-00012 (completed)

This project aimed at developing a method for the production of H₂ from biomass derived ethanol, with “zero” emissions of pollutants. The method basically consisted of the bio-ethanol reformer. The produced H₂ was to be fed to FC powered vehicles.

Coordinator: Gianluca BOLITO

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e-mail: gianluca.bollito@crf.it

EC scientific officer: A. Paparella

BIOHPR, ENK5-CT-2000-00311 (completed)

This project involved the development of a reformer for the production of a hydrogen rich gas from biomass. The concept chosen was an innovative allothermal gasifier concept termed as the 'Biomass Heatpipe Reformer'. The aim was to develop a small-size and simple to built gasifier, with a flexible heat-to-power ratio. Two 200kW prototypes of reformers were to be built and tested, using cotton residues as primary fuel.

Coordinator: Karl JURGEN

TECHNICAL UNIVERSITY OF MUNICH

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EC scientific officer: G. Guiu Exteberria

CHRISGAS, “Clean Hydrogen-rich Synthesis Gas”, FP6 project

An existing biomass-fuelled pressurised IGCC plant will be used as a pilot facility so as to test new process equipment that will allow the production of a hydrogen-rich clean gas.

Coordinator: University of Vaxjo, Sweden

Contact e-mail: -

Project web site: www.chrisgas.com

CLEAN ENERGY FROM BIOMASS, ENK5-CT-2000-00314 (completed)

The project aimed at studying, developing and testing the integration of a Biomass Gasification unit and a Molten Carbonate Fuel Cell for distributed power generation. The



research activities included the assembly and operation of a pilot plant consisting of an internally-circulating, catalytic fluidised-bed gasifier, a novel hot gas clean-up system and a 125 kWe MCFC.

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EFFECTIVE, ERK5-CT-1999-00007 (completed)

The aim of this project was to develop two biogas cleaning units (one based on a biological and the other on a chemical principle). The purified biogas was tested in two 300W MCFC test beds in terms of endurance of the fuel cells. Various non-technical barriers (economic, logistic, legal) were also investigated.

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FUERO, ERK6-CT-1999-00024 (completed)

The FUERO project aimed to identify the relevant operational requirements for the operation of fuel cell systems in vehicles, including studies of energy sources and evaluating the well to wheel efficiency. Close collaboration with other EC contracts was established, including BIO-H2 mentioned above.

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Project web site: www.fuero.org

GREEN-FUEL-CELL

Apparently this project has been approved for negotiation under the 6FP of the EC and is mentioned in various brochures or EC presentations, however, no information has been found about it at CORDIS or on the Internet.

RENEWABLE-H2, ENK5-CT-2002-80633 (completed)

The aim of this project was to make an overview of activities in Europe on renewable hydrogen and to identify the role that renewable hydrogen could play in communities.

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EC scientific officer: W. Borthwick

SUPERHYDROGEN, ENK6-CT-2001-00555 (on-going)

The project aimed at developing a supercritical water gasifier, that would be cost-effective (< 12Euro/GJH₂) and energy efficient (>60%) for the conversion of wet biomass to compressed,



pure hydrogen (>98%Vol). The work involved theoretical modelling and bench-scale tests and included a techno-economic evaluation of the chain.

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EC scientific officer: G. Guiu Exteberria

Some of the previously mentioned projects are described in more detail below.

9.1. AMONCO project

Title: Advanced prediction, monitoring and controlling of anaerobic digestion processes behaviour towards biogas usage in Fuel Cells

The objectives of the AMONCO EC project were to investigate:

- Comprehensive Biogas analysis on a detailed level
- Advanced controlling of the anaerobic digestion process to hinder the formation of trace gases while keeping a high methane yield
- Suitable and cost-effective biogas cleaning processes
- Investigations of the performance of biogas in fuel cells through single cell tests
- Economic feasibility study
- Market driven implementation strategies
- Establishing a Business Interest Group

The proposed RTD work consisted of developing:

1. a knowledge based Decision Support Tool (software) with the capability to predict trace gases in dependence of the fermented substrates
2. a cost-effective Cleaning Process for removing the significant trace gases

In the context of the project such a decision support tool was developed. Single cell tests were performed to evaluate the effect of contaminants on FC performance, as shown below for the case of H₂S. Biological gas cleaning methods were also investigated.

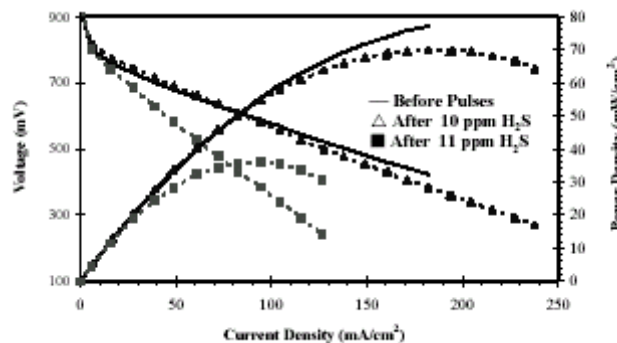


Fig. 25 Effects of contaminants on fuel cell performance

A more extensive presentation of the results obtained is given in chapter 7.3. [AMONCO web site]



9.2. Biocellus project

This project started in June 2004 and thus there are no results available yet. The project aims to address two main challenges [Biocellus web site]:

1. that fuel cell materials and gas cleaning technologies have to treat high dust loads of the fuel gas and gas pollutants like tars alkalines and heavy metals.
2. that the system integration has to allow efficiencies of at least 40 – 50 percent even within a power range of few tens or hundreds of kW in order to achieve the cost targets of 0.05 €/kW.

The BioCellus project addresses in particular these two aims – the investigation of the pollutants impact on the fuel cell and the development and demonstration of an integrated fuel cell system which meets the special requirements of biofuels.

The first part will investigate the impact of pollutants on the degradation and performance characteristics of SOFC fuel cells in order to specify the requirements of the gas cleaning system. These tests will be performed at six existing gasification sites, representing the most common gasification technologies. The selected gas cleaning technology will be tested in order to determine the effectiveness of the purification method and the properties of the produced gas. The second step will involve the development, installation and testing of an innovative integrated SOFC & gasifier concept. This will consist of an allothermal gasifier that will be heated by the heat of the fuel cell through the use of heat pipes. Internal cooling of the stack and recirculation of waste heat will be used to increase system efficiency up to 50%. Economic and environmental aspects will also be investigated.

9.3. CHRISGAS project

The aim of this 6FP IP is to develop a 18MW installation for the production of hydrogen rich synthesis gas from dry biomass. The project organised its kick-off meeting in October 2004, so there are no results available yet. The project will be realised at the Vaxjo Varnamo facility in Sweden which has a biomass-fuelled pressure IGCC (integrated gasification combined-cycle) CHP (combined heat and power) pilot plant facility.



Fig. 26 The Vaxjo Varnamo facility generating 6MW electricity and 9MW of heat from dry biomass



The S&T objectives of the CHRISGAS Project are:

- Conversion of solid biofuel into a medium calorific value gas by gasification at elevated pressure using a steam and oxygen mixture.
- Purification of the generated gas at high temperature, e.g. in a high temperature filter, and by catalytic or thermal steam reforming of not only tars, but in particular of methane and other light hydrocarbons, to generate a raw synthesis gas consisting mainly of carbon monoxide and hydrogen as energy carriers (by the end of year 5 of the project) suitable for conditioning of the hydrogen rich raw synthesis gas to the quality stipulated for synthesis gas.
- Development of a feed system based on piston feeder.
- Operating the Varnamo plant on different types of solid biofuel feedstocks.

The quantitative objectives are listed below.

