Royal Belgian Academy Council

of Applied Science

Hydrogen as an energy carrier

April 2006

“We urge all nations, in line with the United Nations Future Climate Change Conference principles, to take prompt action to reduce the causes of climate change, adapt to its impacts and ensure that the issue is included in all relevant national and international strategies. As national science academies, we commit to working with governments to help develop and implement the national and international response to the challenge of climate change.”
Joint Science Academies’ statement : Global response to climate change, July 2005

Koninklijke Vlaamse Academie van België
voor Wetenschappen en Kunsten
Paleis der Academiën
Hertogsstraat 1, 1000 Brussel

Académie royale des Sciences, des Lettres et des
Beaux-Arts de Belgique
Palais des Académies
Rue Ducale 1, 1000 Bruxelles

The Belgian Academy Council of Applied Science (BACAS) consists of CAWET (a committee of the Koninklijke Vlaamse Academie van België voor Wetenschappen en Kunsten) and CAPAS (a committee of the Académie royale des Sciences, des Lettres & des Beaux-Arts de Belgique). Its members come from academia and from industry.

Why this report ?

The one-way street towards the depletion of the fossil fuels (starting with oil), the economic development of many countries with increasing energy needs, world competition and volatility of prices, the strive at ensuring the security of supply, concerns about greenhouse gases emissions and of a too- rapid climate change, the amount of time and investment required for fine tuning an energy policy or developing new technologies, the reluctance of people to change their behaviour, all these factors put energy as top priority among the most important and difficult problems facing policy and decision makers.

Hydrogen has been and is widely mentioned as part of the solution to these problems.

This report reviews and summarizes in simple terms the extensive and evolving knowledge available on the hydrogen economy, with a special emphasis on Belgium. Care should be taken that our universities and companies do not exclude themselves from the scientific and economic future for supplying the world with sufficient and affordable clean energy.

The goal is to make useful and practical recommendations to the authorities in terms of research & development, demonstration projects and applications.

TABLE OF CONTENTS

EXECUTIVE SUMMARY

Hydrogen is an environmentally attractive fuel. It burns without producing carbon dioxide. It is however not a primary source of energy on earth. It only occurs in nature in combination with others elements, mainly with oxygen in water. But like electricity it can be used as an energy carrier once it has been unbounded from the other elements. This requires unfortunately energy from a primary source.

In the introduction (chapter 1) it is pointed out that electricity is presently the only energy carrier which does not create an environmental impact when used. Hydrogen has the same advantage ~~for environmental protection~~. It is now of the utmost importance to evaluate if the development of a new infrastructure based on hydrogen as an energy carrier is possible, useful or even inevitable. Hydrogen is not a source but a storage medium and an energy carrier. Like any other carrier it must be produced from a primary energy source. Currently more than 80 % of the world energy supply comes from fossil fuels, resulting in strong ecological and environmental impacts. Besides the exhaustion of reserves and resources, air pollution and modification of the atmospheric composition, with their impacts on climate and on human health, are now of primary importance. Greenhouse gas emissions, especially CO_2 produced by the combustion of fossil fuels, are in the centre of our environmental concerns. The consequence is that global warming will most probably occur. This problem has been intensively presented in a previous BACAS report entitled : "*Energy in Belgium tomorrow : taking in account the greenhouse effect*"[1].

The structure of the energy sector is described in chapter 2. It emphasizes the large number of transformation and storage steps required from the primary energy source to the energy carrier and to the final user. The most important carriers are currently liquid fuels, gaseous fuels and electricity. A large number of experts think that hydrogen has a great role to play as an energy carrier in the future energy sector.

In chapter 3 the most important reasons to opt for hydrogen as a promising energy carrier are presented.
The first one is the diversification of the energy sources and the reduction of dependency on fossil fuels. Since hydrogen can be produced from any primary source, it could improve the reliability of the energy supply and stabilize the energy market. It would make the utilization of energy more independent from the production and allow the economic exploitation of energy sources remote from the consumers.
The second reason is the reduction of the environmental impact of the energy system. Indeed most of the anthropogenic impacts on the environment come from the combustion of fossil fuels in the industrial, domestic and transport sectors. Using an energy carrier that is carbon free -which hydrogen is- would reduce most of the related environmental problems. The fear of climate change is bound to make us decrease the emission of greenhouse gases.
The third reason is the control of acceptable costs and the hope of stable prices over time. The supply of energy at reasonable and stable prices is not ensured at all by the producers of crude oil or natural gas. Hydrogen facilitates the diversification of the sources and contributes to the reliability and security of the energy supplies that are needed to secure the world economy.

Hydrogen properties are detailed and discussed in chapter 4. The advantages and the drawbacks of hydrogen as an energy carrier clearly derive from its properties. Hydrogen shows outstanding environmental characteristics at the point of utilisation. It can be obtained from any primary source, often without recourse to electricity. It is very efficient to use but contains little energy per unit volume. While hydrogen is generally easier to store than electricity, its storage is in need of much improvement. No comparison between hydrogen and electricity as energy carriers has been performed as reliable and significant studies and data are presently lacking. Especially a comparison of transport costs, or the full analysis of the energy chain from the primary source to typical end users, was not made because the cost estimates and their forecast change too rapidly.

Chapters 5 to 8 deal with the production, storage, transport and distribution, and utilization of hydrogen. Various methods for producing hydrogen are described, from the current processes using fossil fuels, mainly steam reforming of natural gas, to the most exotic forms of biomass or solar energies. The present utilizations take place in chemical plants for the mass production of ammonia and methanol, as well as in refineries for upgrading their products. The new utilizations in stationary fuel cells, in internal combustion engines and transport applications, etc. are also reviewed.

The introduction of hydrogen as energy carrier will force a major evolution on the energy sector, hence initiating a large spectrum of new technologies that in turn will induce huge RTD efforts in order to make them competitive. The whole supply chain from production to end-use, through transport and distribution, is involved. Reducing the production costs at each step and improving the efficiency are of the utmost importance. Safety features are also essential. Technical domains concerned by these developments are numerous as discussed in chapter 9 '*Need for technical improvement and R&D programs'*. They include material science and engineering, applied electrochemistry, mechanical-, process- and automotive-engineering.

Moving from the fossil fuel economy of today to a hydrogen economy will not happen overnight in one single step. The right phase-in strategy "from yesterday to tomorrow" must be carefully defined if we want to achieve the broad introduction of hydrogen. During the transition, conventional technologies will be essential, and the existing infrastructures necessary for maintaining prosperity. A roadmap for the transition towards a hydrogen energy system is proposed. It distinguishes three transition time horizons :

up to 2010 the use of renewable energy sources can be intensified for producing mainly heat and electricity plus some hydrogen. Since such new resources do not cover by far the present demand, and despite all efforts for savings, many conventional energy sources will be kept in operation. It is therefore essential to improve both the efficiency of the fossil fuel technologies and the purity of these fuels as well as the safety and waste disposal of the nuclear reactors. During this period, hydrogen and fuel cells should also be used in several niche markets. Important research efforts are needed in hydrogen production, storing, distribution and transport, in fuel cells, etc.

up to 2020 the availability of hydrogen will increase and enable starting the commercialisation of cars and trucks that use hydrogen as fuel in suitably modified conventional combustion engines and (or) fuel cell systems. Hydrogen will still be produced from fossil fuels but increasingly from renewable energy sources. Large demonstration projects will study the CO_2 capture and storage, and the efficiency, reliability and environmental impact of these processes will keep improving.

beyond 2020 the hydrogen production will keep growing with the consumers demand for clean energy supplies. Both electricity and hydrogen will progressively replace the previous carbon based energy system. Fossil fuels will progressively be substituted by renewables and by nuclear energy. At that time the hydrogen network will expand faster than in the past and largely be interconnected with the electrical grid.

Conclusions

Although a drastic change of the energy system appears inevitable, the quantitative prediction of the role that hydrogen will play is most difficult. The competition between electricity and hydrogen as energy carriers will increase and debates on this topic will be numerous and lively. It is nevertheless plausible that both solutions will coexist.

Taking into account the economic, social and technological interests at stake, it is of primary importance to further evaluate the prospects of hydrogen as a new energy carrier and the synergies which will necessarily develop with electricity. For hydrogen as well as for electricity, major technological innovations will occur and will lead to the development of very large markets.

As the USA and Japan are allocating huge funds to R&D programmes on hydrogen and fuel cells (respectively 12 and 20 % of the total non-nuclear energy R&D budget), Europe and especially Belgium cannot stay outside this technological field. So far they are lagging far behind the USA and Japan for the development of innovative technologies. There is a high risk that the European industry can end up being excluded from the hydrogen economy.

It must be clear that innovations in the field of a low-carbon energy system go far beyond the development of the individual technologies which are involved in the system. Fundamental research, development, applications and demonstration of new systems are essential while human and social aspects cannot be neglected. Understanding the behaviour of the citizens facing the new technologies is essential.

Recommendations

1. Our government should promote and support research and pilot projects at the level of the European Union for reducing greenhouse gases emissions. Our government must support those European regulations which will stimulate the use of new technologies intended to reduce the pollution and make Europe less dependent on the supply of oil and natural gas.

2. A Belgian technology platform on hydrogen & fuel-cells should be created. It should involve all stakeholders (industry, utilities, government(s), universities, research organisations…) ~~which~~who would provide guidance and support to R&D and key technical challenges on the introduction of hydrogen as an energy carrier. This platform should :

- promote and encourage R&D studies in universities and industry on the production, storage and uses of hydrogen ;
- foster inter-university educational clusters on hydrogen and its related technologies ;
- organise the direct participation of Belgium in the newly created technology platform in the EC (DG research) '*Hydrogen and Fuel cells*'[13] ;
- organise the direct participation of Belgium in other international R&D programmes such as the IEA (International Energy Agency) programmes.

3. The hydrogen energy concept should be introduced within the curricula of schools and universities. The scope of existing courses must be expanded. Specific curricula should be developed by clusters of universities and engineering schools.

4. As coal is likely to remain a permanent source of primary energy for many decades, studies on carbon dioxide capture and storage (CCS) should be enhanced to the benefit of both electricity generation and hydrogen production.

5. As nuclear energy is likely to remain a major source of primary energy, the Belgian nuclear expertise should be maintained and research fostered on new nuclear reactors for hydrogen production and / or electricity generation.

6. Belgium has an important car assembling industry, the design and development centres of which are located outside the country. There is however a strong local industry for components. They should

prepare themselves to a gradual shift from conventional fossil fuelled cars to the new generation of electricity / hydrogen powered cars.

7. As reliable technical and economical data can only be obtained by practical experience, demonstration projects should be initiated, supported or enhanced in the various fields of hydrogen production, storage, transport and utilization. On the other hand, it is well known that successful policy decisions need public acceptance and that unfamiliar hazardous materials do raise suspicion. A good information and sensitization campaign on hydrogen must therefore address the public concerns in addition to pointing out the intrinsic advantages of the new products. In order to bring to the general public the demystification and consciousness of the concept of the "hydrogen economy", these demonstration projects should be given the greatest possible visibility. Some examples :

- hydrogen fuelled buses and boats related to tourist activities ;
- local hydrogen fed heat and electricity generation units for administrations and hospitals ;
- electrolysers linked to wind turbines could stimulate the idea of a carbon-free renewable energy system providing hydrogen to a filling station ;
- small applications such as wheelchairs powered by hydrogen, or fuel cells substituting batteries in small portable appliances could also be considered ;
- live shows on hydrogen in the Technology Parks, PASS and TECHNOPOLIS, in university and other laboratories that organize visits and activities promoting the sciences, should be developed.

8. Government incentives in favour of clean hydrogen / electricity powered cars should be made available, by reducing taxes on the car itself and on the energy provided. Such economic driving forces help changing habits and behaviour towards a new energy system. The increased collective costs yield their return later.

1. INTRODUCTION

Hydrogen is the simplest and lightest of all chemical elements and the most spread in the universe. It is not a primary source of energy as it occurs only in nature in combination with other elements, primarily with oxygen in water and with carbon, nitrogen and oxygen in living materials and fossil fuels. However when split from these other elements to form molecular hydrogen, a process requiring another source of energy, it becomes an environmentally attractive fuel. It can be burned or combined with oxygen in a fuel cell without generating CO_2, producing only water. Like electricity it is a very clean energy at the point of use, but like natural gas it can form explosive mixtures with air.

Let us therefore never forget that in an energy system based on hydrogen, hydrogen is not an energy source but an intermediate medium for storing and carrying energy. Like any other energy carrier it must be produced from a primary energy source.

Electricity is today the only energy carrier with no environmental impact at the point of utilization. Hydrogen shows the same advantage. It is therefore very important to assess if the development of a new infrastructure based on hydrogen as an energy carrier is possible, feasible, useful or even ~~unavoidable~~inevitable.

Currently about 80 % of the total- and 88 % of the commercialised- world energy supply comes from fossil fuels. The distribution of the primary energy consumption is as follows :

Table 1 : Distribution by source of primary energy consumption – 2002 (Source : IEA)

	Oil	Natural gas	Coal	Nuclear energy	Hydroelectricity	Others renewable
World	35.8 %	20.9 %	23.1 %	6.7 %	2.2 %	11.3 %
Belgium	40.7 %	23.8 %	11.9 %	21.9 %	0.1 %	1.6 %

Table 2 : Distribution by source of commercialized primary energy consumption – at end 2004 (Source : BP)

	Oil	Natural gas	Coal	Nuclear energy	Hydroelectricity
World	36.8 %	23.7 %	27.2 %	6.1 %	6.2 %
Belgium	54.2 %	20.9 %	8.7 %	15.5 %	0.7 %

The reserve to production ratio(R/P) is the remaining time before total exhaustion, should the worldwide consumption stay at its current level and no new reserves be discovered. The R/P ratio has been evaluated for each fossil fuel and for the entire world.

