SCIENTIFIC SUPPORT PLAN FOR A SUSTAINABLE DEVELOPMENT POLICY

SPSD II

DEVELOPMENT OF TOOLS TO EVALUATE THE POTENTIAL OF SUSTAINABLE HYDROGEN IN BELGIUM

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GENERAL ISSUES

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PART 1

SUSTAINABLE PRODUCTION AND CONSUMPTION PATTERNS — ENERGY

TRANSPORT

SCIENTIFIC SUPPORT PLAN FOR A SUSTAINABLE DEVELOPMENT POLICY
(SPSD II)

Part 1:
Sustainable production and consumption patterns

FINAL REPORT

DEVELOPMENT OF TOOLS TO EVALUATE THE POTENTIAL OF SUSTAINABLE HYDROGEN IN BELGIUM

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1 INTRODUCTION

1.1 Background

Within the framework of sustainable development the energy supply system is a crucial topic. Spurred on by the Kyoto Protocol the attention for the definition of energy saving programs and the promotion of environment-friendly technologies as renewable energy is increasing. In the longer term however additional alternatives have to be found. Especially for the Belgian context the combination of a further decrease of emissions (CO_2, NO_X,…) with a faze-out of nuclear energy is a major challenge.

At the international level hydrogen as energy carrier is considered to be an important option for the future. In the USA a 'Roadmap to hydrogen' has been developed already and on the European level recently the policy paper 'Hydrogen Energy and Fuel Cells, a vision of our future' has been presented. Within the Belgian energy policy the knowledge on hydrogen is rather limited and this project intends to be the first step in a scientific assessment of hydrogen in the Belgian context.

1.2 Objective

The results of the project can be summarized as follows:

* databases with international knowledge and experiences on hydrogen
* hydrogen module within MARKAL-TIMES, illustrated by a scenario calculation
* initial technology assessment on hydrogen, focussed on the scenario
* translation of the progress in foreign legislation and licence procedures on hydrogen
* definition of relevant policy issues concerning hydrogen

These five objectives are worked out in this report as chapter for each item. An explanation is given in the next paragraph.

1.3 Structure of the project

The structure of the project is presented in Figure 1-1. As can be seen in this scheme the project has been divided into 5 work packages:

1. Databases on knowledge and experiences
2. Technic-economic evaluation
3. Technology Assessment
4. Translation of foreign progress in legislation
5. Policy issues

The project starts with the building of databases concerning technology, legislation and international experiences on hydrogen. These databases serve as input for the tools and opinions to be developed (chapter 2).

Based on the databases a hydrogen-module within the MARKAL-model has been developed, especially focussed on the specific Belgian situation (e.g. energy demand, existing hydrogen infrastructure,…); this module has been tested with some case studies (chapter 3).

In parallel the technology assessment (TA) has been started in which a plausible scenario for using hydrogen in Belgium was defined in dialogue with an experts panel. This scenario was afterwards technic-economically evaluated by MARKAL (chapter 4).

Within the scenario the actual legislation (lacunas, barriers) on hydrogen receives due attention as setting up a clear legislation is a condition for realizing a scenario (chapter 5).

The results of the technic-economic analysis, the technology assessment and the evaluation of the legislation will be translated to policy issues, such as possible policy instruments and policy objectives (chapter 6).