	At the end of Year 3	At the end of Year 5
Demonstration of biomass feed capacity of plant (tonne/hr)	> 0.5	> 2
Demonstration of raw synthesis gas generation capacity (Nm ³ /hr wet gas)	> 500	> 3 500
Gas quality, H ₂ equivalent (H ₂ +CO), (% of dry N ₂ free gas)	> 20	> 50
Hydrocarbons (CH ₄ and above) in gas (% of dry N ₂ free gas)	< 10	< 5
Minimum duration of single measurement period (hours)	8	36
Total accumulated operating hours	100	2000

Table 21 Objectives of the CHRISGAS project

9.4. CLEAN ENERGY FROM BIOMASS

Title: “Biomass-Gasification and Fuel-Cell coupling via high-temperature gas clean-up for decentralised electricity generation with improved efficiency”

The aim of the project was to achieve high efficiency, even in distributed power generation, ultra-clean environmental performance and near-zero greenhouse gas emissions through the use of an integrated gasification – MCFC combination. The assembly and operation of the integrated pilot plant was one of the key objectives, while research activities focused on key areas related to the optimisation of the plant performance. The pilot plant was constructed and consisted of a 500 kW_{th} fast internally circulating fluidised bed (FICFB) gasifier, for catalytic biomass steam-gasification, a hot gas clean-up section, for acid compounds removal by adsorption on a basic powder and fine particle filtration, and a 125 kW_e Molten Carbonate Fuel Cell (MCFC) with its BoP [Germana, 2004].

The composition of the gas produced by the circulating fluidized bed gasifier is shown below:

CO (volume, % dry gas)	19-27
CO ₂	19-22
CH ₄	9-10
H ₂	26-38
N ₂	4-11
Tar (g/Nm ³)	3-10

Table 22 Gas composition from gasifier



An appropriate hot gas cleanup section was designed, assembled and constructed next to the gasifier. The MCFC was developed by Ansaldo Fuel Cells.

The picture below shows the pilot plant with the 500kWth gasifier and the Hot Gas Clean-Up System [downloaded from http://dsiaq.ing.univaq.it/~bio_en/eu2000.html]



Fig. 27 Ansaldo Fuel Cells MCFC pilot plant

9.5. EFFECTIVE project

Title “Holistic integration of MCFC technology towards a most effective systems compound using Biogas as a renewable source of energy”

The EFFECTIVE project focuses on using biogases in MCFCs, with emphasis in reducing agents in the biogas that could jeopardise the performance of fuel cells. The work performed had two parts [Trogisch, 2004]:

1. Develop two different gas cleaning units based on biological and chemical principles in order to reduce H_2S in Biogas from 50 ppm (=state of the art) to 10 ppm (~natural gas spec.).
2. Confirm the expected endurance of MCFC's for Biogas with two Test Beds, each comprising a 300 W FC and their respective laboratory size gas cleaning units.

A total of 15,000 hours of operation of the laboratory scale MCFC were managed, in combination with suitable purification. A broad market study was also undertaken for Germany, Austria and Slovakia.

The main conclusions of the project according to its final report were [Trogisch, 2004]:

- 1) Biogas operation of a MCFC for more than 15,000 hours was achieved thanks to the biogas purification section
- 2) The whole test set up is sensitive towards environmental impacts as it is still a lab system.
- 3) An electrical efficiency of 50% was achieved for the MCFC stack
- 4) Post test analyses indicate no severe interaction between biogas and fuel cell system components



-
- 5) NH₃ reduction by catalytic decomposition takes place in the fuel cell system.
 - 6) Both gas purification systems fulfilled expectations
 - 7) The synergy potential for biogas and fuel cell systems seems to be enormous in relation to a sustainable energy supply
 - 8) Using biogas as renewable fuel for fuel cells is a very promising clean application.
 - 9) A specific legal framework should promote this technology
 - 10) Biogas - MCFC technology for CHP is in competition with gas engines. Justification must be found in environmental issues
 - 11) Demonstration sites should be set up in different sectors. Today a proximity to R&D locations as well as transfer points to modern business is preferable

A very informative textbook was produced in the context of this project, titled “Biogas Powered Fuel Cells” [Trogisch, 2004].



10. CASE STUDIES

There are very few installations around the world with fuel cells operating on biomass or waste derived fuels. On the other hand, a number of projects run laboratory single cell fuel cells with biogas from landfill sites or waste water treatment plants in order to optimise the fuel cell components or the pre-treatment methods. Commercial size application however are very rare indeed. Only one such installation was located in Europe, while some few installations exist in the US and Japan. These are presented below.

10.1. Koln Rodenkirchen waste water treatment plant, Germany

A 200kW PAFC was installed at this waste water treatment plant that treats water from 70,000 people and produces 1,500 to 2,000 Nm³ of ADG per day. The unit was installed by RWE Fuel Cells GmbH in 2000 and was the first such unit in Europe. A gas processing unit was commissioned the previous year.



Fig. 28 PC25C fuel cell in Rodenkirchen WWTP

The reasons that this particular type of fuel cell was chosen were:

- the fuel cell ADG consumption (90Nm³/hr) matched the gas production capacity of the site
- the fuel cell exhibited excellent part load characteristics between 50 and 100% load
- the usable heat and temperature matched the requirements of the fermenters
- it was the only commercially available fuel cell of this size in 1998
- it had already been tested with ADG

The project duration was 5 years, with a load time of over 29,500 hours and a longest run of 5,000 hours. The availability of the fuel cell was 80% and of the fuel cell system 70%. More than 1.8 MNm³ of ADG were consumed at an average electrical efficiency of 37%, producing more than 4 MkWh.



The ADG quality was continuously monitored and had a content of 55-65% CH₄, 30-40% CO₂, 0-10% N₂, 0-2.5% O₂. The total sulphur content was 0-112g/m³, of halides 0-8 mg/m³ and of siloxanes 0-23.5 mg/m³.



Fig. 29 Gas processing unit of Rodenkirchen WWTP

Gas processing was done in two stages:

- 1st stage: gas freezing
- 2nd stage: activated carbon

The parasitic load of the plant was 3.5 kW and required service every six months (activated carbon).

The conclusions drawn after 5 years of operation were:

- the site preparation and fuel cell installation was a straight forward operation
- the 2-stage gas processing produced a gas clean enough to be used by fuel cells
- the fuel cell was capable to run solely and continuously on ADG
- the fuel cell was considered to outperform the common gas engines
- the operation of the fuel cell could be handled by the WWTP staff but monitoring and support by qualified engineers was necessary
- getting a permit was difficult due to the fact that the technology was imported
- the reliability was lower than expected
- a number of shutdowns were due to factors external to the fuel cell
- automatic start-up procedures did not work on ADG
- gas should be processed immediately after the fermenter in order to protect all hardware downstream

10.2. Penrose Power Station, Sun Valley, California, US

A 200kW PAFC was installed at this landfill site in 1994 and was operated till 1995 with LFG. The unit was able to produce a peak power of 137 kW and a steady power output of 120 kW with an efficiency of 36.5%. Tests lasted for a total of 700 hours with an availability of 98.5% [Spiegel, 2000]



10.3. Groton Landfill, Connecticut, US

The PAFC unit of the Penrose test site was moved to the Groton landfill, installed in 1996 and tested till 1997. The respective values measured were peak power of 165kW and a steady power output of 140 kW with an efficiency of 38%. Tests lasted for a total of 3,300 hours with an availability of 96.5%. [Sammes, 2005]

10.4. Portland, Oregon, US

A 200kW PAFC unit of UTC was installed at the waste water treatment plant at Portland and operated on ADG. The unit was installed in 1999 and was operated for 13,000 hours with an average power of 136 kW, an availability of 82% and an electrical efficiency of 38%.

10.5. Calabases, California, US

This was another waste water treatment plant where fuel cell PAFC technology was applied. Two 200 kW FCs were installed and were operated for 6850 hours. Availability was 91.2% and almost 1000 MWh were generated.