Table 3 : R/P ratio of fossil fuels - at end 2004 (Source : BP)

	Oil	Natural gas	Coal
R/P ratio (years)	40.5	66.4	164

The world energy consumption is growing, and proven reserves of fossil fuels do not increase as fast. So these R/P ratios will probably go down in the future.

The prospect is a growth of the energy consumption as a result of :

- the growth of specific (by inhabitant) energy consumption. For example both China and India contribute to the growing demand for high-grade energy faster than their growth in GNP ;
- the growth of the world population.

During the last century, the world population has been multiplied by four while the energy consumption has increased by a factor of twenty.

The current energy systems have strong ecological and environmental impacts such as an exhaustion of resources increases and reserves, air pollution and changes in atmospheric composition, and their impact on climate and human health.

From the 70's to the 90's concerns for the environmental impacts of energy use were focused on acid rain and on photochemical 'smog' caused by organic combustion residues and nitrogen oxides from electricity production and from transportation. Acid rain was reduced by switching to higher-grade, low-sulphur fuels, in combination with flue-gas desulphurization and better burners. Making catalytic mufflers compulsory also helped reducing traffic pollution, leaving nevertheless some residual problems of particles and nitrogen oxides. Nowadays the greenhouse gas emissions, especially CO_2 from fossil fuels combustion, are paramount to our environmental concerns, the effect feared being that a global warming will most probably occur.

This problem has been intensively presented in a previous BACAS report entitled : '*Energy in Belgium tomorrow : taking in account the greenhouse effect'* [1].

The long lead-time required for introducing new technologies in the energy sector doesn't allow any waste of time. We should start immediately and with real determination if we are to achieve a sustainable energy supply. This is clearly mentioned by the European Commission [6] :
"*Our current specific circumstances require the development and widespread deployment of energy technologies which do not depend on oil and gas and do not release significant quantities of CO_2 into the atmosphere. This implies significant changes in the energy industry which cannot be made quickly ; with a turnover of roughly 3,000 billion euros world-wide, it inevitably has substantial inertia. Maximum effort to bring about the required changes must therefore be applied as soon as possible*."

2. STRUCTURE OF THE ENERGY SECTOR

From the primary energy production up to the final utilization of the energy, a great number of transformation and storage steps of the energy are required.

For example, petroleum products undergo many steps between extraction and final utilization. First, crude oil is extracted, e.g. in the Middle East. It is degassed, stabilized and stored before being shipped by tankers to the refineries. Upon arrival it is stored and then refined. Next, the various fuels obtained in the refinery are stored, carried by pipeline or by boat, stored again, mixed with specific additives, before being distributed by trucks to the consumers or to the service stations.

The general structure of the energy sector can be illustrated as follows :

Primary energy production	→	Transformation	→	Storage	→	
Transport	→	Transformation	→	Storage	→	
Distribution	→	Transformation	→	Storage	→	
Utilization						

Such a structure is not specific for fuels derived from petroleum but is valid for any primary energy source delivering energy to any final energy consumer, although the number of steps may vary. It shows why energy carriers must offer specific properties related to their ability of being stored, transported, distributed and used.

Currently the most important energy carriers are solid (coal), liquid (gasoline, diesel oil, jet fuel, ethanol, methanol, liquefied gases, fatty esters,…), gaseous (natural gas, synthetic gas), and electricity.

Today hydrogen is mainly used as a chemical reactant. It is produced in chemical, gas or petrochemical plants, or formed in some gaseous streams like coke oven gas. It is very seldom used as an energy carrier, except as pure liquid for rocket propulsion in the space industry. Many experts consider that hydrogen has a great future as energy carrier.

3. MOTIVATION FOR AN ADDITIONAL ENERGY CARRIER

Electricity appears to be an energy carrier that will gain in importance in the near future. This is obviously not true for the gaseous and liquid fuels which are currently produced from fossil resources, as they have important environmental impacts, especially greenhouse gas emissions. That is why in addition to electricity, which is not easy to store, it seems useful to develop another energy carrier (and its related network) that does not present the same drawbacks as the present fuels. Hydrogen is the most considered one. The reasons to opt for hydrogen as an additional energy carrier in the future are the following.

3.1 Primary sources diversification and reduction of the dependency on fossil energy

More than eighty percent of our present energy supply is coming from fossil resources. This situation is not sustainable in the long term not only because the reserves are finite but also because the known reserves are geographically not equally distributed but concentrated in a few areas of the world. As an example, two thirds of the known reserves of oil are located in the Middle East. A major part of the gas used in Europe will be imported from the former Soviet Union. This concentration creates actually geopolitical tensions and problems. They could dramatically increase when reserves begin to shrink if alternative solutions are not developed and implemented. This energy dependency is extremely high for countries with insufficient resources, or almost none such as Belgium. An energy carrier which could be produced from any primary energy source - especially from renewables - would improve the reliability of the energy supply. This is the case for hydrogen. It is comparable to electricity but probably easier to store. The penetration of hydrogen, produced in the near term from a broader range of fossil fuels (gas, coal or unconventional oil such as bituminous shale or asphalted sand) will indeed improve immediately the availability of energy for any type of utilization. More importantly, with the progressive integration of renewable energy sources, it will also ensure some of the long term energy supply.

The use of hydrogen as an energy carrier would facilitate the valorisation of energy sources far remote from the consumers if hydrogen as a gas could be stored and transported more easily than electricity. Thus the exploitation of remote energy sources could become feasible. It was even suggested that solar panels could be installed in sunny regions, even in deserted areas, and that the produced energy, stored as hydrogen, could be transported to the consumers. This would challenge the transport of electricity as presently contemplated through high voltage direct current lines.

3.2 Reduction of the environmental impact of the energy system

Most of the manmade impacts of energy consumption on the environment come from combustion of fossil fuels, in the industrial, domestic and transport sectors. The use of an energy carrier that is carbon free or that allows avoiding combustion could significantly reduce many environmental problems.

The reduction of fossil fuel utilization and the development of ‘clean’ technologies instead of a ‘end of the pipe’ pollution abatement can greatly contribute to the reduction of anthropogenic environmental impacts.

We are compelled to limit the greenhouse gas emissions under the threat of a climate change. Experts from all over the world warn us that, if we don’t succeed, we face catastrophic climate changes, which in turn will induce migration of people and collapse of the economies in the northern hemisphere. Although Belgium signed the Kyoto protocol, it is now quite obvious that it will not physically meet the restrictions on emissions. Industry is not the single one cause, for transport and households contribute to large amounts of emissions. It is very difficult to curb the increase in the last two uses without decreasing our comfort and changing our lifestyle.

In addition we must decrease pollution in urban areas and on the main highways. The real challenge is to keep mobility with reduced pollution. The existing fuels and engines in our cars, trucks and buses must therefore be replaced by zero or low emission systems. Pollution in traffic dense areas will reach an unbearable level, and drastic restrictions to traffic will affect our mobility. In the near future we can expect traffic regulations similar to those already applied in several cities (Sao Paolo, Mexico City, London,…). Others may follow soon. The growth in mobility also appears unaffordable.

In this context a carbon-free energy carrier seems to be an ideal solution. It almost eliminates any pollution related to energy utilization. In this respect hydrogen as well as electricity are carriers that both offer a carbon-free system and exhibit suitable technological characteristics.

3.3 Maintain acceptable costs and be sure to stabilize the prices for a long time

In competitive and deregulated energy markets, meeting peak demands requires some production overcapacity. Overcapacity increases the cost and reduces the competitiveness. An energy carrier that can be stored and used for peak shaving is therefore attractive. Hydrogen seems easier to store than electricity with the presently available technologies.

The supply of primary energy, at reasonable and stable prices, is not ensured at all by the producers of crude oil or natural gas. Hydrogen facilitates the diversification of the energy producing sources. Intended to reduce the dependency on oil and gas, it makes additionally the energy user less dependent on any single producer. The excessive increase in price of one primary energy source would be less durable as the switch towards another supply would be possible. The energy market would become more stable and reliable.

4. ADVANTAGES AND DRAWBACKS OF HYDROGEN AS AN ENERGY CARRIER

Hydrogen is a very light odourless and colourless gas with very different properties from the other gaseous fuels. Its main properties as an energy carrier are presented hereafter and detailed in table 4 to 6 in Appendix A.

Water is made of 11.2 % hydrogen by weight. Gaseous hydrogen density is 0.09 kg/m^3 (air is 14.4 times as dense and methane 8 times). Hydrogen boils at -253° C.

Hydrogen has the highest <u>energy to weight</u> ratio of all fuels. 1 kg of hydrogen contains the same amount of energy as 2.1 kg of natural gas or 2.8 kg of gasoline.
The <u>energy to volume</u> ratio amounts for the liquid to about 1/4 of crude oil, and for the gas to about 1/3 of natural gas.

Hydrogen burns in air at volume concentrations from 4 % to 74.5 % (methane burns at 5.3 to 15 % and propane at 2.1 to 9.5 % volume concentrations). The highest flame temperature of hydrogen of 2318 °C is reached at 29 % volume concentration in air, whereas hydrogen in an oxygen atmosphere can reach temperatures up to 3000 °C (the highest temperature reached in air for methane is 2148 °C and for propane 2385 °C).

The minimum required ignition energy required for a stoechiometric fuel/oxygen mixture is 0.02 mJ for hydrogen, 0.29 mJ for methane and 0.26 mJ for propane. Since even the energy of a static electric discharge from the arching of a spark is sufficient to ignite natural gas, the lower value for hydrogen ignition (only one tenth) is therefore not a practical disadvantage. The temperatures for spontaneous ignition of hydrogen, methane and propane in air are 585 °C, 540 °C and 487 °C respectively.

The explosive concentrations in air for hydrogen and methane lie (detonation limits) between 18.3 to 59 % and 6.3 to 14 % respectively. The explosive range for hydrogen is clearly much greater, whereas methane is already explosive at a much lower concentration.

The 0.61 cm^3/s diffusion coefficient of hydrogen is 4 times that of methane. Hydrogen therefore mixes with air considerably faster than methane or petrol vapours. From a safety point of view, it is advantageous in the open air but presents a disadvantage in badly ventilated indoors. Since both hydrogen and natural gas are lighter than air they rise quickly, hydrogen being much the faster. Propane and petrol vapour on the contrary are heavier than air and lay on the ground, leading to accumulation and presenting a greater hazard of major explosions.

Historically the main reasons for promoting hydrogen as an energy carrier are its outstanding properties for environmental protection.

Burning hydrogen with air under appropriate conditions in combustion engines or gas turbines results in very low or negligible emissions. Trace hydrocarbon and carbon monoxide emissions, if any, can only come from the combustion of lubricating oil in the combustion chamber of internal combustion engines. Nitrous oxide emissions increase exponentially with the combustion temperature. They can therefore be reduced through appropriate process control. As hydrogen offers more flexibility than other fuels, a lower combustion temperature can be achieved (e.g. with a high air to fuel ratio) leading to a distinct reduction in NO_x emissions compared to petroleum products and natural gas. Particulate and sulphur emissions are completely avoided but from minimal quantities of lubricant residues.

The use of hydrogen for propulsion in low temperature fuel cells (PEMFC) completely eliminates all polluting emissions. The single by-product resulting from the generation of electricity from hydrogen and air is demineralised water.
The use of hydrogen in fuel cells at higher temperature (MCFC and SOFC) causes up to 100 times fewer emissions than conventional power stations.

Let us remember however that hydrogen originates from a primary source. If it is obtained from methane, methanol or a fossil fuel, the reforming process itself will results in carbon dioxide emissions. This carbon dioxide from the reforming process is highly concentrated, therefore making it much cheaper to recover than from diluted exhaust gases of gas turbines. Hydrogen shows therefore an economical advantage, should the capture and storage of carbon dioxide become a practical reality. Several production processes drastically reduce - or even avoid emissions, especially of carbon dioxide (CO_2)- in the whole fuel cycle. This is the case for the most diverse renewable energies.

Hydrogen has some advantageous properties which are at least as important as its outstanding environmental characteristics. They are listed below and put in balance with their drawbacks.

Main advantages

- Uncoupling of primary energy sources and utilization.
- Hydrogen is a gas, thus easier to store than electricity.
- Hydrogen can be obtained from any primary energy source, including renewable.

- Decentralized production is possible. Hydrogen is viewed as capable of providing services where electricity is not available, in particular as a fuel for vehicles and energy storage in remote areas.
- Very efficient when used in fuel cells.
- Very good experience of hydrogen as a chemical reactant (ammonia, methanol, oil refining).
- Very good safety records (for a specific range of applications however).

Drawbacks

- Poor overall energy efficiency when produced from electricity made with fossil fuels.
- Very low density and poor specific volume energy density.
- Need for high pressures and very low temperatures if stored in the liquid phase.
- Specific safety problems and poor public acceptance (Hindenburg syndrome, Apollo 16, Challenger space shuttle).
- No existing infrastructures for transport, distribution and storage.
- Rather high cost (up to now).

It must be clear that when one compares hydrogen to another energy carrier, both the energy efficiency of the whole chain from the primary energy source down to the utilization, and a life cycle assessment of the environmental impacts must be worked out. Very often, hydrogen is compared with electricity in very general terms and the results show much better efficiency for electricity [16].