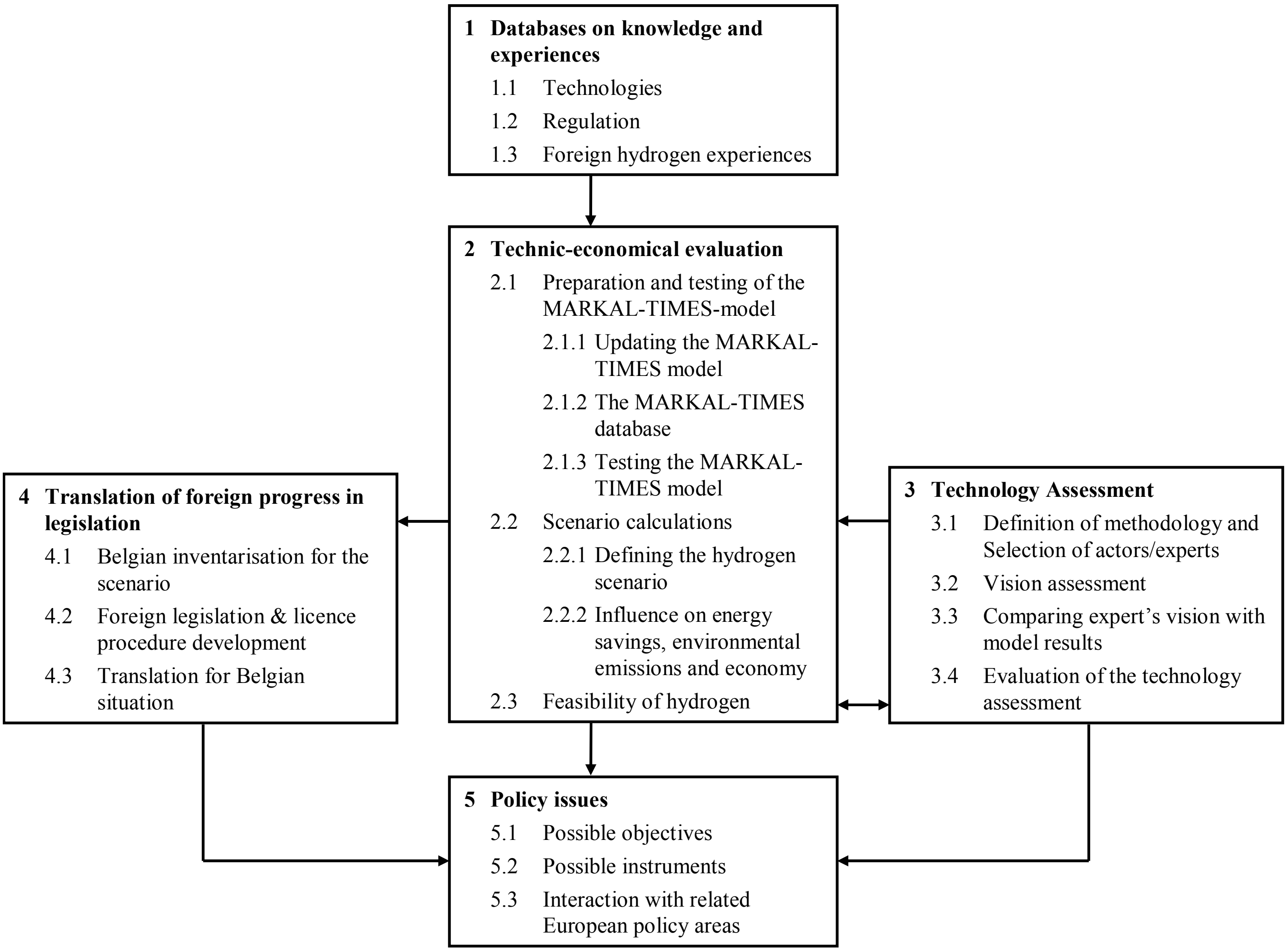


Figure 1-1: Structure of the project

2 DATABASES ON HYDROGEN KNOWLEDGE AND EXPERIENCES

2.1 Objective

The objective of this work package is to make available international knowledge and experiences on hydrogen technology and on policy in databases.

In Belgium hydrogen is traditionally used by the chemical industry. Belgium has already an impressive hydrogen transport network. In spite of this, the knowledge on hydrogen as an energy vector is limited. However, internationally a wide range of research, knowledge and experience (from catalyst modelling, well-to-wheel studies to the operation of street buses) is present. In many countries and regions hydrogen information networks rise up. The character of the research and networks is mainly technological.

In this work package data has been gathered covering technologies, regulation and foreign hydrogen experiences. They have been updated during the project. These databases serve as input for the tools and opinions to be developed.

2.2 Methodology

The knowledge about hydrogen has been split into three items:

* technologies (with attention to the different stages, being production, transport/ distribution, storage and conversion/end use of hydrogen);
* regulation (inventory of existing Belgian and regional regulation and legislation on hydrogen, as well as inventory of foreign regulation and legislation);
* foreign experiences (demonstration projects: descriptions and results, national hydrogen programs/policies: USA, EU, Japan and roadmaps in those regions).