10.6. Santa Barbara, California, US

Two 250 MCFC of FuelCell Energy Inc. were installed at the waste water treatment plant of Santa Barbara. The unit is scheduled to operate in Dec 2005.

10.7. King County, Washington, US

A 1MW MCFC unit of FuelCell Energy Inc. was installed at a cost of 22m\$US at the waste water treatment plant of King County, US. The site is currently processing wastewater from about 1.4 million people producing biogas that is scrubbed and is provided to the local natural gas network. The quantities produced can generate 4MW_e. The fuel cell installed (the single largest unit in the world) will use the biogas produced more efficiently than the current gas scrubber-network combination.



Fig. 30 King County's waste water treatment plant (left) and 1MW fuel cell plant (right)



10.8. Kirin Brewery, Japan

A 250kW MCFC of FuelCell Energy Inc. was installed at the Kirin brewery near Tokyo. The fuel cell is operated in cogeneration mode, using a methane-rich digester gas produced from the effluent from the brewery process. The thermal output of the fuel cell is used by the anaerobic digester, which treats the brewery effluent.



Fig. 31 250kW fuel cell operating on brewery ADG



11. MARKET POTENTIAL OF FUEL CELLS IN STATIONARY APPLICATIONS

Fuel cells are hailed as the energy conversion technology of the future, where in combination with hydrogen they are expected to provide clean power to humanity's energy needs in transport, stationary and portable applications. Biofuels derived from biomass or waste are equally considered as one of the sustainable solutions to present and future energy needs in stationary centralised or distributed generation applications and in transport. Biofuels can be used today in conventional energy conversion technologies like boilers, internal combustion engines or turbines if mixed to fossil fuels, or in slightly modified versions of these devices when used in pure form.

The potential of using fuel cells however opens up a different world of bio-energy altogether since this involves a move from combustion technologies to electro-chemical devices that are more efficient, much quieter and produce almost zero emissions. However, there are still many barriers to be overcome till such fuel cell – biofuel combinations become everyday, economically viable solutions. Almost all of the barriers are related to the fuel cell and not the biofuel and involve reducing costs, increasing operating life, improving tolerance to contaminants and simplifying pre-treatment requirements. Some alterations to the methods producing biofuels could also result however, if this biofuel is to be used in fuel cells.

It should be noted at this point that the potential of the fuel cell-biofuel combination has meant that other technologies that are either commercial or about to be commercialised are receiving fewer funds for them to be able to penetrate the bio-energy market. Such technologies are microturbines and Stirling engines. On the other hand, biofuel driven fuel cells will benefit from funds spent for developing fuel cells that run on more conventional fuels like natural gas or pure hydrogen as well as from work done on transport applications of fuel cells.

A number of studies have been undertaken in the past in Europe and the US on the market potential of CHP systems, on the potential of biomass based CHP and on the market potential of fuel cells. The reader is asked to refer to the study "Microturbines in Bioenergy" [Lymberopoulos, 2004] to read through analyses for the market potential for cogeneration, the market potential of biomass cogeneration and the drivers and barriers of biomass cogeneration.

In the current study an analysis of the barriers and benefits of biofuel based fuel cell systems is presented, as well as the market potential of fuel cells for stationary and transport applications, followed by a SWOT analysis for such energy systems.

11.1. Barriers and benefits of bio-fuel based fuel cell systems

Fuel cells are a still developing technology that can yet enter only a few niche commercial markets. Some of these markets could indeed be associated with biofuels. However, there are technical, economic and policy barriers that still need to be addressed [Xenergy, 2002]

The technical barriers are:

- Improved reformers suitable for a variety of bio-fuels and fuel cells, working at high efficiencies
- Current qualities should be maintained in smaller scale or compact reformers



- Improved fuel clean-up or pre-treatment technologies that reduce the levels of contaminants at the required levels but at reduced cost, while exhibiting higher flexibility due to varying composition of fuels with time
- Standardised and efficient biomass-to-biofuel conversion technologies (not directly related to fuel cells)
- Lack of infrastructure in transporting biomass feedstock to biomass energy conversion facilities, as well as for transporting gaseous or even liquid biofuels

It is, like for many other technologies, the economics that will decide the application potential of bio-fuel driven fuel cells, with the following issues having importance:

- The individual high costs associated with the production of bio-fuels, with their reforming and purification and with the fuel cells means that the combined bio-fuel driven fuel cell systems have a considerable cost. Economics improve if the produced heat can be utilised (in CHP), however it should be noted that the total (electrical and thermal) efficiency of fuel cell systems is not far higher than micro gas turbine systems. Economics could improve further though if external costs can be accounted for, like credits for CO₂, NO_x and SO_x emissions
- The cost of the biomass feedstock is another critical factor. Economics are better if a fuel with little or even zero cost can be used, i.e. wastes
- The extensive cultivation of energy crops could one day lead to reduced costs and increased energy yields
- The nature of the produced bio-fuel can also affect the economics since gaseous biofuels are most probably to be used in the vicinity of the production site while liquid biofuels have a volumetric energy density that allows for the transportation and remote (from the production site) use of the bio-fuel

Lastly appropriate policy measures would help promote the use of bio-fuel driven energy producing plants, including:

- Increased funding for R&D in the field of biomass conversion, fuel treatment and fuel cells
- Setting of specific targets for electricity generation from biomass based fuels, in a way similar to the EC directives for the use of bio-fuels in transport
- Improved tariffs for RES-based electricity
- Policies to support farmers diversify to energy crops, so as to avoid the social problems encountered when subsidies for specific products are withdrawn
- The internalisation of external costs (e.g. carbon tax) would certainly make bio-fuels based energy applications more cost competitive since such applications are CO₂ neutral. However, this well applies to all other bio-fuels driven CHP technologies (ICEs, gas turbines, Stirling engines)

The application of bio-fuels driven fuel cells in stationary or transport applications would have many benefits, including:

- Reduction of emitted greenhouse gases and SO_x and NO_x emissions compared to fossil fuel generation
- Environmentally sound method of dealing with major agricultural or municipal waste streams
- Use of indigenous fuels
- Diversification of the usually problematic agricultural sector to new commercially attractive energy crops



11.2. Market potential of fuel cells for stationary applications

Frost & Sullivan have performed an analysis of the European market potential of fuel cells in stationary applications [Frost & Sullivan, 2002]. A market for fuel cells in stationary applications is expected to develop due to:

1. the residential heating market for new houses where micro-CHP solutions will play an ever increasing role
2. the gap that will develop in the coming years in the power generation field, with aging power plants not being able to comply with ever more stringent environmental standards. Their decommissioning will create a huge power generation gap / market that will be only partially filled by centralised units. A large share of this market will be covered by small distributed generation units like fuel cells.

This world market for stationary applications of fuel cells for such heating and power applications are estimated as half a million units till the year 2010, which is but a modest part of the estimated 7 million units of the boiler market. It is estimated that this market will be of the order of 3 billion Euro by the year 2011, the biggest part of this market being in Germany

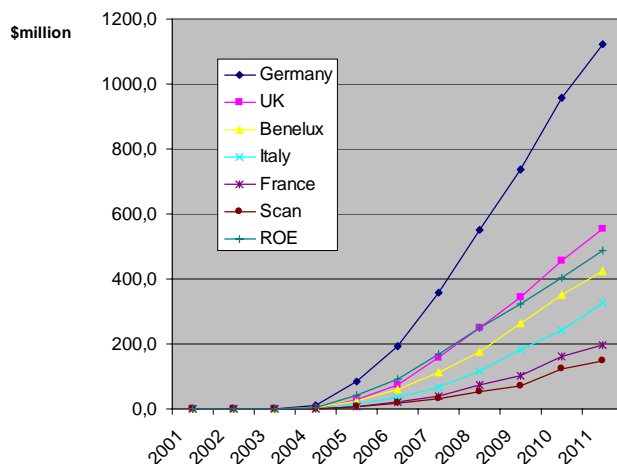


Fig. 32 Market potential for stationary fuel cell applications in Europe (ROE stands for Rest of Europe)

With respect to larger capacity markets like commercial and industrial CHP applications in the range of 100kW to 1 MW, there the fuel cells will have to compete with micro-turbines and ICEs and will have a chance if prices of the order of 1000 Euro/kW can be achieved.