One should be very careful when making such evaluations. One must consider each case separately with all its features. For example, one study of car propulsion was made for comparing electricity stored in Li-ion batteries with a PEMFC fed by hydrogen. In both cases, the primary energy source was assumed to be natural gas. The goal of the study was to analyse each step from the extraction of the gas to the driving of the car, including materials production, plant construction, distribution, etc. All the efficiencies employed in the life cycle of this energy application were detailed. The conclusion of this study -only valid for Belgium - was that the car propelled by the fuel cell has a bigger efficiency than the car propelled by electricity stored in the Li-ion battery. However, should electricity be made from nuclear energy and hydrogen produced by electrolysis, Li-ion battery would be a better solution. This illustrates why global efficiencies comparisons must be made carefully for each individual case.

No comparison between hydrogen and electricity as energy carriers has been performed as reliable studies and data are presently lacking. Especially a comparison of transport costs (in € / km*kWh), or the full analysis of the energy chain ‘from cradle to grave”, from the primary source to typical end users, was not made because the cost estimates and their forecast change too rapidly.

5. PRODUCTION

5.1 From fossil fuels

Various hydrogen technologies have to some extent been tested and used for decades. For example there is an existing demand for hydrogen in the chemical and petrochemical industries for the synthesis of basic chemicals (e.g. ammonia, ethylene and methanol). In the same industries hydrogen is also inevitably produced as by-product (e.g. electrolytic production of chlorine and sodium or potassium hydroxides). Another and even more important hydrogen producer and consumer is the refining industry which processes fuels (e.g. hydrogen production by thermo-cracking, hydrogen consumption for desulphurization and hydrogenation of fuels). As a result of these needs, several large-scale processes have been developed for producing hydrogen mainly from fossil fuels and to some extent from water.

Steam reforming

Steam reforming of natural gas is currently the least expensive method and is responsible for more than 90 % of hydrogen production worldwide. Natural gas is first cleared from sulphur compounds. It is then mixed with steam and send over a nickel-alumina catalyst inside a tubular reactor heated externally, where carbon monoxide (CO) and hydrogen (H_2) are generated. This step is followed by a catalytic water-gas shift reaction which converts the CO and water to hydrogen and carbon dioxide (CO_2). The hydrogen gas is then purified.

The endothermic reforming reaction is :

$$CH_4 + H_2O + 206\ kJ/kg \Rightarrow CO + 3\ H_2.$$

It is usually followed by the exothermic shift reaction :

$$CO + H_2O \Rightarrow CO_2 + H_2 + 41\ kJ/kg$$

The overall reaction is :

$$CH_4 + 2\ H_2O + 165\ kJ/kg \Rightarrow CO_2 + 4\ H_2$$

The residual stream from the initial purification step is part of the fuel gas burned in the reformer in order to supply the required heat. Hence the CO_2 contained in this gas is currently vented with the flue gas. If CO2 were to be captured, an additional separation step would be needed.

The technology is suitable for large reformers (e.g. 100 000 tons per year), where yields higher than 80 % can be achieved. Smaller-scale reformers especially designed for feeding small fuel cells, show lower efficiencies.

Partial oxidation

In the partial oxidation process natural gas (or other liquid / gaseous hydrocarbons) and oxygen are injected into a high-pressure reactor. The oxygen to carbon ratio is optimally set for maximizing the yield of CO and H_2 and avoiding the formation of soot. Further steps and equipment remove the large amount of heat generated by the oxidation reaction, shift the CO with water to CO_2 and H_2, remove the CO_2 - which can then be captured - and purify the hydrogen produced. This process needs oxygen, which is usually provided by an air distillation plant. Partial oxidation can also be helped by an oxidation catalyst. It is then called catalytic partial oxidation.

The partial oxidation reaction for natural gas is:

$$CH_4 + \frac{1}{2}\ O_2 \Rightarrow CO + 2\ H_2$$

After the partial oxidation reaction, the process gas is similar to that of the steam reforming process. Since the reaction is exothermic, a heating system is not required, which is a major advantage resulting in size -and capital cost - reduction. Partial oxidation is however typically less energy efficient than steam reforming.

Auto-thermal reforming

In the auto-thermal reforming process, natural gas or liquid hydrocarbons, steam and oxygen are reacted in a single vessel with a combustion zone and a reforming zone. The heat from the exothermic partial oxidation reaction balances that for the endothermic steam reforming reaction. The process gas then goes to the standard shift reaction and hydrogen purification steps.

Auto-thermal reforming is as compact and load-flexible as partial oxidation while nearly reaching the higher efficiency of steam reforming. Currently auto-thermal reforming is only used in very large units (more than 100 000 ton/yr).

Coal gasification

Coal is a practical option for making hydrogen in large plants. Worldwide coal reserves are very important indeed and technologies for converting coal to hydrogen are commercially available. The major concern is that, due to the high carbon content of coal, the corresponding carbon dioxide emissions are larger than those from any other feedstock. Large-scale use of coal gasification implies that carbon capture and storage technologies can be developed.

Coal can of course produce electricity and then hydrogen through the electrolysis process (see below). The gasification technology however is better for making hydrogen from coal. Coal gasification involves partial oxidation of the coal with oxygen and steam in a high-temperature and high-pressure reactor. The reaction proceeds in a highly reducing mixture that creates mainly CO and H_2 , mixed with steam and CO_2. This "syngas" undergoes the shift reaction, increasing the H_2 yield. The gas can then be cleaned in conventional ways to recover elemental sulphur (or make sulphuric acid). Hydrogen and carbon dioxide can be easily separated.

The use of oxygen at high temperature and high pressure minimizes the nitrogen oxides (NO_x) by-produced. The slag and ashes drawn from the bottom of the reactor contain heavy metals and are encapsulated in an inert, vitreous material, which is currently disposed of as road filler. Part of the syngas goes to a gas turbine, which makes electricity for the air distillation, and process steam.

The cost of producing hydrogen in a large coal gasification plant is today slightly higher than that made from natural gas. Coal gasification techniques are however less mature than the steam reforming of natural gas. The economics of making hydrogen from coal differ somewhat from other fossil fuels : the unit capital costs are larger for the coal plants, while the unit raw material costs are lower.

Carbon dioxide capture from plants using fossil fuels to make hydrogen – as well as those making electricity from combustion of the same fuels – is likely to become mandatory.
Several technologies are being developed and tested for storing carbon dioxide:

- secondary injection in oil-producing wells ;
- injection into depleted oil or gas reservoirs ;
- adsorption in uneconomical coal seams ;
- storage as liquid - or its hydrate the carboxylic acid – in deep ocean sites.

All these technologies need concentrated carbon dioxide. The chemical and petrochemical industries have substantial experience in achieving this, mainly through absorption and desorption of CO_2 in alkyl amines. This process is however expensive. The processes described in this chapter that do not use air provide the CO_2 rather concentrated. They show in this regard quite an economical advantage over the old combustion processes still widely used to produce electricity.

5.2 From biomass

Biomass and biomass-derived fuels are renewable energy sources that can be used to produce sustainable hydrogen.

Using biomass instead of fossil fuels to produce hydrogen reduces the average amount of carbon dioxide in the atmosphere, since the carbon dioxide released when the biomass is oxidised was previously absorbed from the atmosphere and fixed by photosynthesis in the growing biomass.

Hydrogen can be produced from biomass resources such as wood, agricultural residues, consumer waste or crop specifically grown for energy uses. Current technologies for converting biomass into molecular hydrogen include gasification / pyrolysis of biomass coupled to subsequent steam reforming. The main conversion processes are indirect-heat gasification, oxygen-blown gasification, and anaerobic fermentation.

Biomass-to-hydrogen conversion is presently unable to produce hydrogen on a large scale at a competitive price, even when compared with hydrogen generated from distributed natural gas. It could however contribute to recover energy from domestic and agricultural waste in a very clean way. The environmental impact of growing significant quantities of biomass as energy crops, including genetically engineered, high-yield crops, will most likely place significant strains on natural resources and land availability in our country.

The cost for collecting and transporting biomass is inherently high. It would result in building many small biomass gasification plants without the economy of scale. The route to biofuels might prove more attractive.

5.3 From electricity

From any primary energy source converted into electricity (nuclear, wind, solar, hydraulic...) hydrogen can be produced by the electrolysis of water. Water molecules are split into hydrogen and oxygen.

Making electrolytic hydrogen uses considerably more energy than the hydrocarbon processes. Nevertheless, electrolysis is of interest for several reasons. First it is seen as a potentially cost-effective way of producing hydrogen locally. Electrolysers are compact and can realistically be located at existing fuelling stations. Secondly electrolysis offers a way to produce hydrogen with electrical power generated from renewable sources. Currently the renewable sources solar, wind, and hydropower produce only electricity. Seen literally as a means of converting electricity into fuel, electrolysis is one way of linking power from renewable sources to transport markets. Of course as already mentioned the electrolytic hydrogen competes with the more direct route of supplying electricity to electrical batteries for electrical or hybrid vehicles. It can only be considered in specific cases. Finally, electrolysers operating in tandem with power-generating devices (including fuel cells) display a new architecture for distributed energy generation.

From nuclear energy

Hydrogen can be produced from nuclear electricity by electrolysis. Despite the rather high efficiency of converting electricity into hydrogen (up to 80 % under pressure), the global efficiency is much reduced by the rather weak efficiency of the nuclear power plant (± 33 % for current reactors). Storing hydrogen for peak shaving could however justify some electrolytic production.

A more efficient hydrogen production would be obtained from high temperature water electrolysis coupled to new reactors operating at much higher outlet temperatures. The efficiency of the high-temperature electrolysis of steam increases from about 20 % at 350 °C to about 50 % at 950°C[17].

From wind turbines

Of all renewable sources, wind shows possibly the highest potential for producing pollution-free hydrogen, using the electricity generated by the wind turbines for electrolysis. This is particularly true for distributed systems. In order to succeed the cost of the wind turbines and electrolysers has to decrease, and the turbine-electrolyser-storage system has to be further optimized. Today the cost of hydrogen produced from wind amounts to 6 to 10 times that of large-scale units using natural gas. This gap could be halved in the near future.

From photovoltaic cells

At the present time the cost of hydrogen from photovoltaic electricity through electrolysis is 25 times higher than that of hydrogen produced from coal or natural gas plants. The expected decrease in the cost of photovoltaic cells and of electrolysers would bring this down to a factor of 6.

5.4 From high-temperature heat by thermo-chemical water splitting

From nuclear energy

Several high-temperature thermo-chemical reactions are under study, which have high efficiency and practical applicability with nuclear heat sources. One of the most promising may be the sulphur-iodine (SI) cycle, where three chemical reactions achieve the dissociation of water:

$I_2 + SO_2 + 2\,H_2O \Rightarrow 2\,HI + H_2SO_4$ (120 °C)

$H_2SO_4 \Rightarrow SO_2 + H_2O + ½\,O_2$ (830-900 °C)

$2\,HI \Rightarrow I_2 + H_2$ (300-450 °C)

the overall reaction being : $H_2O \Rightarrow H_2 + ½\,O_2$

The efficiency of the sulphur-iodine process increases from 30 % at 750 °C to 60 % at 1000 °C. Other thermo-chemical cycles show efficiencies of 40 to 50 % at typical temperatures of 700 °C.

Several high-temperature nuclear reactors have been developed that could produce heat at the required temperature. The high-temperature helium reactor and the molten-salt reactor appear to offer the best perspectives for hydrogen production. Other reactor types may be used if efficient hydrogen production processes can be developed at temperatures of 500 °C.

From solar energy

The solar water splitting is similar to the nuclear thermo-chemical process. The high temperature is obtained by concentrating solar energy.

5.5 From photochemical energy

By photo-catalysis

The cleanest way to produce hydrogen is the direct splitting of water into hydrogen and oxygen by sunlight. Multijunction cell technology developed by the photovoltaic industry is being used for photo-electrochemical light harvesting systems that generate sufficient voltage to split water and are stable in a water / electrolyte environment. Regarding production costs, it seems that a photo-electrochemical device where all the functions of photon absorption and water splitting are combined in the same equipment may have the best potential for producing hydrogen at reasonable costs. Experimental systems produce solar-to-hydrogen electricity with a conversion efficiency of 12 %.

By bioconversion

Some photosynthetic microbes produce hydrogen from water in their metabolic use of light. Photo-biological technology shows great promise. Since oxygen is produced together with the hydrogen, the technology of the hydrogen-making enzyme systems must however overcome the limitation of their sensitivity to oxygen. Research is addressing this issue by screening for naturally occurring organisms that are more tolerant to oxygen, and by creating new genetic forms of these organisms that can sustain a hydrogen production in the presence of oxygen.

5.6 By-product of chemicals production processes

By-product of sodium or potassium chloride electrolysis

Hydrogen is a by-product of sodium or potassium chloride electrolysis that produces chlorine and caustic soda or potash :

$$NaCl + H_2O + electricity \Rightarrow ½ Cl_2 + NaOH + ½ H_2$$

$$KCl + H_2O + electricity \Rightarrow ½ Cl_2 + KOH + ½ H_2$$

Chlorine is one of the most common chemicals in the world. It is produced in huge quantities.

By-product of refinery and petrochemical plants

Hydrogen is a by-product of catalytic reforming of gpetrol, made to improve the octane number. It is also a by-product of steam cracking of hydrocarbons for the production of ethylene. This hydrogen is used in other refinery operations. Smaller volumes of hydrogen are by-products in coke-ovens and usually are kept for internal use. All by-product hydrogen requires some purification steps before use.

5.7 Conclusion

Currently most of the worldwide hydrogen production (more than 90 %) originates from the steam reforming of natural gas. Other technologies should be developed such as using electricity from renewable sources for water splitting, coal gasification with CO_2 capture (CCS), and biomass gasification with or without CCS. Next to nuclear energy, these could become very important in the next decades.