The information is based mainly on the following sources:

– The European Hydrogen and Fuel Cell Technology Platform: www.HFPeurope.org
– IEA Hydrogen Coordination Group, an incentive to bundle worldwide research providing a state-of-the-art overview on hydrogen research:
  "Hydrogen & Fuel Cells, Review of national R&D programs", IEA, Paris, 2004
– HySociety, a European project addressing political, societal and technical challenges for hydrogen, www.hysociety.net
– ESTO Study 'Trends in Vehicle and Fuel technologies', Vito, MERIT, OPTI and JRC-IPTS, Draft October 2002
– M. Altman, P. Schmidt, R. Wurster, M. Zerta, W. Zittel, 'Potential for hydrogen as a Fuel for transport in the Long Term (2020 – 2030) – Full Background Report', IPTS, EUR 21090 EN, March 2004
– 'Annex "Full Background report" to the GM Well-to-Wheel Analysis of Energy Use and Greenhouse Gas emissions of Advanced Fuel / Vehicle Systems – a European Study', LBST, 2002
– E. G. Padro, V. Putsche, 'Survey and Economics of Hydrogen Technologies', NREL/TP-570-27079, September 1999
– R. Edwards, J.-C. Griesemann, J.-F. Larivé and V. Mahieu, 'Well to wheels analysis of future automotive fuels and power trains in the EU context', January 2004, often called: "CONCAWE-study"

– A.D. Little, 'Energy Efficiency and Emissions of Transportation Fuel Chains', Phase I Technical Report to Ford Motor Company, February 1996.

The full description of the hydrogen and fuel cell technologies can be found in annex 1. It includes detailed information on hydrogen production technologies, on hydrogen storage and distribution as well as on hydrogen conversion and end use. The section on end-use describes the types of fuel cells, the hydrogen application in vehicles and in stationary systems.

The full description of foreign experiences are included as annex 2. It gives an overview of 15 demonstration projects and related projects, of hydrogen programs and policies in the USA, Europe, Japan, Germany, France and Canada, as well as the roadmaps in the USA, Europe and Japan.

The regulation has been published in the form of a website (www.podopadd.be.tf). This enables direct links to the sites of various standards and regulation.

While the effectiveness of hydrogen in terms of primary energy demand (efficiency), emission and costs depends on how it is produced and consumed, annex 3 gives an introduction on pathway analysis and infrastructure assessments as performed in the European HySociety project (in which political, societal and technical challenges for developing a European hydrogen economy have been addressed). This shows the efficiency of hydrogen from production up to use compared with conventional application.

Under 'results' we give in this chapter:
– A global overview of hydrogen and fuel cells technology. The concepts are described and guide numbers are given like the efficiency and the system size.
– An outline of demonstration programmes.
– An introduction into the website on regulation and an overview of the international standardisation organisations with their work related to hydrogen and fuel cells.
– A summary of hydrogen policies in the United States, Japan and Europe.

2.3 Results

2.3.1 Introduction to hydrogen and fuel cells

- **Properties of hydrogen**

Hydrogen (H_2) is the first element of the periodical system and is under normal conditions a colourless and odourless gas. Table 2-1 shows some characteristics of hydrogen in comparison to other fluids.

Firstly, hydrogen appears to be very light, over 14 times as light as air. This gives the advantage that hydrogen under release quickly rises, favouring safety items: it will not rest at the ground like LPG. The density of liquid hydrogen (71 g/l) is about 10 times less than the density of gasoline (720 g/l). The boiling point of hydrogen is very low: -252 °C or 20 K. Therefore, an intensive effort has to done to liquefy hydrogen and that in order to keep it liquid a number of technical measures has to be taken. For natural gas too the boiling point is low (-161 °C) but it is already 90 °C higher.

Hydrogen, with a low energy density, has a high energy content expressed in MJ/kg: 120 MJ/kg in comparison with methane 50 MJ/kg or gasoline 46 MJ/kg. Differently stating: 1 kg of hydrogen contains the same amount of energy as 2.4 kg of methane and 2.6 kg of gasoline. Comparing the energy-contents in function of volume, expressing it in MJ/Nm^3 (lower heating value), then the specific energy content is of course relatively low: 10.8 MJ/Nm^3. For methane it is 35.9 MJ/Nm^3.