Many FC manufacturers count on UPS and back-up power applications (no heat exploitation), however these are niche and not mass markets. Also, it will only be PEM FCs that will be able to suit such applications.

A similar study was performed in the context of the AMONCO project by German company EBV on the market potential of fuel cells that would run on ADG, in order to determine the maximum market potential. However, whether this market potential will be exploited by fuel cells only or will be shared by ICEs and micro-turbines was not determined by the study but was identified to be dependent on the benefits and drawbacks of each technology [Schliecker, 2004]



Substrate	Substrate Potential in Mio. t/a	Biogas Potential in Mio. m ³ /a	Potential for electricity production GWh/a	Potential for heat production GWh/a	Potential for installed el. capacity MW
Manure and other agricultural residuals	180	5,491	12,493	16,063	1,562
Energy Crops	58	10,000	22,750	29,250	2,844
Sewage Sludge	33	833	1,896	2,438	237
Organic Waste	15	1,543	3,306	4,250	413
Total	286	17,777	40,445	52,001	5,056

Table 23 Potential for ADG energy exploitation in Germany [Schliecker, 2004]

Substrate	Substrate Potential in Mio. t/a	Biogas Potential in Mio. m ³ /a	Potential for electricity production GWh/a	Potential for heat production GWh/a	Potential for installed el. capacity MW
Manure and other agricultural residuals	13.2	333	758	975	95
Energy Crops	0.8	138	314	404	39
Sewage Sludge	1.2	29	66	85	8
Organic Waste	1.2	108	246	316	31
Total	16.4	608	1,384	1,780	173

Table 24 Potential for ADG energy exploitation in Slovakia [Schliecker, 2004]

Substrate	Substrate Potential in Mio. t/a	Biogas Potential in Mio. m ³ /a	Potential for electricity production GWh/a	Potential for heat production GWh/a	Potential for installed el. capacity MW
Manure and other agricultural residuals	26.9	753	1,714	2,204	214
Energy Crops	6.6	1,150	2,616	3,364	327
Sewage Sludge	3.7	94	213	274	27
Organic Waste	1.2	88	201	258	25
Total	38.4	2,085	4,744	6,100	593

Table 25 Potential for ADG energy exploitation in Austria [Schliecker, 2004]



11.3. Market potential of fuel cells for transport applications

It is frequently mentioned that it is the potential of fuel cells to provide clean means of transport at the point of use that has promoted hydrogen and fuel cells to the top of the energy research agenda. With millions of cars sold every year around the globe, the potential market is enormous. Car manufacturers though are not all-out dedicated to any particular FC technology or fuel for that technology. Indeed when it comes to using hydrogen as fuel, some (few) manufacturers favour internal combustion engines running on hydrogen and use fuel cells as auxiliary power sources like battery substitutes. The situation becomes more complicated when other parameters come into play like whether the vehicle is a private vehicle, where it is assumed that until a hydrogen refueling infrastructure is in place, conventional fuels will be stored and reformed on-board the vehicle, while for fleet vehicles like busses, it is expected that from the start pure hydrogen will be fed at the vehicles' depot filling station.

11.4. SWOT analysis for biomass driven fuel cells

A Strength-Weaknesses-Opportunities and Threats (SWOT) analysis for biomass driven fuel cells is shown below. This analysis is based on technical literature, private communications and personal experience.

Strengths and Weaknesses refer to the product itself (biomass driven fuel cells) while Opportunities and Threats refer to the external environment affecting market development of the product.

Strengths

Fuel cell Technology

- highest efficiency for power only or CHP applications at 1kW to 1MW power range
- fuel cells suitable to utilise fuels of varying contents, through the use of appropriate reforming techniques
- no rotating parts in the cell stack, meaning low maintenance requirements
- low noise
- high grade waste heat for SOFCs and MCFCs
- suitable as a DG technology for stand alone or grid connected operation
- lowest emissions of available CHP technologies
- size of plants suitable to disperse nature of biomass

Environment

- biomass cogeneration is CO₂ neutral on life cycle basis
- achieve greater use of renewable energy
- minimal emissions
- reduce impacts from waste disposal, providing solutions for waste streams

Distributed generation of heat and power

- installation close to load, avoid electricity transmission and distribution losses
- help improve local energy security, exploitation of indigenous fuels.

Biomass related issues

- biomass based CHP plants would enable diversification in agriculture and forestry
- create rural revenue streams and local jobs



- help to improve land management practices such as forestry thinning and clearing
- biomass and waste fuels can be stored, meaning that biomass driven plants are “dispatchable” (compared to other RES that are stochastic)
- parts of the fuel to energy chain are well proven, like the production of landfill or sewage gas

Weaknesses

Fuel Cell Technology

- high capital cost
- few commercial units available
- suitable power conditioning equipment required for stand alone operation
- auxiliary systems required to operate with biomass derived fuels, consisting of reformers, purifiers, driers, filters, etc. that increase complexity and cost

Environment

- -

Distributed generation of heat and power

- existing power grids unsuitable for accommodating large number of small power plants
- attention must be paid to issues like voltage and frequency produced, reactive power, etc.
- high cost of kWh produced.

Biomass related issues

- benefits of biomass fired CHP systems cannot be accounted for in their totality since external costs of fossil fueled power plants are not cared for in today’s energy system
- biomass energy wrongly perceived by policy makers as old and unattractive
- the establishment of biomass fuel supplies is novel and risky in some countries
- chicken and egg problem to invest in biomass cogeneration until fuel supply chains are in place and vice versa
- biomass can be transported but has relatively low calorific value to make transport viable.
- parts of the fuel to energy chain are still unproven, specially at the scale of a fuel cell, including biomass gasification and pyrolysis
- many biomass applications have a low heat demand or operate seasonally (agro-industries)
- occasional mismatch between biomass cogeneration site and site of heat demand

Opportunities

Fuel Cell Technology

- capital costs of fuel cell systems to drop when series production levels are achieved, while cross benefits could come from transport sector applications
- trigeneration becoming commercially proven
- international standards for biomass derived fuels will lead to better conformance to specifications
- local job opportunities
- initial fuel cell pilot applications utilising biofuels running successfully and accumulating valuable experiences



Environment

- Emissions trading and the Kyoto protocol may stimulate the use of biomass in CHP plants

Distributed generation of heat and power

- costs of stand alone systems are relatively high

Biomass related issues

- possible development of a Directive for renewable energy heat
- increased taxation of fossil fuels, from which biomass would be exempt
- current EU and national financing schemes for innovative RES applications
- diversification of energy companies
- some biomass fuels are available for free (mostly applies to wastes)
- increasing pressure to divert wastes from landfill into incineration or energy related projects

Threats

Fuel Cell Technology

- fuel cells could never reach their reduced cost targets that would allow increased orders and thus mass production
- trigeneration even more difficult to achieve locally for the case of distributed biomass based microturbine plants
- few purely commercial applications running on biomass, most still pilot
- competing technologies (ICEs) performing perfectly adequately, specially in CHP mode

Environment

- -

Distributed generation of heat and power

- Inadequate legislative framework in terms of regulations and permits
- Current CHP market static, having negative impact on R&D of biomass based CHP
- In increasingly liberalized energy markets, direct subsidies become less available and there is a move to market-based mechanisms
- Uncertain economic conditions for investors
- Current electricity prices are very low
- Third party access to electricity networks complex