6. STORAGE

From the primary source to the final consumer, storing energy is an essential process at several steps of the system. This process enables to satisfy peak demand - when the energy consumption exceeds the production capacity - and to store energy in the reverse situation. It is also essential for all mobile and portable applications. In this respect any liquid or gaseous fuel has a great advantage over electricity. Liquid fuels allow storing large amounts of energy in a small tank (e.g. a car) while gaseous fuels with their rather low density require specific storage conditions.

In gaseous form, hydrogen can be stored efficiently under pressure. The volume at atmospheric pressure of one kilogram of gaseous hydrogen is about 11 cubic meters. The gas must therefore be compressed to several hundred atmospheres and be stored in specially designed pressure vessels.
In liquid form, hydrogen can only be stored at cryogenic temperatures in well insulated tanks (see appendix A, table 4).
Compared to gasoline hydrogen has roughly three times the energy content per unit weight, but one fourth only per unit volume.

6.1 Physical storage

Compressed hydrogen

Hydrogen can be compressed with a sizeable input of energy and stored in high-pressure tanks. Compared to liquid fuels like gasoline which are put in similar tanks, hydrogen has a low energy to volume density. This storage though can fit stationary applications with no size or weight restrictions or special demands where weight brings stability, such as forklifts or wheelchairs. For transport applications however, the high-pressure tanks are too large and too heavy for the energy provided. The research in this field – mostly industrial research – is developing new fibre-composite high-pressure vessels, which might in principle compete with other storage technologies.

At 200 bar, steel tanks weigh 70 kg and contain only 900 g hydrogen. Even at 700 bar, 4.6 litres of hydrogen are needed to produce the same energy as one litre of gasoline and, in this case, fibre reinforced synthetic polymer vessels weights are currently 22 kg for 1200 g hydrogen.

Liquid hydrogen

The cryogenic storage is achieved by cooling hydrogen to 20 K (-253 °C). This transformation of gas into liquid enables huge amounts of hydrogen to be shipped by tanker, truck and rail. But the liquefaction process requires a large fraction of the hydrogen energy (about 30 %). Moreover very special material is required for the tanks that must also be very well insulated at those extremely low temperatures. They are very expensive. Therefore improving the liquefying process and the insulation properties of the storage vessel are today important research topics.

Sludge hydrogen

Sludge hydrogen is a mixture of solid and liquid hydrogen obtained by further decreasing the temperature below 14 K (-259 °C). It has very limited applications at the present time. Its use in space technology is currently being investigated.

Adsorption on high porosity materials

Carbon-based materials, and recently carbon nanotubes, have been considered as promising candidates for high-density storage of hydrogen for more than a decade.

Microscopic tubes of carbon, two nanometers ($2*10^{-9}$ m) across, enable carbon nanotubes to store hydrogen within the tube structure in microscopic pores. In principle carbon nanotubes could store an interesting quantity of hydrogen. But up to now this has only been proven at rather low temperature (77 K).

Several research programmes aiming at understanding the potential of carbon nanotubes for hydrogen storage are still in progress. Others are devoted to the reduction of manufacturing costs.

Glass microspheres

High-pressure hydrogen can be stored in glass microspheres. The diameter and the thickness of the glass microspheres are about one millimetre and several dozens micrometers respectively. The stored hydrogen is released by heating or breaking the glass. Research about this futuristic method is in progress in France at the CEA.

6.2 Chemical storage

Metal hydrides

Metal hydrides are specific combinations of metallic alloys that act on hydrogen as would a sponge soaking up water. They have the property of absorbing hydrogen and of releasing it when the temperature is increased. Usually absorbed hydrogen represents only 1 or 2 % of the total weight of the tank. Some metal hydrides reach a storage capacity of 5 to 7 %, but in this case high temperatures are needed to recover the hydrogen.

The volume of gas absorbed is relatively low but the advantage of hydrides is their ability to safely delivering very pure hydrogen at constant pressure.

Other chemicals

As previously mentioned hydrogen is the most abundant element in the universe but it only occurs bounded to other elements in many chemical compounds. Some of these compounds can be produced by chemical reaction and used as hydrogen storing systems. When the reverse reaction occurs, hydrogen is released. The reactions involved are linked to the compound.

Ammonia cracking, methanol cracking, and dehydrogenation of cyclohexane into benzene are some examples. The fact that hydrogen is produced when needed eliminates the need for a storage unit for the hydrogen produced.

6.3 Conclusion

The storing of hydrogen is currently under intensive research which makes it difficult to draw conclusions. There is no best choice as each choice shows some drawbacks and makes it difficult at this time to point out the best compromise. The criteria are numerous and include the following :

- energy density ;
- energy overall efficiency for storage and recovery ;
- loading conditions (temperature, pressure and flow rate) ;
- storage conditions (temperature, pressure) ;
- utilization conditions (temperature, pressure and flow rate) ;
- safety :
  - in usual operation ;
  - in abnormal or accidental circumstances (temperature, chemical reactivity…) ;
- cost and commercial availability ;
- technical experience ;
- reliability and life time ;
- energy payback period, i.e. the time taken by the system to deliver energy that exceeds the energy consumed for building it.

7. TRANSPORT AND DISTRIBUTION

The development of a new infrastructure for transport and distribution of hydrogen has been analysed in several reports, in particular those from the IEA [11]. A partial summary of this report including the key R&D areas is given hereafter.

Whether produced from fossil or non-fossil sources, the widespread use of hydrogen will require a new and extensive infrastructure to produce, distribute, store and dispense it as a vehicular fuel or for stationary applications, such as electricity generation. Depending on the source from which hydrogen is produced and the form in which it is delivered, many alternative infrastructures can be envisioned. Tradeoffs in economies of scale between process and distribution technologies, and such issues as operating cost, safety, and materials can also favour alternative forms of infrastructure.

In terms of transport and distribution, a general consensus appears on two broad approaches :

- small-scale local hydrogen production, based on either electrolysis or gas reforming, thus utilising existing electricity or gas distribution infrastructure ;
- large-scale dedicated hydrogen production infrastructure, including pipelines and / or road transport.

The first option has a number of attractive features from the point of view of minimising distribution costs, but it would make it more difficult to achieve the economies of scale associated with large-scale hydrogen production, with capture and storage of CO_2 when hydrogen is produced from fossil fuels. It also requires an increase of both gas and electricity production and distribution infrastructures. These investments could add up to that required to integrate renewable energy into the electricity grid system.

Current hydrogen delivery infrastructure exists only for the limited industrial hydrogen markets for chemical and refining industries in Europe and in the United States. Those limited systems lack the scope or scale needed to deliver hydrogen outside of these few industrial areas to a potential large-volume of end-user applications. Therefore, it is likely that significant capital investment in a dedicated hydrogen delivery infrastructure will be required before a hydrogen economy can be realised. Alternative approaches include using the existing natural gas delivery infrastructure. These systems would however require significant modification for use in the delivery and distribution of hydrogen. For example, hydrogen has physical properties that may cause embrittlement of some high-strength steel piping materials and components (e.g. compressors and valves) currently used for natural gas.

The evaluation of the options also includes the use of an alternative liquid fuel as a hydrogen carrier, such as hydrogen-rich liquid fuels (e.g., coal-derived methanol and Fischer-Tropsch liquids). Analysis is also needed to evaluate the trade-offs that exist between the use of existing liquid fuel and natural gas infrastructure to deliver hydrogen-rich fuels and the massive capital investments required for implementing a system with central hydrogen plants, associated pipelines, and distribution centres in a dedicated hydrogen infrastructure. These hydrogen-rich fuels could possibly be economically reformed at end-use locations instead of central locations. The cost of small-scale, on-site reforming and the associated benefits should be evaluated against the large capital cost of a dedicated hydrogen infrastructure.

In any case, an efficient transportation and distribution of hydrogen from the production site to the end-user is needed for the wide-spread use of fuel cells envisioned by the hydrogen economy. Key R&D areas for improving hydrogen transportation and distribution infrastructure include :

- high-pressure gaseous storage and supporting technologies ;
- hydrogen pipelines based on natural gas pipeline technology ;
- hydrogen compressors ;
- compressed gas tube trailers ;
- cryogenic liquid storage, insulation and supporting technologies ;

- cryogenic tankers for bulk-transport of liquid hydrogen ;
- absorbent / adsorbent hydrogen storage solid media and supporting technologies ;
- hydrogen bulk storage systems and bulk dispatch terminals ;
- fuelling stations and supporting technologies ;
- safety devices for these systems and associated standards and regulations.

It must be emphasized that several hydrogen pipeline networks have been used for more than 50 years in Europe and in the United States. In particular, a network of more than 1000 km connects producers and consumers of hydrogen in northern France, Belgium and the Netherlands (shown on Figure 1 below). The transportation of very pure hydrogen in liquid state by truck is also a common practice in Europe as well as in the United States and in Japan.

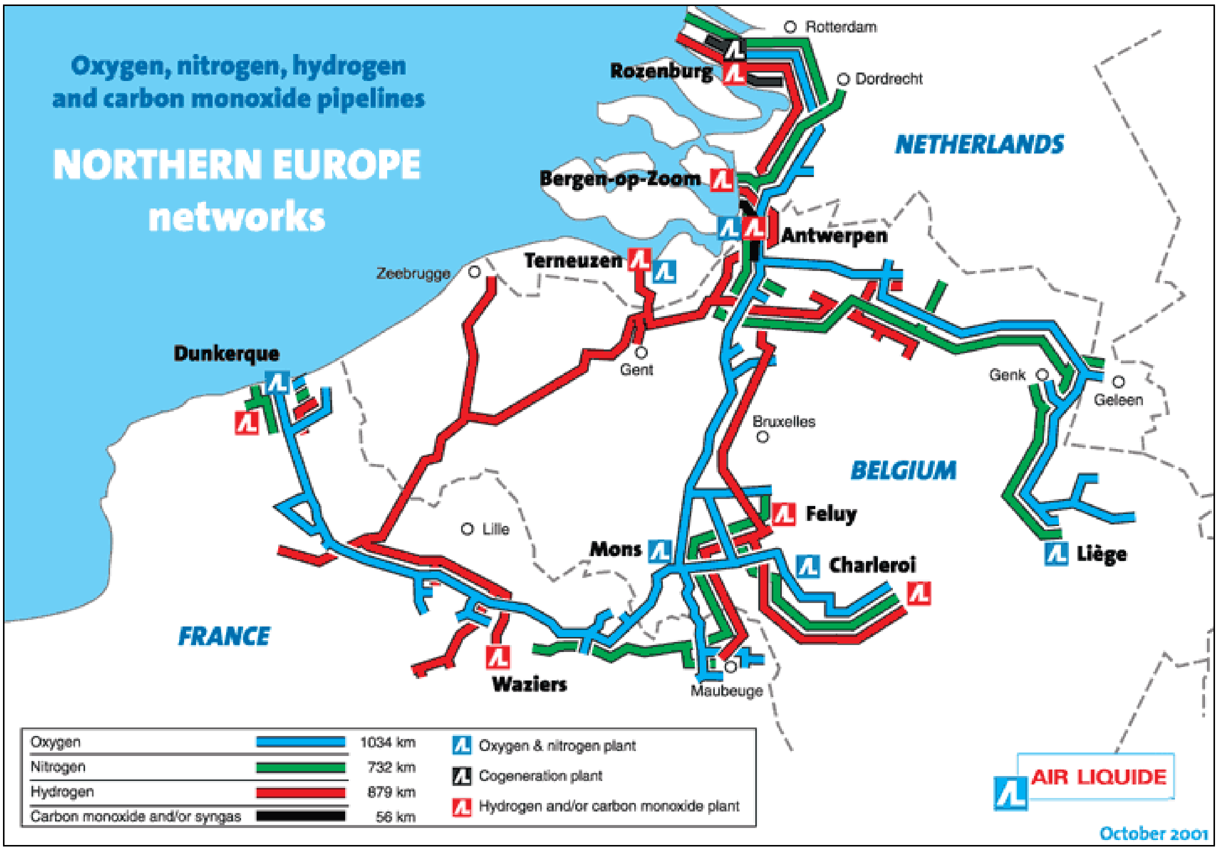

Figure 1 : Air Liquide gas networks in North Europe [Source : Air Liquide - www.airliquide.com]

8. UTILIZATION

8.1 Present utilization

Markets today can be divided in two groups : large chemical plants and refineries that consume 95 % of the total hydrogen market from local production plants on the one hand, and small applications on the other hand that are essentially chemical non-energy applications or relate only indirectly to the energy sector.
Further details are given in Appendix B.

8.2 Future utilization

Stationary applications

Residential and commercial applications

Mixed with natural gas, hydrogen could be used in existing natural gas equipment. With no change to the devices up to 3 % volume (5 % as agreed in France) of hydrogen can be added to the gas. More hydrogen requires modifications to the burners and other equipment of the consumer.

Industry

With proper adjustments all types of industrial natural gas burners can be fed with hydrogen. Hydrogen could then be used earlier as natural gas for steam generation. However in order to maximize its energy efficiency, hydrogen is better used with fuel cells that produce simultaneously heat and electricity (cogeneration).

Electricity production

For the International Energy Agency [10], decentralized electricity production from primary hydrogen makes only sense in three instances :

- if hydrogen is used as an energy storage for intermittent electricity production ;
- if the efficiency is much higher than for other fuels ;
- if hydrogen is used for decentralized electricity generation, where it is not possible to capture CO_2 from small-scale cogeneration units.

Hydrogen can be used in fuel cells which can achieve a high electric efficiency. The total energy efficiency may even exceed 90 % if the waste heat can be used. Stationary fuel cells (FC), which often are Molten Carbonate FC or Solid Oxide FC, can be fed with natural gas or even heavy fuel. In this case, hydrogen has the clear advantage of avoiding CO_2 emissions.