Hydrogen has the reputation to be dangerous in comparison to, for example, natural gas (methane). The following numbers give some insight in this aspect. The limits between a mixture of hydrogen and air is flammable, covers a large range: from 4 to 72%. For methane this is 5 to 14%. In addition the energy needed for ignition (0.02 mJ) is 10 times less than for methane (0.29 mJ). However, it has to be kept in mind that a spark contains at least 1 mJ of energy, so, enough for both. The combination of low ignition energy and wide flammability ranges requires a number of specific demands for the selection of components in an installation.

Characteristic	Hydrogen	Remark/ reference
density of gaseous H_2	0.090 g/l	14 times as light as air
density liquid H_2	71 g/l	gasoline: 720 g/l
boiling point	-252 °C	methane: -161 °C
energy contents *	120 MJ/kg	methane: 50 MJ/kg
		gasoline: 46 MJ/l
	10.8 MJ/Nm3	methane: 36 MJ/Nm3
flammable mixture in	4.1 – 72.5 %	methane: 5.1 – 13.5 %
ignition energy	0.02 mJ	methane: 0.29 mJ

* on lower heating value

Table 2-1: characteristics of hydrogen, compared with other fluids.

- **Production of hydrogen**

Hydrogen in its free form does hardly exist in nature. Nevertheless worldwide around 500 billion Nm^3 of hydrogen is consumed annually. This means that companies are producing hydrogen over the world. Hydrogen is mainly produced by the following processes:
– electrolysis
– reforming
Other ways of production like bio-organisms, gasification of biomass, are under development.

Electrolysis
In case of electrolysis water is transformed into hydrogen and oxygen by an electrical current. This process is elementary and well known but energy intensive. Currently only some percentages of the worldwide hydrogen production is generated in this way. The environmental impact of hydrogen production by electrolysis depends on the type of electricity production needed for the process. If it stems from fossil fuels there will be emissions of environmentally polluting gases. If the electricity is produced from renewable energy, the hydrogen production is very clean.

An advantage of electrolysis is that the hydrogen and oxygen have a high purity. For electrolysers we can make a distinction between systems that produce hydrogen and oxygen under pressure (e.g. 30 bar) and those who produce them nearly at atmospheric pressure. A disadvantage is that electricity is an expensive energy resource, making this type of hydrogen also relatively expensive. In Oevel electrolysers are built for the Canadian company Hydrogenics.

Mainly two types of electrolysers exist: based on polymer electrolyte membrane (PEM) and based on an alkaline electrolyte. The latter is most common. This one either produce the hydrogen atmospherically or under pressure (typically 10 bar, 100 bar would be possible). The alkaline electrolyser is a bit more efficient than the PEM electrolyser: about 60% on the lower heating value, which will increase to 70% (LHV) in the future.

A note on efficiencies in general can be made. According to engineering's conventions efficiencies are expressed in 'lower heating value (LHV)'. It means that the reaction gases are in its vapour form. For hydrogen, with only water as reaction product, not taking into account the energy content of water vapour (by condensing it like in a condensing gas boiler) results into a loss of 15 %. This means that the maximum production efficiency for hydrogen is 85 % (LHV). A future's electrolyser with 70 % efficiency is close to this limit.

The purity of hydrogen made by electrolysis is between 99.9 and 99.999 %. Possibly drying and extra purification is necessary for using the hydrogen in combination with fuel cells.

Alkaline electrolysers are especially used for decentralised production with a typical flow rate of 100 Nm^3/h of hydrogen, consuming 500 kW of electricity. PEM electrolysers are generally at least ten times smaller.

In annex 1 tables are given with the efficiencies of electrolysers, their energy input and the greenhouse gas emissions, based on the power input.

Reforming

The major part of the hydrogen (> 95 %) is produced from fossil fuels by various types of reforming techniques. Reforming is a chemical process in which fuels in presence of steam and/or oxygen are transformed in a hydrogen rich mixture. The reforming technique mostly applied is steam reforming of natural gas. Here natural gas is brought together with steam at a temperature of 850 °C and a pressure of 25 bar. The hydrogen-rich gas that is formed, contains also CO and the hydrogen content is increased in following steps by the so-called water-gas shift reaction.

Important for Belgium is that at the site of BASF-Antwerp in October 2003 a hydrogen production facility of 100.000 Nm^3/h was opened by Air Liquide. It belongs to the biggest ones in the world.