Biomass related issues

- potential end users have no experience of fuel cell technologies
- renewable energy incentives focus on electricity and exclude heat
- Changes in Common Agricultural Policy leading to uncertainties and greater financial demands for farmers and agro-industries who focus on food production, considering issues like biomass cogeneration as too high-risk

The previous SWOT analysis is summarised in the following table:



Strengths	Weaknesses
<ul style="list-style-type: none"> ➤ Highest efficiency for power only or CHP applications at this power range ➤ Fuel cells suitable to utilize fuels of varying contents, through the use of appropriate reforming techniques ➤ low maintenance requirements, low noise ➤ high grade waste heat for SOFCs and MCFCs ➤ suitable as a DG technology for stand alone or grid connected operation ➤ lowest emissions of commercially available CHP technologies ➤ size of plants suitable to disperse nature of biomass ➤ biomass cogeneration is CO2 neutral ➤ minimal gas emissions ➤ reduce impacts from waste disposal, providing solutions for waste streams ➤ install close to load, avoid transport losses ➤ exploitation of indigenous fuels ➤ create rural revenue streams and local jobs ➤ help to improve land management practices such as forestry thinning and clearing ➤ dispatchable biomass based plants ➤ production of landfill or sewage gas well proven 	<ul style="list-style-type: none"> ➤ high capital cost ➤ few units commercially available ➤ suitable power conditioning equipment required for stand alone operation ➤ auxiliary systems required to operate with biomass derived fuels (reformers, purifiers) ➤ existing power grids unsuitable for accommodating large number of small power plants ➤ high cost of kWh produced ➤ external costs of fossil fueled power plants are not cared for in today's energy system ➤ the establishment of biomass fuel supplies is novel and risky in some countries ➤ chicken and egg problem to invest in biomass cogeneration until fuel supply chains are in place and vice versa ➤ biomass can be transported but has relatively low calorific value to make transport viable. ➤ biomass gasification and pyrolysis unproven at few kW's scale scale ➤ many biomass applications have a low heat demand or operate seasonally (agro-industries) ➤ occasional mismatch between biomass cogeneration site and site of heat demand
Opportunities	Threats
<ul style="list-style-type: none"> ➤ capital costs of fuel cell systems to drop when series production levels are achieved ➤ trigeneration becoming commercially proven ➤ local job opportunities in installing and operating ➤ initial fuel cell pilot applications utilizing biofuels running successfully and accumulating valuable experiences ➤ possible development of a Directive for renewable energy heat ➤ increased taxation of fossil fuels, from which biomass would be exempt ➤ current EU and national financing schemes for innovative RES applications ➤ diversification of energy companies ➤ some biomass fuels are available for free (mostly applies to wastes) 	<ul style="list-style-type: none"> ➤ fuel cells could never reach their reduced cost targets that would allow increased orders and thus mass production ➤ trigeneration even more difficult to achieve locally ➤ few pure commercial applications running on biomass, most still pilot ➤ competing technologies (ICEs) performing perfectly adequately, specially in CHP mode ➤ Current CHP market static, having negative impact on R&D of biomass based CHP ➤ In increasingly liberalized energy markets, direct subsidies become less available ➤ Uncertain economic conditions for investors ➤ Current electricity prices are very low ➤ Third party accept to electricity networks complex ➤ potential end users have no experience ➤ renewable energy incentives focus on electricity and exclude heat

Table 26 SWOT analysis for biofuel "fired" fuel cells



12. CONCLUSIONS

Energy is vital in all aspects of human activity. The way energy is being produced and consumed today is not sustainable. Many changes will need to be realised in terms of the ways we produce and consume energy. Energy saving and energy efficiency measures need to be realised at the demand side, while Renewable energy sources need to be used at the supply side.

For the transition to this new energy era to be smooth, changes will need to be initiated today and indeed the energy stakeholders, with support from governments, are investing in the development and application of such technological solutions.

Hydrogen, electricity and biofuels are considered the main energy carriers of the future. Hydrogen is an energy vector that can be produced from a variety of energy sources, fossil in the short term and non-fossil in the long term. Fuel cells can be the enabling technology for the most efficient and clean way to use hydrogen.

Biofuels can be a source of hydrogen, following a conversion or transformation process that can take place upstream or even inside a fuel cell depending on the particular fuel cell type. Some purification or gas upgrading steps might also be required. Given the right gas treatment processes almost any type of biomass-based raw material can be turned into a gas suitable for any type of fuel cell. However, high temperature fuel cells are the types most suitable for using biofuels in an optimum way in stationary applications. This is due to the fact that they can perform internal reforming, are tolerant to contaminants while the large percentage of CO₂ present in the biogas takes part in the reactions and helps increase efficiency.

For the case of gas engines or gas turbines, CO₂ is a diluent that reduces the efficiency of combustion. The efficiency of fuel cells (35-50%) is much higher to that of gas engines or gas turbines (20-30%) while emissions are much lower. In combined heat and power mode the differences are not that significant, with total efficiency (electrical and thermal) ranging between 70-80%. Fuel cells on the other hand have a much higher cost (3,000-5,000 Euro /kW) compared to 1,000 Euro/kW for engines and gas turbines for capacities of the order of a few 10s of kW. For smaller capacities of the order of a few kW the fuel cells have only Stirling engines to compete with. The efficiency of fuel cells can drop with time as the fuel cell stack catalyst is poisoned by various contaminants in the fuel.

Technical barriers that need to be overcome for the use of fuel cells in biofuel applications are:

- Improved reformers suitable for a variety of bio-fuels and fuel cells, working at high efficiencies
- Qualities should be maintained in smaller scale or compact reformers
- Improved fuel clean-up or pre-treatment technologies that reduce the levels of contaminants at the required levels but at reduced cost, while exhibiting higher flexibility due to varying composition of fuels with time
- Standardised and efficient biomass-to-biofuel conversion technologies (not directly related to fuel cells)



-
- Lack of infrastructure in transporting biomass feedstock to biomass energy conversion facilities, as well as for transporting gaseous or even liquid biofuels

Some measures that could be taken to help overcome barriers are:

- Increased funding for R&D in the field of biomass conversion, fuel treatment and fuel cells
- Setting of specific targets for electricity generation from biomass based fuels, in a way similar to the EC directives for the use of bio-fuels in transport
- Improved tariffs for RES-based electricity
- Policies to support farmers diversify to energy crops, so as to avoid the social problems encountered when subsidies for specific products are withdrawn

The current study provided a review of the pathways that can be followed to use biofuels in fuel cells. The review is by no means exhaustive; one should take into consideration that each of the many and varied steps involved in using biomass to produce power and heat using fuel cells is a scientific field in its own right.



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- Rouge, S., CEA
- Steinberger, R., FZ-Julich
- Trogisch, S., Profactor Produktionsforschungs GmbH
- van der Drift, ECN
- Verykios, X., University of Patras



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Journal of Power Sources 126 (2003) 16–22, available on-line from www.sciencedirect.com



15. WEB SITES

AMONCO project

http://www.eva.ac.at/projekte/biogas_fuelcell.htm

Ansaldo fuel cells

<http://www.ansaldofuelcells.com>

Axane fuel cell systems

http://www.axane.fr/axane/gb/produits/roller_pac/concept.html

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16. ANNEX - MAJOR FUEL CELL MANUFACTURERS

There are numerous companies that are involved in the development and production of fuel cells or fuel cell system components. These are from either well established companies and players in the power industry or the catalysis / solid ionics industry, or are recently established SMEs mostly formed as spin-offs of research institutes or industrial gas producers.

A thorough listing of organisations active in fuel cell development can be found at various web sites, one of the most thorough being that of Fuel Cell Today [www.fuelcelltoday.com]. Below some of the companies whose products have reached a level of commercial maturity are presented in alphabetical order, with information originating either from the Fuel Cell Today web site or the web sites of the companies mentioned.