Transport applications

Recently hydrogen has been introduced as a clean fuel in several vehicles. Basically hydrogen can be used in Internal Combustion Engines (ICE) similar to custom-produced petrol engines or in a fuel cell where the electrochemical reaction of hydrogen with oxygen produces electricity and heat.

Hydrogen and the Internal Combustion Engine

When the engine is basically a custom-produced gasoline engine, the use of hydrogen fuel requires adjusting the mixture process for the accurate control of the hydrogen intake and of the load cycle. The use of H_2 generally involves lean combustion. Surplus air absorbs heat in the combustion chamber and keeps the flame temperature below the critical limit at which uncontrolled ignition can occur. Nitrogen oxides emissions can still be an issue as those are related to the combustion temperature. The combustion of hydrogen should therefore be kept as lean as possible.

Since the lean limit of H_2 is much higher than for petrol, and since large variations of lambda are acceptable, the power output of the engine can be controlled by the fuel fed into the engine (as for diesel) making a throttle unnecessary. Thus a greater volumetric and total efficiency is achievable, and an optimized hydrogen engine can reach efficiencies close to that of diesel engines. Efficiencies of 35 % have been reported by Bayerische Motor Werke. Peak efficiencies of 50 % are even mentioned in the literature. This should be carefully weighed however since the ICE efficiency varies with the load while fuel cells do not. General Motors announces (technology 2010) a petrol-equivalent fuel consumption of 17 % lower than a petrol car and only 3 % higher than a diesel car, i.e. 6.37 litre of petrol equivalent per

100 km. Bi-fuel engines (based on hydrogen and petrol) cannot integrate all measures for efficiency optimization, and this may restrict the engine efficiency of hydrogen operation.

Due to the ultra-lean combustion, the power and torque output of an atmospheric engine fed with hydrogen are 40-50 % lower than when the same engine is operated on petrol. The loss of power can be compensated for by the introduction of a turbocharger (and intercooler), and comparable performance criteria can thus be met.

The two car manufacturers BMW and Ford are today the strongest advocates of this technology. Prototype vehicles have been produced, even in small series, and field testing is underway.

Despite the relatively moderate extra costs associated with H_2-ICE, this technology can be seen as a temporary step in order to boost the use of hydrogen as fuel and create the demand that justifies investments in the fuel distribution and refuelling infrastructure. Over the longer term, the fuel cell is expected to be the top choice technology due to a better efficiency. Should the industry fail to meet the costs or performance targets of fuel cells however, H_2-ICE may remain a valid option with its relatively low cost-structure. On the other hand, the lower well-to-wheel total efficiency it offers may seriously jeopardize the whole idea of using hydrogen at all.

The introduction of a hybrid version can increase the efficiency of a H_2-ICE similarly to the hybrid vehicles, such as the Toyota Prius existing on the market today. This expensive increase in efficiency will reduce the cost advantage of H_2-ICE vehicles over fuel-cell vehicles. It nevertheless needs further practical checking. The US-company Quantum has developed in 2005 a H_2-ICE prototype based on the Toyota Prius.

A mixture of up to 20 % volume hydrogen with natural gas (called hythane) can be burned in an ICE. Minor changes allow the natural gas engine to run on hythane with similar environmental performances. The CO_2-emissions however are lowered in proportion to the hydrogen content. The overall benefit of using hythane can be found in the infrastructure. Hythane can be obtained by injecting hydrogen into the natural gas grid, which is broadly available in many regions in the EU. This could solve the infrastructure issue at short notice. For the 2008 Olympic Games in Beijing more than one thousand diesel buses will be converted to hythane to curb the local air pollution.

Hydrogen and fuel cells

Prototype fuel-cell vehicles (FCV) are rapidly appearing everywhere. In less than ten years, the fuel-cell vehicles have evolved from research novelties to operating prototypes and to demonstration models. However their large scale introduction is not expected in the near future. The IPTS study stated that the market introduction of FCV may be subdivided into three phases: 1) test and demonstration, 2) market introduction and infrastructure build-up, 3) market jump implying mass production and development of refuelling stations infrastructure. Most analysts expect that the first phase will last until around 2010, the second phase will last another 5 years and phase 3 would start around 2015. More pessimistic views have also stated that the phase 3 may not start before 2025. They also see the high cost of fuel cells as most prohibitive. The EU High Level Group and the European Car Manufacturers Association have 2020 as a hypothetical starting point.

Today, Polymer Electrolyte Membrane Fuel Cell - also called Proton Exchange Membrane Fuel Cell or Polymer Electrolyte Fuel Cell - is the technology of choice for transport applications. The main reasons are a suitable operating temperature (with some problems of cold starting), and a high power density. Engineering for mass-production and integration with the balance-of-plant and associated sub-systems are two key themes for Research and Technology Development work. Cutting costs is also a major issue.

The fuel-cell technology has the advantages of the electric drive (no emissions of pollutants, low noise) while it avoids the constraints of the battery technology. The components of the drive (electric motor) are the same as for the battery-powered electric vehicle and, therefore do not represent any major technical or economic problem. Hybrid FC-Battery vehicles are being considered in present EU R&D programmes.

Even if the electric drive components for a FCV can gain from the experience of battery-powered electric vehicles, the fuel-cell technology for vehicle propulsion is new. Not so much is known about their lifespan or other issues of user friendliness. Early experiences from the prototype and demonstration vehicles of the Original Equipment Manufacturers suggest that they can be made very straightforward and as simple to drive as the other electrical vehicles. This should be a prerequisite for user acceptance As for any prospective very expensive new technology, all performance characteristics of a fuel-cell vehicle need to be similar - or even superior - to the conventional technologies, regardless of the energy issues.

Fuel-cell vehicles have today one or the other major architecture : the direct electric drive, similar to a battery-powered electric vehicle in which the fuel cell replaces the battery, and the hybrid drive, in which the fuel cell is combined with a battery to power the electric motor. The latter has the advantage of reducing the dynamic load on the fuel cell resulting in a longer life, as well as recovering the braking energy, which increases the efficiency of the vehicle. Compared to their non hybridized equivalent, hybrid drive fuel-cell vehicles will however show less gain in efficiency than conventional ICE vehicles (10 % compared to 25 %). This is due to the better efficiency of the fuel cell at partial load. They nevertheless will have the flexibility advantage of electrical grid connection for battery loading.

Since the FCV’s considered here are directly fed with hydrogen, the same remark applies as for the ICE vehicles running on hydrogen i.e. a dedicated refuelling network is missing. The progress in increased energy density of the on-board fuel tanks however will practically lower the drawback of the scarce refuelling network.

Today, fuel-cell vehicles are available only as prototypes-demonstrators, but all major OEM car manufacturers have some kind of FC vehicle development programme going on. It is hard to name a company in the lead. Both Toyota and Honda show much commitment. They have extensive in-house programmes, and can also produce their own fuel-cell stacks. So does GM. Others are linked to specialised FC companies : Daimler-Chrysler and Ford to Ballard Power Systems, a Canadian company in the forefront of PEM fuel-cell development, Nissan and Hyundai to United Technologies (UTC).

The fuel-cell vehicles are further tested in demonstration projects. In Europe the main public programmes are CUTE (Clean Urban Transport for Europe) for urban buses and ZERO-REGIO for passenger cars, both sponsored by the European Commission. In the United States the present administration offers strong political and public support via a “FreedomCar” programme. Demonstrations are located mainly in the State of California, where a consortium named Californian Fuel Cell Partnership coordinates the activities of multiple actors. Other US locations with FC activity are Washington DC (District of Columbia), and areas around Detroit (Michigan) and Orlando (Florida). Also in Japan a major hydrogen / fuel-cell vehicle development and demonstration initiative (Japan Hydrogen Fuel Cell) is government sponsored.

Fuel cells have a higher efficiency than combustion engines, but their cost is significantly higher. It is expected that these costs will go down with higher production volumes and lower component costs. The price of a fuel cell car in 2010 is expected to be 60 % higher than the former petrol-fuelled vehicle. The development targets set by the European Hydrogen and Fuel Cell Platform are to reduce the costs of fuel-cell systems down to 100 EUR/kW by 2015, with a lifetime above 5000 h. By 2030 this cost would decrease further to 60 EUR/kW, indicating the start of an extensive market.

As to the introduction of fuel-cell vehicles, many scenario analyses have been carried out. Roadmaps set goals for hydrogen-fuel market introduction in several countries around the world. For example the Japanese goals are fifty thousand fuel-cell cars in 2010, and 5 million in 2020, approximately 9 % of the

car fleet. The EU has set the goals for the penetration of alternative motor fuels to 20 % by 2020, with hydrogen assumed to take 5 %.
Figure 2 shows four scenarios of the fleet penetration of fuel-cell vehicles. The Shell scenario “New Order” assumes a world-wide collaboration within the automotive industry, and a political framework supporting the introduction of FC vehicles. The Shell scenario “Creative Diversity” assumes that industry, initially, will not succeed in offering FC vehicles for sale at attractive economics and performance in everyday use. After some 10 years, FC vehicles leave their market niche through significant technological advances and start entering the mass market. The “Rapid introduction” scenario is an optimistic scenario that follows the typical market development curves of innovations in the car sector. Those scenarios see market introduction starting in 2010 and gaining a fleet penetration of 1 to 7 % in 2020.

There are no specific introduction scenarios for the Hydrogen Internal Combustion Engines. H_2-ICE’s could enhance the penetration of hydrogen into the fleets. The lower costs of the H_2-ICE compared to the FCV makes the “New Order” scenario more realistic, which foresees an accelerated development of the required hydrogen infrastructure. On the longer term however the market of H_2-ICE will not develop further due to their worse energy efficiency.

Belgium has a peculiar situation for hydrogen in the EU. There are large hydrogen pipeline and production infrastructures. This could be the backbone for the development of a real hydrogen economy across the country. In order to tap this resource several demonstration projects must be set up. They would create new knowledge and develop technologies that could be exported to other EU-countries and around the world. They could also bring world leaders of the hydrogen technologies into investing here. This would make Belgium a country-wide “Hydrogen Valley” with new suppliers. If and when FCV become significant the Belgian automotive industry could gain new selling points and avoid the transfer of production capacities to new developing countries.

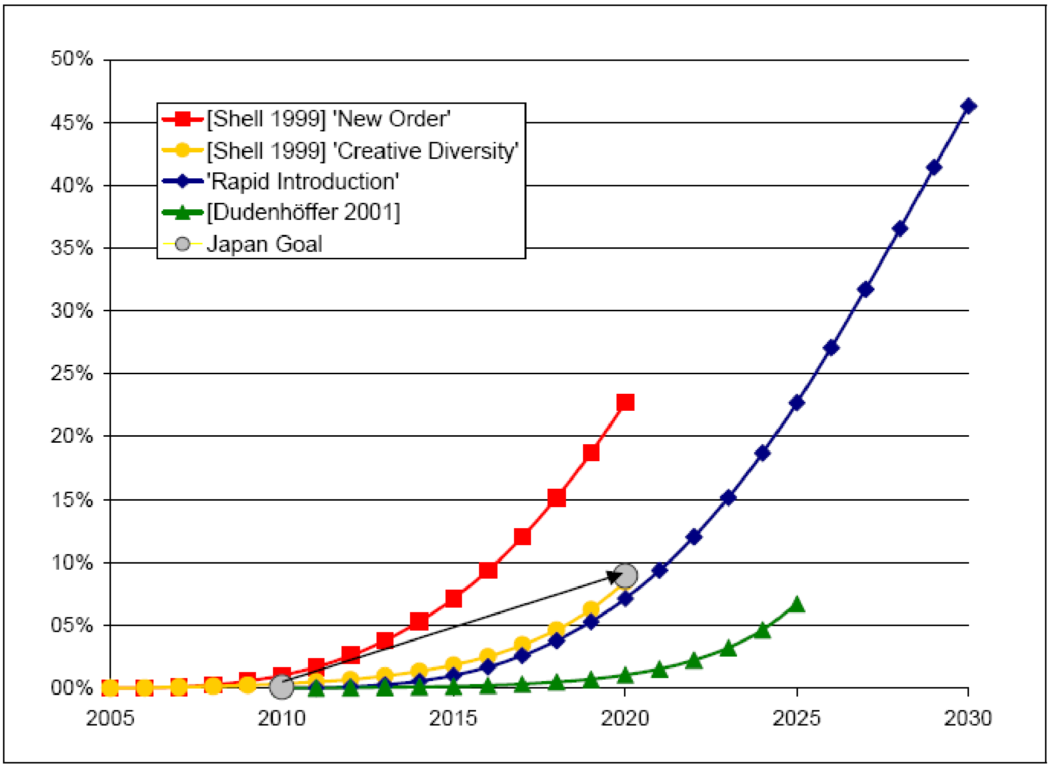

Figure 2 : Scenarios for fleet penetration of fuel cell vehicles (IPTS)

9. NEED FOR TECHNICAL IMPROVEMENT AND R&D PROGRAMMES

The introduction of hydrogen as an energy carrier will force a major evolution on the energy sector. It will consequently force the development of a large spectrum of new technologies which in turn will induce huge R&D efforts in order to make them competitive. The whole supply chain from production through transport and distribution to the end-user is involved. Reducing the production costs at each step as well as improving the efficiency and the lifespan are the most important tasks. Safety features are also essential. Numerous technical fields are implicated in these developments such as:

Material science and engineering

- Materials showing resistance to hydrogen corrosion.
- New adsorbent and porous materials for hydrogen purification and storage.
- Catalysts for hydrogen production.
- Catalysts for hydrogen oxidation in fuel cells.
- Materials with specific electrical properties and multifunctional material for fuel cells.
- Membrane technology for fuel cells and for hydrogen purification.

Applied electrochemistry

- Any types of Fuel Cells : Alkaline (AFC), Polymer Electrolyte Membrane or Proton Exchange Membrane (PEMFC**)** or Polymer Electrolyte (PEFC), Phosphoric Acid (PAFC), Molten Carbonate (MCFC**),** Solid Oxide (SOFC), Direct Methanol (DMFC, using methanol rather than H_2).
- Electrolysers.
- New development in battery and super-capacitor technologies for Fuel Cell Vehicles (FCV), for the hybrids Fuel Cell Battery Vehicles (FCBV) or Hydrogen Electrical Vehicles (HEV), as well as for Battery Electrical Vehicles (BEV).

Mechanical engineering

- High-pressure engineering for hydrogen transport and storage.
- Cryotechnical engineering for hydrogen storage, for rocket and aircraft propulsion.

Process engineering

- New processes for hydrogen production.
- CO_2 capture and storage (CCS).
- Biotechnology : H_2 from algae, biomethanisation, bioconversion into hydrogen.

Automotive engineering

- Power electronics for FCV, as well as for HEV, FCBV or BEV.
- Power management strategies.

10. ROADMAP FOR IMPLEMENTATION

What must be achieved in order to bring hydrogen into an economy that has been dominated by fossil fuels, which now provide nearly 80 % of its energy requirements ?

Generally speaking any new technology has to provide the market with competitive advantages such as lower costs, superior performances, sustainability and new outlets. If the benefits of the new technology are merely social or environmental, then some regulatory and public investment policies are needed in order to bring down the costs and make the development affordable.

For hydrogen, some short-term benefits do not currently warrant its higher costs compared to the conventional technologies. Moving from the fossil-fuel economy of today to a hydrogen economy will not happen overnight in one single step. The right phase-in strategy "from yesterday to tomorrow" must be carefully defined in the future energy scenarios if we want to achieve the broad scale introduction of hydrogen. During the transition, the conventional technologies and the existing infrastructures will be necessary for keeping the economy prosperous.

"*We are facing a 'chicken and egg' problem that will be difficult to overcome. Who will invest in the manufacture of fuel cell vehicles if there is no widespread hydrogen supply? At the same time, who will invest in facilities to produce hydrogen if there are not enough fuel cell vehicles to create sufficient income for hydrogen producers?*" [5]

In the transportation sector, the use of hydrogen and fuel cells will create a new concept of car technology. As long as the fuel-cell technology is not operational however, hydrogen can still be fed to slightly modified internal combustion engines of the existing car technology. Dual-fuel gasoline / hydrogen internal combustion engines can then support the hydrogen demand during the transition. Hydrogen internal combustion engines and hydrogen hybrids can also help during the transition in the same way.

It is advisable in the meantime to start acquiring experience with the use of hydrogen, although hydrogen cannot yet be mass-produced by new technologies mainly based on renewable energy sources. It will come from steam reforming of natural gas - as it does today for its use in the chemical and oil industries – with some carbon dioxide capture and storage increasing over time, as well as the other new methods of production.

Another important success factor is public acceptance. Actually it is a decisive factor. In order to gain public acceptance, programmes that demonstrate the technology must be launched. One of these is the European programme CUTE, created to test hydrogen buses in several European cities, but unfortunately none of them in Belgium. In the same spirit Belgium could elaborate a demonstration programme involving for example a river boat for tourism, a drone (pilotless-aircraft), service vehicles, busses, or wind generated hydrogen for peak shaving.

It seems essential to develop during the transition period those applications which are niche markets such as urban buses, forklift trucks and wheelchairs. These vehicles need neither an extensive fuel supply nor a full infrastructure. They can afford the higher prices of the hydrogen drive systems. Although limited in volume these niche market segments could trigger a substantial reduction of fuel cell cost and create new industrial activities and markets.

The transition to hydrogen and fuel cells should happen step by step, along the following broad lines :

In the short term (to 2010)

As a first step in the early period, the use of renewable energy sources can be intensified for producing electricity and hydrogen. Since the amount of energy available in this way does not cover by far the present demand and despite all efforts for energy saving, it is still necessary to keep operating many conventional energy sources for the whole transition period. It appears therefore essential to keep improving the efficiency of fossil-fuel technologies and decrease their environmental impact.

During this period, hydrogen and fuel cells should also be applied in several niche markets. This would stimulate the hydrogen market, generate experience as well as progress on learning curves, take advantage of the existing hydrogen pipeline network, etc. By the same token, the demonstration projects can also improve public acceptance.

Important research efforts are needed in several fields for hydrogen production, storage, distribution and safety, fuel cells, materials, costs, reliability and life span, etc., as sketched in the previous chapter.

In the medium term (from 2011 to 2020)

The increased availability of hydrogen will enable the sale of cars and trucks using hydrogen as a fuel in suitably modified conventional combustion engines and (or) fuel-cell systems. Hydrogen is still produced from fossil fuels but increasingly from renewable energy sources. Large demonstration projects are build for CO_2 capture and storage, and the efficiency and reliability of these processes are improved.

In the longer term (beyond 2020)

In the long run hydrogen production will keep growing with consumers demand for clean energy supply. Both electricity and hydrogen will progressively replace the outdated carbon energy system. Fossil fuels will gradually be substituted by renewables and by nuclear energy. At that time the hydrogen network will expand faster than in the past and become largely interconnected with the electricity grid.

In a previous report [13] the European Commission has presented a skeleton proposal for the main elements and time lines of a European roadmap for the production and distribution of hydrogen, as well as fuel cells and hydrogen systems (Figure 3).

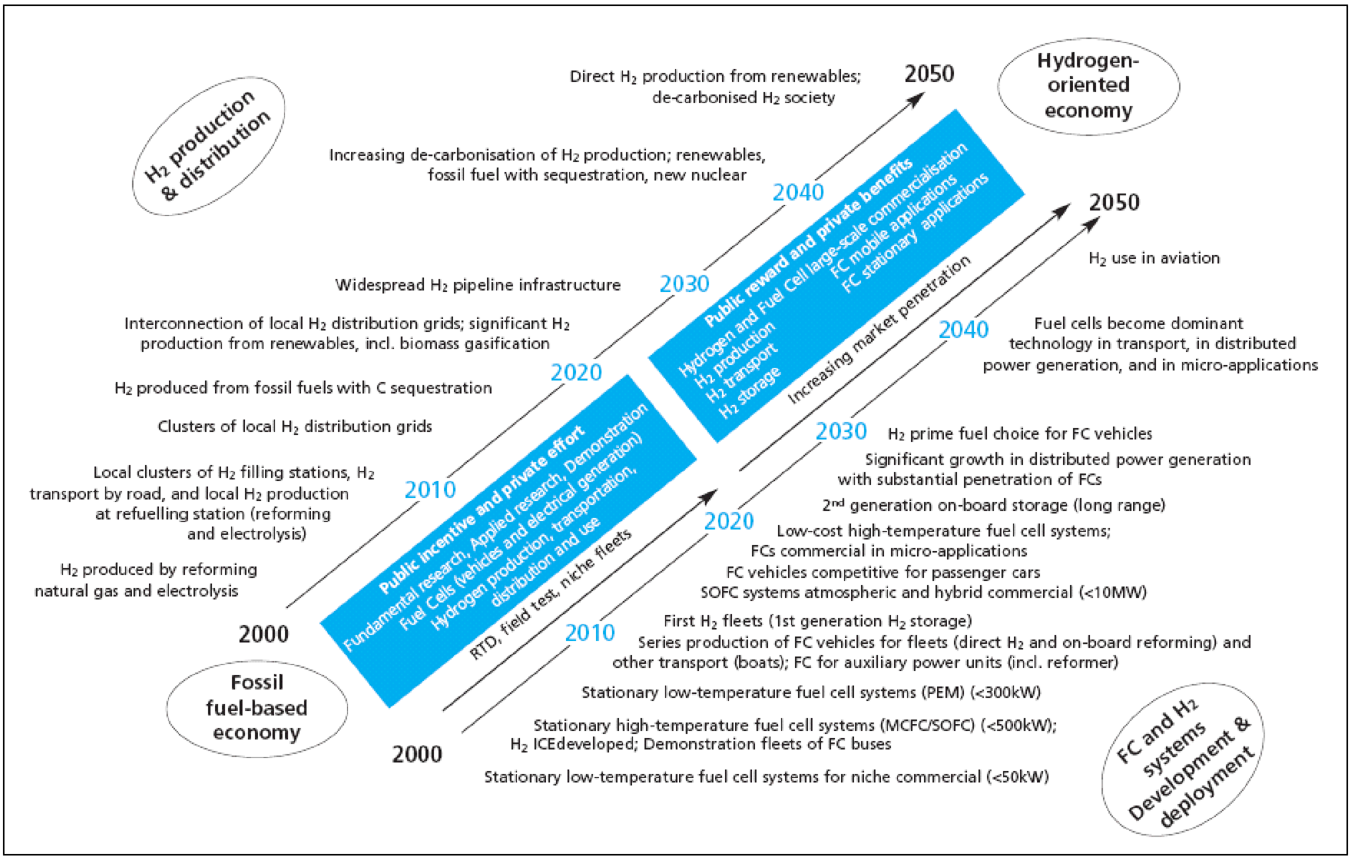

Figure 3 : European roadmap for hydrogen and fuel cells [13]

Before entering the transition phase, it is very important to identify the different hurdles on the track to a progressive implementation of hydrogen systems. These obstacles are not only of a technical kind but also and perhaps more of a legal, administrative, societal, economical or financial nature. If not properly taken into account, these could prevent the new energy systems from ever existing.

11. CONCLUSIONS

Although a drastic change of the energy system appears inevitable, the quantitative prediction of the role that hydrogen will play is most difficult. Competition between electricity and hydrogen as energy carriers will increase and debates on this topic will be numerous and lively. It is nevertheless plausible that both solutions will coexist.

Taking into account the economic, social and technological interests at stake, it is of primary importance to further evaluate the prospects of hydrogen as a new energy carrier and the synergies which will necessarily develop with electricity. For hydrogen as well as for electricity, major technological innovations will occur and will lead to the development of very large markets.

As the USA and Japan are allocating huge funds to R&D programmes on hydrogen and fuel cells (respectively 12 and 20 % of the total non-nuclear energy R&D budget), Europe and especially Belgium cannot stay outside this technological field. So far they are lagging much behind the USA and Japan for the development of innovative technologies. There is a high risk that the European industry will end up being excluded from the hydrogen economy.

It must be clear that innovations in the field of a low-carbon energy system go far beyond the development of the individual technologies which are involved in the system. Fundamental research, development, applications and demonstration of new systems are essential while human and social aspects cannot be neglected. Understanding the behaviour of the citizens facing the new technologies is essential.

12. RECOMMENDATIONS

1. Our government should promote and support research and pilot projects at the level of the European Union for reducing greenhouse gases emissions. Our government must support those European regulations which will stimulate the use of new technologies intended to reduce pollution and make Europe less dependent on the supply of oil and natural gas.

2. A Belgian technology platform on hydrogen & fuel-cells should be created. It should involve all stakeholders (industry, utilities, government(s), universities, research organisations…) which would provide guidance and support to R&D and key technical challenges on the introduction of hydrogen as an energy carrier, e.g. This platform should :

- encourage and promote R&D studies in universities and industry on the production, storage and uses of hydrogen ;
- fostering inter-university educational clusters on hydrogen and its related technologies ;
- organise the direct participation of Belgium in the newly created technology platform in the EC (DG research) '*Hydrogen and Fuel cells*'[13] ;
- organise the direct participation of Belgium in other international R&D programmes such as the IEA (International Energy Agency) programmes.

3. The hydrogen energy concept should be introduced within the curricula of schools and universities. The scope of existing courses must be extended. Specific curricula should be developed by clusters of universities and engineering schools.

4. As coal is likely to remain a permanent source of primary energy for many decades, studies on carbon dioxide capture and storage (CCS) should be enhanced to the benefit of both electricity generation and hydrogen production.

5. As nuclear energy is likely to remain a major source of primary energy, the Belgian nuclear expertise should be maintained and research fostered on new nuclear reactors for hydrogen production and / or electricity generation.

6. Belgium has an important car assembling industry, the design and development centres of which are located outside the country. There is however a strong local industry for components. They should prepare themselves to a gradual shift from conventional fossil fuelled cars to the new generation of electricity / hydrogen powered cars.

7. As reliable technical and economical data can only be obtained by practical experience, demonstration projects should be initiated, supported or enhanced in the various fields of hydrogen production, storage, transport and utilization. On the other hand, it is well known that successful policy decisions need public acceptance and that unfamiliar hazardous materials do raise suspicion. A good information and sensitization campaign on hydrogen must therefore address public concerns in addition to pointing out the intrinsic advantages of the new products. In order to bring to the general public the demystification and consciousness of the concept of the 'hydrogen economy', these demonstration projects should be given the greatest possible visibility. Some examples :

- hydrogen fuelled buses and boats related to tourist activities ;
- local hydrogen- fed heat and electricity generation units for administrations and hospitals ;
- electrolysers linked to wind turbines could stimulate the idea of a carbon-free renewable energy system providing hydrogen to a filling station ;
- small applications such as wheelchairs powered by hydrogen, or fuel cells substituting batteries in small portable appliances could also be considered ;
- live shows on hydrogen in the Technology Parks, PASS and TECHNOPOLIS, in university and other laboratories that organize visits and activities promoting the sciences, should be developed.