16.1. Ansaldo Fuel Cells SpA

Ansaldo Fuel Cells (AFCo) was formed in December 2001 to continue the fuel cell work carried on by Ansaldo Ricerche, from which it inherited all fuel-cell related technology, patents, right, obligations and key personnel, having as mission the industrial production and commercialization of Fuel Cells, and particularly Molten Carbonate Fuel Cells power plants in the range 0,1 -10 MW. Ansaldo Fuel Cells benefits from over 20 years of investments in fuel cells development by Ansaldo Ricerche: the latter, after working with various types of cells technologies (PAFC, PEM, MCFC), has focused its efforts on Molten Carbonates Fuel Cells which appear to be the most attractive technology for mid-sized (up to 20/30 MW) applications [Ferrari, 2005]

Recent achievements of Ansaldo Fuel Cells include conditioning and testing of the first full size area stack (FA150R), core of the “Series 2TW” unit known as TWINSTACK (Fig. 33) . The positive testing of the FA150R stack has validated a number of substantial technological improvements that were included in the stack itself, mainly aimed at reducing stack cost, increasing stack life and at simplifying the manufacturing, assembly and conditioning procedures, in view of a commercial manufacturing of MCFC systems. Such a validation confirms that the technical choices made so far are valid for the stacks to be used in the entire demo phase, and allows the existing demo and development program to be carried on with high confidence of success.

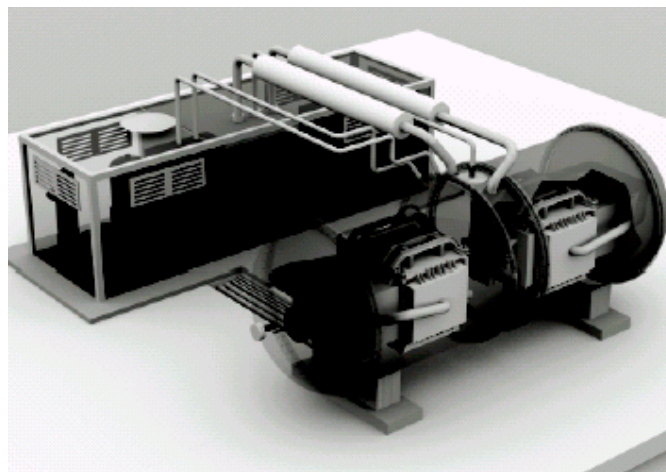


Fig. 33 The Ansaldo TWINSTACK MCFC concept



The “Series 2TW” is aimed to run on a variety of methane-rich gaseous fuels with emissions of $\text{NO}_x < 0.003$ ppm, $\text{SO}_x < 0.0005$, and $\text{CO} < 0.001$ for the case of natural gas. The demonstration and testing programme envisaged is depicted in the table below. As it can be seen, a number of test sites will be running on biofuels including biogas, landfill gas and digester gas [Ansaldo fuel cells web site].

	Size (Class)	Fuel	Site	Status	Supports
First of a Kind	“Series 2TW”	Natural Gas	Guadalix-Madrid (E)	Ongoing	EU
Naval Application	“Series 2TW”	Diesel	Marmara (TK)	Ongoing	WEAO
Biomass Application	“Series 1ST”	Biomass gasification	Trisala (I)	First part completed	EU/Ital. Dept. of Univ. & Research
Hybrid Cycle	“Series 1ST”	Natural Gas	Milano (I)	Ongoing	EU
Technodemo	“Series 1ST”	Natural Gas	Bosco Marengo (I)	Ongoing	Italian Dept. of Environment
Landfill Application	“Series 1ST”	Landfill Gas	Giugliano – Napoli (I)	Memorandum of Understanding	Campania Region
H₂/CO₂	“Series 2TW”	Hydrogen	Milano Bicocca (I)	Under Negotiation	Ital. Dept. of Univ. & Research
Flexible T.F.	“Series 1ST”	Hydrogen/CO	Terni(I)	Signed	Ital. Dept. of Univ. & Research
Further Demos	“Series 1ST” and “Series 2TW”	Syngas, Coal gas, Digester gas	Various	Under Discussion	



Fig. 34 The fuel cell stack (left and the first of a kind Series 2TW (right))

Ansaldo Fuel Cells inaugurated a new manufacturing facility in Terni, Italy with a total surface of 8000 m² and an initial capacity of 3 MW/year.



16.2. Axane

Axane is a wholly owned Air Liquide subsidiary whose mission is to develop complete packaged systems that produce energy from fuel cells powered by hydrogen. Axane is targeting three markets:

- Portable multi-application generators (500 W to 10 kW), including the Back-Pack (figure 35) and the Roller Pac 2kW AC power generator shown in figure XXX
- Stationary applications (more than 10 kW)
- Mobile applications for small hybrid vehicles (5 kW to 20 kW)



Fig. 35 A 500W portable fuel cell powered 230V AC electrical generator of Axane

Axane is coordinating the FEBUSS EC project in the context of which a standardised 100kW PEM fuel cell will be developed for transport applications. Emphasis will be placed in designing the fuel cell system as a whole [Axane web site]

16.3. Ballard Power Systems

Ballard is the world leader in PEM fuel cell technology. Part of the hydrogen economy “boom” should be attributed to the activities of Ballard. The company was founded in 1979 to research and develop batteries. Since 1983 the company has been developing PEM fuel cells, and is now also manufacturing and marketing this technology. Ballard is commercialising fuel cell engines for transportation applications and fuel cell systems for portable and stationary products. Ballard is also commercialising electric drives for fuel cell and other electric vehicles and power conversion products.

Ballard is partnering with various companies including DaimlerChrysler, Ford, EBARA, ALSTOM and FirstEnergy, to commercialise fuel cell systems of vehicles. ALSTOM and Ballard for example will invest US \$ 37 million in the construction of a Europe-wide subsidiary for the production and



marketing of stationary power systems on the basis of the PEM fuel cell technology. ALSTOM Ballard is a subsidiary of Ballard Generation Systems. 51% is owned by ALSTOM, 49% by Ballard.

Their products cover stationary and transport applications. Concerning stationary applications, Ballard produce fuel cells from 1 to 250 kW systems for standby, emergency, and uninterruptible power supply applications, premium power, residential power, and distributed generation. With EBARA of Japan, Ballard is developing a 1kW system for meeting the power and heat demands of typical Japanese homes, with an electrical efficiency of 34% and a heat recovery of 47%, giving a total efficiency of 81%. With respect to the transport sector, Ballard fuel cells are powering 150 out of the 176 fuel cell powered passenger vehicle demonstrations for 2004 and all of the 33 buses operating in the context of the CUTE project. No demonstrations have been reported with bio-fuels. [Ballard web site]



Fig. 36 The Nexa 1.2 kW DC power module of Ballard (left) that powers the AirGen™ fuel cell generator of Ballard [Ballard web site]

16.4. FuelCell Energy Inc.

This is a US company concentrating on the development of MCFCs with power ranging from 250kW to 2 MW. They have patented the Direct FuelCell that operates directly on fuels (from NG to diesel) without the need for an external reformer. The company has teamed up with MTU CFC Solutions (mentioned later), each company holding a stake of the other and is closely collaborating with the National Energy Technology Laboratory of the US DoE. The company is also looking to diversify to marine applications (auxiliary power), fuel cell & gas turbine hybrid technologies and SOFCs for applications up to 100 kW. A number of its products have been installed in waste water treatment plants or landfill sites, operating on the produced biogas. These are mentioned under chapter 12 presenting case studies.