8. Government incentives in favour of clean hydrogen / electricity powered cars should be made available, by reducing taxes on the car itself and on the energy provided. Such economic driving forces help changing habits and behaviour towards a new energy system. The increased collective costs yield their return later.

~~8.~~

13. REFERENCES

[1] *Energy in Belgium tomorrow : taking in account the greenhouse effect,* BACAS report, 2002

[2] *L'hydrogène, vecteur énergétique de l'avenir?*, Henri VANDER POORTEN, Michel CRAPPE, Revue E, 121 (2), 5-19, 2005

[3] *Only Hydrogen for Future Land Transport System?*, MAGGETTO Gaston, VAN MIERLO Joeri, Proc European Fuel Cell Forum, Lucerne, 4-8 July 2005

[4] *The hype about hydrogen : Fact and Fiction in the Race To Save the Climate*, Joseph J. ROMM, Island Press, 82 (41), 48-49, 2004

[5] *The Hydrogen Economy : Myth of Possible Reality ?*, Patricia VAN ARNUM, Chemical Market Report, April 12th, 2004

[6] *Key Tasks for future European Energy R&D*, Community research, European Commission, 2005

[7] *Carrying the energy future : comparing hydrogen and electricity for transmission, storage and transportation*, Patrick MAZZA & Roel HAMMERSCHLAG, Institute for Lifecycle Environmental Assessment (ILEA), Washington, June 2004

[8] *Hydrogen today and tomorrow*, www.ieagreen.org.uk

[9] *Filling up with Hydrogen*, Mitch JACOBI, Chemical & Engineering News, 83 (34), 42-47, 2005

[10] *Prospects for Hydrogen and Fuel Cells*, Draft 03/03/2005, IEA, Paris

[11] *Hydrogen & fuel cells*, Review of National R&D Programs, International Energy Agency, 2004

[12] *Putting energy in the spotlight – BP Statistical Review of World Energy June 2005*, www.BP.com

[13] *Hydrogen Energy and Fuel Cells: A vision of our future*, Final report of the high level group, European Commission, 2005

[14] *Nouvelle technologies de l'énergie*, invited report by the French Government on March 17, 2003

[15] *Livre vert : Vers une stratégie européenne de sécurité d'approvisionnement énergétique*, Commission européenne, 2001

[16] *The Future of the Hydrogen Economy : Bright or Bleak ?*, Ulf BOSSEL, Baldur ELIASSON, Gordon TAYLOR, Final report, 15 April 2003

[17] *Nuclear options for Hydrogen and Hydrogen Based Fuel Production,* YILDIZ, KAZIMI, MIT-NES-TR-001, 2003.

Appendix A : Comparative hydrogen properties

Table 4 : Main properties of hydrogen

Gas density	0.0899 kg/Nm^3
Liquid density	70.99 kg/m^3
Boiling point	20.4 K
Melting point	14 K
Lower Heating Value (LHV)	121 MJ/kg
Burning range	4–74.5 % volume
Detonation range	18.3–59 % volume
Stoechiometric ratio (with air)	34.5

A brief comparison with methane and propane appears in table 5 and the weight and volume energy density compared to some common fuels in table 6 and table 7 (tank included).

Table 5 : Comparison between hydrogen, methane and propane

		H_2	CH_4	C_3H_8
lower heating value:	MJ/kg	121	50	46.4
	kWh/kg	33.33	13.90	12.88
	MJ/Nm^3	10.783	35.882	93.215
	kWh/Nm^3	2.995	9.968	25.893
upper heating value:	kJ/kg	141 890	55 530	50 410
	kWh/kg	39.41	15.42	14.00
	MJ/Nm^3	12.745	39.819	101.242
	kWh/Nm^3	3.509	11.061	28.123
lower Wobbe index:	MJ/Nm^3	40.898	48.170	74.744
	kWh/Nm^3	11.361	13.381	20.762
upper Wobbe index:	MJ/Nm^3	48.34	53.454	81.181
	kWh/Nm^3	13.428	14.848	22.550
density	kg/m^3	0.08988	0.7175	2.011
gas constant	J/kg K	4124	518.8	188.5
ignition temperature in air	°C	530	645	510
ignition limit in air	vol-%	4.1-72.5	5.1-13.5	2.5-9.3
max. flame velocity	cm/s	346	43	47

Table 6 : Weight and volume energy density comparison between hydrogen and some common fuels

Energy carrier	Form of Storage (tank not included)	Energy density by weight [kWh/kg]	Energy density by volume [kWh/l]
Hydrogen	gas (30 MPa)	33.3	0.75
	liquid (-253°C)	33.3	2.36
	metal hydride (included)	0.58	3.18
Natural gas	gas (30 MPa)	13.9	3.38
	liquid (-162°C)	13.9	5.8
LPG (Propane)	liquid	12.9	7.5
Methanol	liquid	5.6	4.42
Gasoline	liquid	12.7	8.76
Diesel	liquid	11.6	9.7
Electricity	Pb battery (chemical)	0.03	0.09

Table 7 : Weight and volume energy density of stored hydrogen, tank included

	P	T	kg H_2/m^3	g H_2/kg
Gaseous hydrogen	70 Mpa	298 K	25	65
Liquid hydrogen	0.1 Mpa	20 K	30	70
Hydride (Ti)			≈ 35	20
Adsorbed on C	0.1 MPa	77 K	≈ 39	100

Appendix B : Present utilization of hydrogen

B 1. Large chemical plants and refineries produce and consume locally 95 % of the total hydrogen market.

Crude oil refining

The largest use of hydrogen occurs in crude oil processing and refining. Hydrogen enhances the performance of petroleum products and removes organic sulphur. Let us mention two processes :

- Hydrocracking improves gasoline yields. Heavy oil molecules are cracked (broken) into lighter, easier to refine, and more marketable products which also comply with the regulations for lower emissions and less by-products. The result is a higher gasoline yield with higher octane.
- Catalytic hydrotreating of several petroleum cuts produces gasoline, diesel oil and other fuels with a very low sulphur content that meet the present regulations.

The hydrogen quantities needed for these utilizations are growing strongly on two accounts : the petroleum products must be cleaner and the ratio of hydrogen to carbon in fuels is increasing.

Basic chemicals

Large quantities of hydrogen are used to produce ammonia (NH_3), methanol (CH_3OH), and key products such as fertilizers and many others.

Ammonia : ammonia is produced by reacting nitrogen with hydrogen. The overall reaction – which involves several steps including feedstock desulphurization - is given as :

$$N_2 + 3\,H_2 \rightarrow 2\,NH_3 \qquad \text{(between 100-250 bar and 350-550 °C)}$$

Worldwide capacity, excluding China, approaches 130 million tons per year. About 85-90 % of all ammonia produced ends up as fertilizer.

Methanol : methanol is produced by the high-pressure catalytic reaction of carbon monoxide and hydrogen, both derived from natural gas, or by the partial oxidation of natural gas hydrocarbons. Low-cost production lines with new catalysts, and the so-called oxygen, or enriched air, blown twin-stage reforming of natural gas at low pressure are recent improvements. The gas obtained from the steam reforming and (or) the oxidation of natural gas is processed to methanol according to the following reactions :

$$CO + 2H_2 \Rightarrow CH_3OH$$
$$CO_2 + 3H_2 \Rightarrow CH_3OH + H_2O$$

Recent technology advances have allowed building larger plants. The largest operating plant started in Trinidad with a capacity of 1.7 million tons/year and other large plants have been announced in Asia, the Middle-East and the Caribbeans. The next group of plants ready to go on stream have a capacity of about 10.000 tons/day, twice the capacity of the current world-scale units.

World production was estimated at 31-33 million tons per year (2002), the main uses being formaldehyde and MTBE (Methyl-ter-butyl-ether, a gasoline additive).

B 2. Merchant hydrogen for specialties and small applications represents 5 % of the total production.

Figure 4 shows the various applications in North America, in 2001.

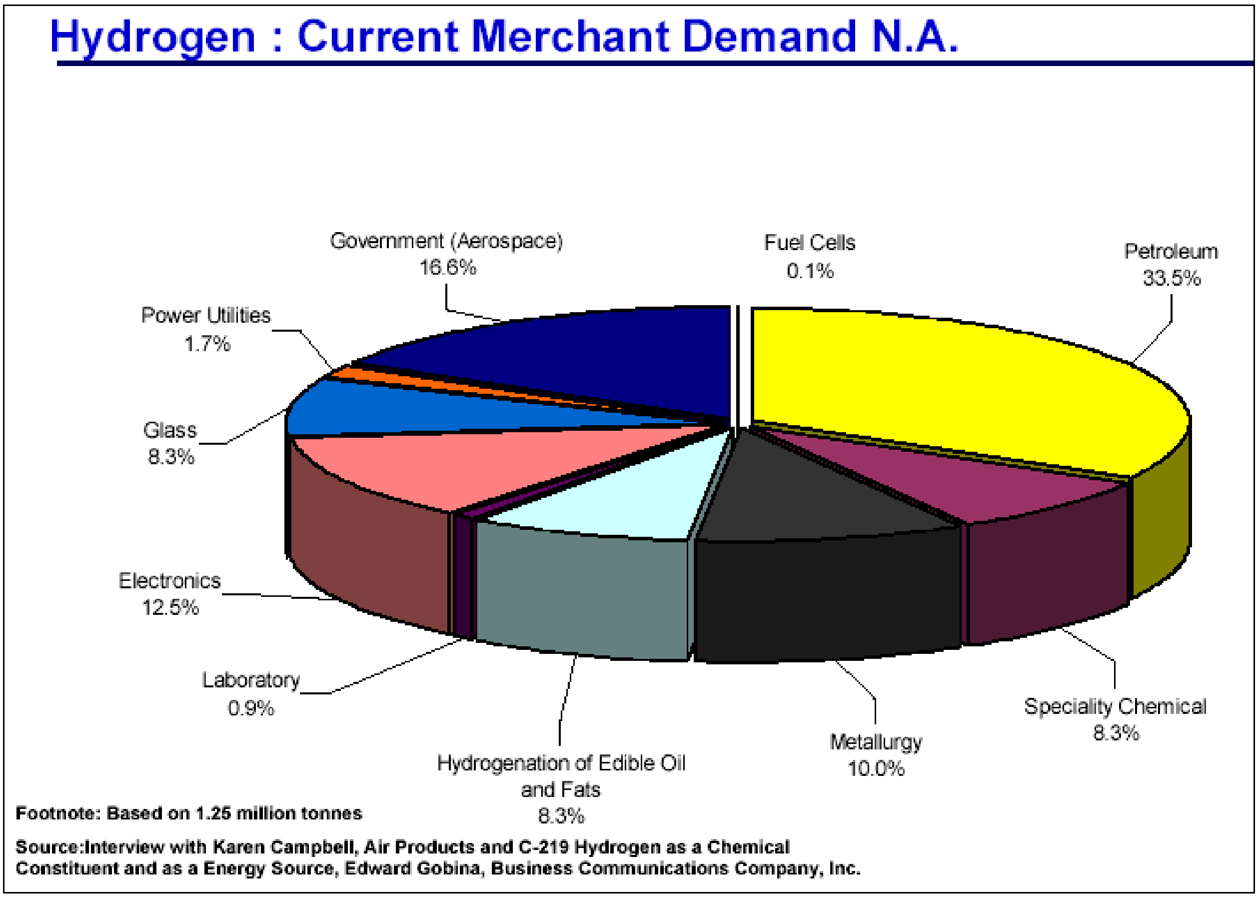

Figure 4 : Current merchant demand for hydrogen in North America
[Source : Dynetek Industries - http://www.gov.pe.ca/photos/original/dev_solutions.pdf]

Hydrogen is needed in many applications and markets :

Food : hydrogen is used to hydrogenate liquid oils (such as soybean, fish, cottonseed , corn …oils) that produce semisolid materials such as margarine, fat, etc. Hydrogenation increases the oxidative stability of edible fats and oils in order to avoid spoilage and odours.

Sorbitol : produced by hydrogenation of glucose, sorbitol is used in food, pharmaceuticals, cosmetics, etc.

Pharmaceuticals and bio / specialties / intermediates : in addition to sorbitol, hydrogen is needed for many syntheses. The best known are those of vitamins A and C.

Chemicals (specialties) : Hydrogen is widely used for synthesising "specialties", intermediates for pharmaceuticals and chemically advanced materials such as hydrogen peroxide, many chemicals with a hydrogenation step used for soaps, insulation or plastics, hydrogen transfer agents,....

Metal production and fabrication : hydrogen acts as a protective processing atmosphere for the manufacturing of carbon and stainless steel - with argon for austenitic stainless steel - , in plasma welding and cutting operations, etc. Hydrogen consumption in metal production is growing with an increased demand in furnaces. In the past, the furnaces used approximately 6 % hydrogen in their atmosphere. Now, it's quite common to have 100 %.

Electronics : during the production of semi-conductor and printed circuits, hydrogen acts as a controlled atmosphere to insure the high purity required in these applications.

Aerospace : hydrogen is used as fuel for spacecraft and rockets, but also as an energy source that powers life-support systems while yielding drinkable water as by-product.

Glass polishing and glass / optical fibre manufacturing : hydrogen acts as a controlled atmosphere to ensure an oxygen-free atmosphere.

Power generation : hydrogen is used to cool high-speed generators and is also used in the cooling water system of nuclear reactors (to eliminate oxygen).

Another summary is given (Figure 5) by Air Liquide for 2003 world markets.