*Fig. 37 A 500kW installation at El Estero waste water treatment plant, Santa Barbara, CA
[FuelCell Energy web site]*

With respect to the fuel cell – gas turbine hybrid, the system uses an unfired gas turbine operating on the Brayton cycle, which through a number of heat exchangers, is driven by the heat produced by the fuel cell. The gas turbine thus transforms the waste heat of the fuel cell into mechanical energy and then electrical energy, increasing the electrical efficiency of the system by 15-20% points, to a total of around 70% electrical efficiency. This is the highest figure that can be reached at this small MW power range. The innovative aspect of this fuel cell – gas turbine hybrid concept is that the fuel cell and turbine operate at different pressures. Indeed the fuel cell operates at ambient pressure while the gas turbine operates efficiently at between 3 to 15 bar pressures. The system can be combined with micro-turbines for small power applications or gas turbines for applications of the range of 40MW. This type of combination allows for better load following, where the gas turbine can follow the load using stored thermal energy while the fuel cell can be operated at constant power. [FuelCell Energy web site]



Fig. 38 Fuel Cell – gas turbine hybrid of FuelCell Energy



16.5. Helion

Helion is a fuel cell manufacturer focusing on advanced PEM technology for power generation ranging from several kW to several hundred kW. The company also monitors all technological developments concerning SOFC technology for high-power generation of about several MW. In 2001 the company presented its first 2kW PEM small stationary prototype unit. In 2003 a more advanced 5kW PEM unit followed. The unit is demonstrated and tested in the context of the HELPS EU funded project (Fig. 39 below) co-ordinated by Technicatome (parent company of Helion) where it is part of a hydrogen based back-up system for telecom applications. The company has further plans to develop a 10kW PEM and/or SOFC stationary unit.



Fig. 39 Picture of Helion 5 kW FC

16.6. Intelligent Energy

This company is providing complete fuel cell based energy systems. Intelligent Energy has also developed the fuel cells technology used. The result is a PEM fuel cell with a volume density of 2.5 kW per litre used in two ranges of systems: the first are based on ambient pressure open cathode PEMFC stacks, which are scaleable up to a power output of 500W. For larger outputs it has developed a pressurised PEMFC stack using metal bi-polar plates. 4kW and 15kW stacks of this type have been exhibited.

A 4kW portable genset unit (complete with battery for 8kW peak output) has been developed for the military. The same platform will be used in a CHP system. Larger units are under development, including a 50kW system (incorporating two 25kW stacks) that Intelligent Energy are developing for Boeing, who will use it to power a single engine lightweight aeroplane (Fig. 40). The company is planning to investigate developing in-house fuel processors, which could open a way for the use of biofuels.



Fig. 40 Intelligent Energy Combined heat and power for the Japanese residential market(left) and fuel cell power train for light aircraft(right) [Intelligent Energy web site]

16.7. IRD Fuel Cells A/S

This is a Danish company developing fuel cell materials, fuel cells and fuel cell systems. It is specialising in PEM and Direct Methanol fuel cells. It has collaborated with Fiat in the development of a fuel cell powered vehicle and with European Fuel Cell GmbH in the stationary market for the development of units for supplying power and heat to homes.

The company is developing PEMFC power generators, some of which can operate in CHP mode, in the range of 2.5 to 50 kW. The company has supplied a 10kW PEMFC system for the Utsira wind-hydrogen project of Norsk Hydro.



Fig. 41 a 50kW PEMFC CHP unit of IRD Fuel Cells A/S (left) and a 10kW unit the company produced for the Utsira project (right) [IRD Fuel Cells web site]

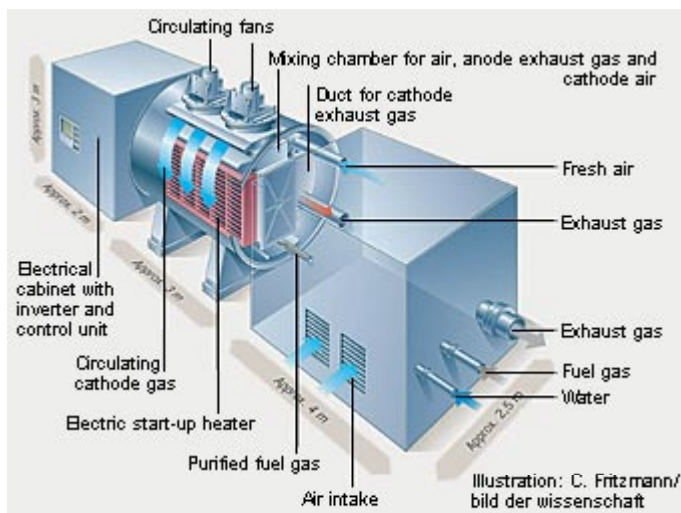


16.8.MTU CFC Solutions GmbH

MTU CFC Solutions, is a subsidiary business unit of MTU Friedrichshafen, a joint venture of MTU Friedrichshafen and RWE Fuel Cells GmbH. MTU Friedrichshafen is involved in manufacturing large diesel engines and complete propulsion systems. The company manufactures diesel engines in the power range between 35 and 9,000 kW.

Since 1990 MTU CFC Solutions has been involved in the development and manufacture for molten carbonate fuel cells ("HotModule", 250kW). Since 2000, MTU is also involved in PEM technology in order to develop fuel cell drive systems for off-highway applications. The focus of this work has been on propulsion systems for ships and on-board power generation. The aim is to develop scalable fuel cell systems on a modular basis so that they can be modified to match the requirements of the various applications as closely as possible. In October 2003, MTU has presented a PEM fuel cell powered sailing vessel using Ballard Power fuel cell units.

The HotModule in particular is a fuel cell that could well be applied to biogas energy applications. A schematic of the unit is shown in Figure 42



*Fig. 42 Left: Schematic of the HotModule components [MTU CFC Solutions web site]
Right: Application at Michelin factory in Karlsruhe [FuelCell Energy web site]*

The modular system of a complete HotModule consists of three components, into which are integrated all functions of the system. The fuel purifiers (to the right of the picture) process the feed in gas in preparation for use in the fuel cell. It is desulphurised, heated and humidified. The fuel cell module (centre of picture) contains the fuel cell stack, a mixing chamber for fresh air, anode gas, cathode air, a hood for collecting the exhaust air from the cathodes, two circulation fans and a forced ventilation unit for bringing the system up to operating temperature. Finally the last module (right of the picture) performs the control and allows the connection of the system to the local electricity grid.



16.9. NedStack BV

NedStack is a Dutch company developing PEM and DMFC fuel cell components, fuel cell stacks and fuel processors, aiming at reduced costs and increased life spans. Nedstack has developed and patented conductive composite cell plate materials and a mass production process for large-scale production of bipolar plates. Three types of conductive composite materials have been developed for low, medium and high temperature PEM fuel cells. NedStack is also developing a small, fully integrated fuel processor (ATR) for the conversion of hydrocarbons into a hydrogen rich gas that can be fed to a fuel cell aiming for low thermal mass (for short start-up times) and a high thermal efficiency [NedStack web site]

16.10. Nuvera Fuel Cells

Nuvera is an Italian company that is part of the DeNora group. The company manufactures stacks and fuel processors for PEM fuel cells for residential and transport applications (1-80kW). Nuvera is designing and manufacturing 5 kW units that can provide primary and/or auxiliary backup power to residential homes. These units are being developed and tested for manufacturers of home power generators and backup power equipment. In particular the company has the following products [Nuvera web site]:

- In the stationary applications market, Nuvera is marketing the Avanti system consisting of a fuel processor and a PEM fuel cell. The system can produce 5 kW of electricity and 7 kW of heat. The electrical efficiency quoted is 30% (based on High Heating Value) and includes the reforming process and parasitic losses.
- The Forza product line for stationary large-scale stationary applications. This is a scalable, base-load system that converts excess hydrogen disbursed from manufacturing facilities, such as membrane chlor-alkali plants, into DC electricity (shown below)



Fig. 43 The Forza large-power fuel cell

- The Andromeda 80kW PEM fuel cell for automotive applications, featuring low cost metallic fuel cell stack hardware, thinner designs and thus higher specific power.
- The Star auto-thermal reformer for transport applications developed in collaboration with the Department of Energy of the US, suitable for the reforming of gasoline. Reformers sizes vary



between 500W and 250kW. Nuvera has investigated all types of reformers (steam, partial oxidation, auto-thermal) for the reforming of almost all types of hydrocarbons, including renewable fuels like ethanol. The company has also invested in the development of catalysts to be used in the fuel processors.