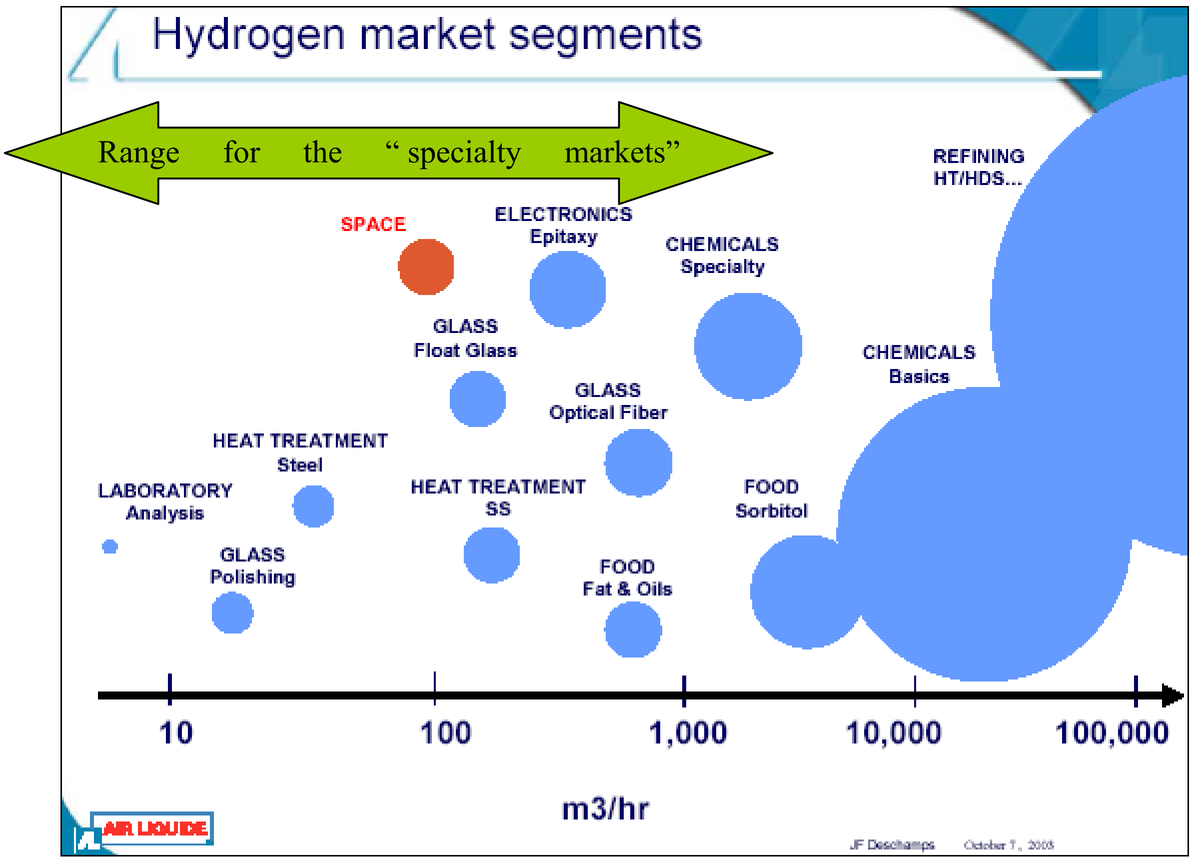

Figure 5 : Hydrogen market segments in 2003 [Source : Air Liquide - www.airliquide.com]

This map shows the growth of the market (ordinates), the size of various markets (the area of circles) and the size of the typical consumer (the volume needed per hour).

List of acronyms

- AFC : Akaline Fuel Cell
- BEV : Battery Electrical Vehicle
- CEA : Commissariat à l'Energie Atomique
- CCS : CO_2 capture and storage
- CUTE : Clean Urban Transport for Europe
- DMFC : Direct Methanol Fuel Cell
- EU : European Union
- FC : Fuel Cell
- FCV : Fuel Cell Vehicle
- FCBV : Fuel Cell Battery Vehicle
- HDS : Hydrodesulphurization
- HEV : Hydrogen Electrical Vehicle
- HT : High Temperature
- ICE : Internal Combustion Engine
- IEA : International Energy Agency
- IPTS : Institute for Prospective Technologies Studies
- MCFC : Molten Carbonate Fuel Cell
- MTBE : Methyl ter-butyl ether
- OEM : Original Equipment Manufacturer
- PAFC : Phosphoric Acid Fuel Cell
- PASS : Parc d'Aventures Scientifiques
- PEMFC : Polymer Electrolyte Membrane Fuel Cell
- SOFC : Solid Oxide Fuel Cell

Working group members

- Prof. Albert Germain , ULg, chairman
- Ir. Jean-Jacques Van de Berg (CAPAS), secretary
- Prof. Ronnie Belmans, KULeuven
- Dr. Charles Bienfait , SOLVAY S.A. (CAPAS)
- Dr. William Bracke (CAPAS)
- Mr Marc Brykman, Shell
- Dr.Ir. Luc Chefneux , Groupe Arcelor (CAPAS)
- Prof. Jean-Pierre Contzen (CAPAS)
- Em. Prof. Romain Coussement, KULeuven
- Prof. William D'haeseleer, KULeuven
- Ir.Paul Govaerts , SCK-CEN (CAWET) (†)
- Ir. Dries Haeseldonckx, KULeuven
- Dr.Ir. Jan Kretzschmar , VITO (CAWET)
- Prof. Gaston Maggetto ,VUB (CAWET)
- Dr.Ir. Urbain Meers (CAWET)
- Ir. Stan Ulens (CAWET)
- Prof. honor. Michel Theys , ULB (CAPAS)
- Em. Prof. Achiel Van Cauwenberghe, UGent (CAWET)
- Prof. Joeri Van Mierlo, VUB
- Dr. Hugo Vandenborre, Hydrogenics
- Ir. Delphine Wery, ULg

CAPAS MEMBERS

President :
Prof. Ir. Pierre KLEES
BIAC

Vice President :
Prof. Philippe BOURDEAU
Honor. ULB

Member of the Bureau
Prof. André DELMER
ARB

Honorary Presidents :
Baron A. JAUMOTTE
Honor. Rector ULB, ARB
Prof. N.M. DEHOUSSE
Honor. ULg

General delegate :
Ir. Jean-Jacques VAN DE BERG
Solvay

Members :
Prof. Jean-Marie ANDRÉ
ARB
Prof. Radu BALESCU
Honor. ULB
Dr. Charles BIENFAIT
Solvay Technologies
Baron Philippe BODSON
CIB
Ir. William BRACKE
Fina Research
Prof. Armand BROUCKE
Honor. VUB
Prof. Arsène BURNY
Honor. Gembloux
Prof. André CALVAER
Honor. ULg
Ir. Jean-Pierre CONTZEN
MCT
Prof. Marcel CROCHET
Rector UCL
Prof. Bernard DELMON
Honor. UCL
Ir. Jean-Pierre GERARD
Fafer
Ir. René HANNON
Alcatel-ETCA
Ir. Jean-Pierre HANSEN
Suez-Tractebel
Prof. Léo HOUZIAUX
Per. Sec. ARB
Ir. Christian JACQMIN
SONACA
Prof. Claude JAMAR
Centre Spatial Liège
Ir. Jacques LAURENT
Belgonucléaire
Prof. Willy LEGROS
Rector ULg
Ir. Manfred LOEB
Immobel
Ir. Paul-Etienne MAES
UCB
Ir. Guy MARECHAL
Philips
Prof. Joseph MARTIAL
ARB
Dr.Ir. Jacques PELERIN
Arcelor
Prof. André PREUMONT
Honor.ULB
Baron Philippe ROBERT-JONES
Honor. Per. Sec. ARB
Prof. Jean-Pierre SWINGS
Inst. Astr. Geophys.ULg
Prof. Michel THEYS
WIN-Belgacom
Prof. Paul VANDENPLAS
Honor. ERM
Prof. André VANDER VORST
UCL
Prof. Claude VERAART
UCL
Prof. René WINAND
Honor. ULB

Associate Members :
Dr.Ir. Luc CHEFNEUX
Cockerill Sambre
Dr. Marco CITTA
CREF
Ir. Jean-Pierre CONNEROTE
Electrabel
Prof. Michel CRAPPE
Honor. FPMs
Dr. Eric DEROUANE
ARB Associate
Prof. Michel GERADIN
Ulg
Prof. Léon GHOSEZ
Honor. UCL
Ir. Michel-Daniel JUDKIEWICZ
Proviron
Ir. William KIRKPATRICK
K Partners
Dr. Paul LEVAUX
Honor. FNRS
Ir. Clément ROME
Cockrrill-Sambre
Prof. Jacques RONDAL
Ulg
Prof. Alexandre SAMII
FOPES (UCL)
Mme Marie-José SIMOEN
FNRS
Ir. Jacques VAN HULSE
ACEC
Dr. J. VAN KEYMEULEN
IRSIA
Dr. Marco VAN OVERMEIRE
AIB-Vinçotte-Nederland

CAWET MEMBERS

President :
Dr.ir. Guy HAEMERS
INVENTURES Group Europe

Vice President :
Prof. Ludo GELDERS
Industrial Management, Katholieke Universiteit Leuven

Secretary :
Ir. Paul GOVAERTS
SCK•CEN, Mol

Honorary Presidents :
Prof. Achiel VAN CAUWENBERGHE
Control Engineering, Universiteit Gent
Ir. Valentin VAN den BALCK
Berenschot, Brussel
Prof. Daniël VANDEPITTE
Civil Engineering, Universiteit Gent

External Communications Officer :
Dr.ir. Paul VERSTRAETEN
Sidmar, Gent

Members :
Prof. Etienne AERNOUDT
Metals and Materials Engineering, Katholieke Universiteit Leuven
Prof. Jean BERLAMONT
Hydraulics, Katholieke Universiteit Leuven
Ir. Luc BOSSYNS
Aquafin, Aartselaar
Prof. Bart DE MOOR
Electrical Engineering, Katholieke Universiteit Leuven
Ir. Marc FRANCKEN
Gevaert, Antwerpen
Burggraaf Dirk FRIMOUT
Ministerie Economie, Brussel
Prof. Derrick GOSSELIN
Suez Energy International, Brussel
Prof. Charles HIRSCH
Fluid Mechanics, Vrije Universiteit Brussel
Dr.ir. Jan KRETZSCHMAR
VITO, Mol
Ir. Robert LENAERS
NV Vanhout, Geel
Dr.ir. Jan LEURIDAN
LMS International, Leuven
Prof. Gaston MAGGETTO
Elektrotechniek en Vermogenselektronica, Vrije Universiteit Brussel
Ir. Leo MICHIELS
Proviron, Oostende
Ir. Norbert VAN BELLE
Janssen Pharmaceutica, Beerse
Prof. Hendrik VAN BRUSSEL
PMA, Katholieke Universiteit Leuven
Prof. Erick VANDAMME
Industrial Microbiology, Universiteit Gent
Prof. Georges VAN DER PERRE
Biomechanics and Graphic Design, Katholieke Universiteit Leuven
Prof. Joos VANDEWALLE
ESAT, Katholieke Universiteit Leuven
Ir. Willy VAN OVERSCHEE
IBM, Brussel
Dr.ir. J. VAN REMORTEL
Alcatel Bell, Antwerpen
Ir. Joost VAN ROOST
ExxonMobil, Breda
Ir. Ivo VAN VAERENBERGH
REM-B, Zoersel
Prof. Pierre VERBAETEN
Computer Science, Katholieke Universiteit Leuven
Prof. Ronny VERHOEVEN
Hydraulics, Universiteit Gent
Prof. Ignaas VERPOEST
MTM, Katholieke Universiteit Leuven
Prof. Willy VERSTRAETE
Microbial Ecology, Universiteit Gent
Prof. Jacques Baron WILLEMS
Electrical Systems, Universiteit Gent

Associate Members :
Ir. Herman DEROO
KVIV, Antwerpen
Prof. Robert GOBIN
Graphic Design, Katholieke Universiteit Leuven
Mr. Erik JACQUEMIJN
Stichting Flanders Technology International, Mechelen
Dr. Henri MALCORPS
Royal Meteorological Institute, Brussel
Ir. Michel NAZE
Capsugel, Bornem
Ir. Alfons PEETERS
Eternit, Brussel
Ir. Paul VAN DER SPIEGEL
Keerbergen
Dr. Jan VAN KEYMEULEN
Kasteelbrakel
Prof. Hendrik VAN LANDEGHEM
Technische Bedrijfsvoering, Universiteit Gent
Prof. Pascal VERDONCK
Hydraulics, Universiteit Gent

Honorary Members :
Ir. Jean BEECKMAN, Dr.ir. Stan BEERNAERT, Prof. Hugo DE MAN, ir. Jozef DEMAN, ir. Jean-Pierre DE PAEMELAERE, ing. Lucien DE SCHAMPHELAERE, Prof. Walter Baron FIERS, Prof. Gilbert FROMENT, Prof. René JACQUES, ir. Jan JONGBLOET, Roland MAES, Dr.ir Lars MALMROS, Dr.ir. Urbain MEERS, Prof. Jacques PETERS, Prof. Niceas SCHAMP, Ir. Marcel SOENS, Ir. Stan ULENS, Prof. Jean VAN BLADEL, Prof. Marc Baron VAN MONTAGU, Prof. Marc VANWORMHOUDT, Ir. Roland WISSAERT

BACAS Steering Committee

Dr.ir. G. HAEMERS, president CAWET and BACAS
Prof. L. GELDERS, vice-president CAWET
Ir. P. GOVAERTS, secretary CAWET
Prof. A. VAN CAUWENBERGHE, past president

Ir. P. KLEES, president CAPAS
Prof. Ph. BOURDEAU, vice-president CAPAS
Prof. N. DEHOUSSE, past president
Ir. J.J. VAN DE BERG, Secretary CAPAS