16.11. P 21 GmbH

This is a German company founded in December 2001 as a spin-off out of the Mannesmann/Vodafone group. The company focuses in the development of PEM fuel cells for UPS or telecom applications ranging from 1 to 21 kW. The company is marketing its PremiumPower product, which is a PEM based system for 48V applications, shown in the following figure.



Fig. 44 A 48V emergency back-up system of P 21

16.12. Plug Power

Plug Power is a US manufacturer of fuel cells systems aimed for power and heat generation for the home market. The company acquired fuel cells manufacturer H-Power in 2002. The systems developed run on natural gas or LPG and utilise reformers and PEM fuel cells. The company has installed tens of fuel cell based systems in the US and Europe for testing and demonstration and is considered a leader in this field. Work is also done on systems for UPS telecommunication applications using fuel cells running on pure hydrogen. [Plug power web site]

16.13. Rolls Royce Fuel Cell Systems

Rolls Royce is one of the leading players in the power and aviation industry. Since 1992 the company has been involved in fuel cells R&D, concentrating on SOFC for stationary power generation. In the context of these endeavours, it has developed a planar stacks with the trade name Integrated Planar Solid Oxide Fuel Cell (IP-SOFC). The developed system is close to commercialisation in the form of a 800kW unit that is hybridised with a 200 kW gas turbine, constituting a 1MW power plant.

Rolls Royce considers SOFCs to be the most appropriate type of fuel cell for stationary power applications, with potential to expand in transportation, military and marine applications. Some of the features of the developed FC are [Rolls Royce web site]:

- The fuel cell is produced by screen printing on low cost ceramic type materials using proven production processes and minimal exotic materials aiming for simplicity of manufacturing.



- The system uses commercial-grade materials, has few components and is low in weight and cost.
- The FC system has nearly double the simple-cycle efficiency of existing power generation technologies
- It is estimated that size and weight of the system are suitable for distributed generation with potential for power densities equivalent to gas turbine systems.
- The FC system produces negligible air emissions, minimal noise profile and can be entirely recycled at the end of its useful life.
- Unique, modular design enables field change-out without interruption of supply and enhanced support through state-of-the-art diagnostic and prognostic systems.
- In terms of safety, the system contains less than ten seconds of fuel supply at any time.

16.14. RWE Fuel Cells GmbH

The company is a subsidiary of RWE which is one of the largest energy utility companies in Europe. The company is active in the development, testing and demonstration of various types of fuel cells including PEMFCs, PAFCs, MCFCs, but also in providing services through fuel cells.



Fig. 45 The RWE fuel cell pavilion, Meteorit-Gelände, Essen [RWE web site]

16.15. Siemens – Westinghouse

Siemens is a leading company in a number of sectors, including power generation. In the 60s the company was involved in AFC development. Since then the company has shown interest in SOFC and PEM technologies. Units of Siemens have been installed in navy submarines. Siemens has acquired the fossil power plant business and tubular SOFC technology from Westinghouse which lead to the foundation of Siemens Westinghouse. [Siemens web site]

The Siemens Westinghouse solid oxide fuel cell (SOFC) is made up of an electrolyte and two electrode layers in a tubular design that eliminates the need for seals required by other types of fuel cells and also allows for thermal expansion. Various fuel cells of power rating of 0.4 to 250 kW have been demonstrated at various sites around the globe, with running times in excess of 20,000 hours for some of the systems. Its 100kW tubular SOFC system has displayed an electrical efficiency of 46% when operating with NG and a reliability of 98%.

Hybrid SOFC – gas turbine systems are also investigated that can obtain 55% electrical efficiencies at the 250kW range and 60% efficiency at the MW range.

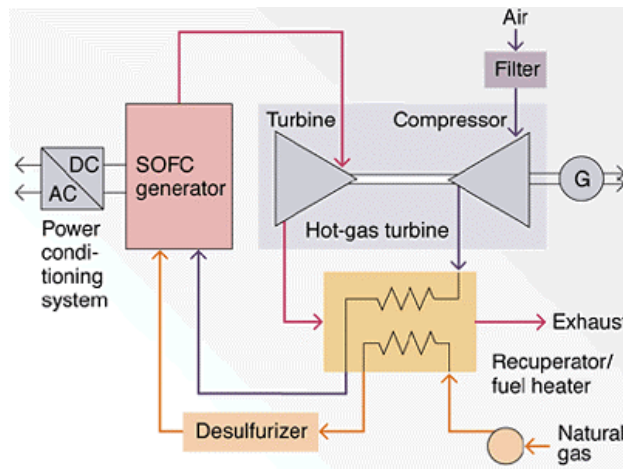


Fig. 46 The SOFC – gas turbine hybrid concept of Siemens

Unlike the FuelCell Energy Inc hybrid concept, the Siemens hybrid system presented above features a fuel cell operating at elevated pressure, provided by the compressor, which in turn is driven by the hot fuel cell gases that rotate the turbine. Gases between the fuel cell and the gas turbine are thus in the same closed loop. Research work however has also covered atmospheric cycles (fuel cell operating at atmospheric pressure) where the turbine is fed by a series (cascade) of heat exchangers. It is considered that this type of hybridisation offers somewhat lower efficiencies but would be less complex to develop and simpler to implement. [Siemens web site]



Fig. 47 A 220-kW hybrid system with a Solid Oxide Fuel Cell (SOFC) generator integrated with a micro gas turbine demonstrated at the University of California, Irvine and sponsored by Southern California Edison [Siemens web site]

The company considers biofuels (biogas and syngas) as viable fuels for its SOFC system. The company is a partner in the Biocellus EC project that will investigate the impact of biofuels on SOFC performance.

16.16. Sulzer Hexis

Sulzer Hexis develops, produces and distributes fuel cell systems for single-family homes. The company was founded in 1997 as a daughter company of the Sulzer Group. The business conception is based on the project «HEXIS» (Heat Exchanger Integrated Stack) initiated by the Group in 1991.



[Sulzer Hexis web site]. Sulzer Hexis is considered as one of the most promising of the fuel cell manufacturers and their 1kW_e product is one of the earliest to address the residential market.



Fig. 48 The Sulzer Hexis 1kW_e & 2.5kW_{th} SOFC unit for home applications

16.17. UTC Fuel Cells

This is US company that is a leader in its field. The company, previously known as International Fuel Cells, is now a part of United Technologies Corporation. It has developed and sold more than 200 units of its PC25 200kW PAFC (today sold with the PureCell trade name) that have been installed all around the globe, accumulating more than 6 million hours of operation. The units have been run mostly on natural gas but also on biofuels. The company is now moving into PEM fuel cells, aiming for the transport sector, in collaboration with BMW, Hyundai and IVECO. [UTC Fuel Cells web site]



*Fig. 49 The Portland facility operated on ADG from a wastewater treatment plant
[UTC Fuel Cells web site]*

16.18. Vaillant

Vaillant is one of the major European manufacturers of heating appliances. Vaillant is specialising in natural gas heaters of the type that hang on walls. The company is collaborating with Plug Power of the US in promoting fuel cells as potential CHP units for domestic applications. Vaillant is providing 4.6 kW units as part of the “Virtual Power Plant” project.