Natural gas is reformed into hydrogen with help of water vapour and oxygen. In the ideal combination no heat is released neither absorbed:

$$CH_4 + 0.44\ O_2 + 1.12\ H_2O \leftrightarrow CO_2 + 3.12\ H_2$$

So, 1 mole of methane has the same calorific value as 3.12 mole of hydrogen (on higher heating value (condensed water)). This ideal reaction does not exist. The reforming reaction runs in two steps. First, a reforming reaction at high temperature producing hydrogen and CO, followed by a so-called gas-water shift reaction, transforming the CO with help of vapour into CO_2 and H_2:

$$CO + H_2O \leftrightarrow CO_2 + H_2 + \text{heat (41 kJ/mol)}$$

The equilibrium of this reaction is towards CO_2 at low temperature.

The reforming reaction can be carried out in three ways: with vapour (steam reforming), with oxygen (partial oxidation) or a combination (autothermal reaction). Almost only steam reforming is applied:

$$CH_4 + H_2O + \text{heat (206 kJ/mol)} \leftrightarrow CO + 3\ H_2$$

Combining this with the gas-water-shift reaction results into the overall balance:

$$CH_4 + 2\ H_2O + \text{heat (165 kJ/mol)} \leftrightarrow CO_2 + 4\ H_2$$

So, more hydrogen is formed than in the ideal reaction. This is compensated by the high heat input for the strongly endothermic reaction. While a mixture of hydrogen and carbon dioxide is formed (using natural gas instead of CH_4 also nitrogen and some by-products are formed), gas separation is necessary to obtain the hydrogen. The efficiency is around 75 % (LHV) resulting into 99.95 % pure hydrogen. Purer hydrogen can be achieved at the cost of the efficiency. A typical plant produces 100.000 Nm^3/h H_2 (300 MW (LHV)). Figure 2-1 gives an overview of the process.

Autothermal reforming, using a combination of water vapour and air is used for small-scale units. No external heat is required in this case, what is an advantage for small systems. The reaction results however in more by-products, lowering the efficiency. Partial oxidation, using only oxygen, is an exothermic reaction. So, heat is released at the expense of hydrogen formation. Also more by-products are formed. This pathway is used for higher carbonaceous fuels as gasoline, for which steam reforming is not possible.

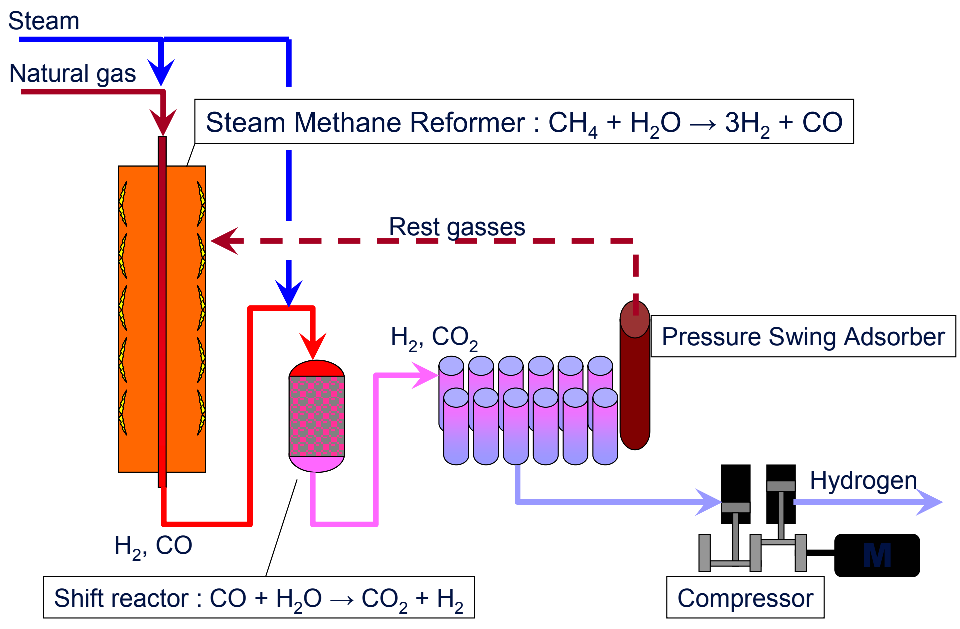


Figure 2-1: Overview of natural gas steam reforming (with thanks to Air Liquide).

It is not likely that large-scale reforming will change much in the future. New developments are on membrane reformers, separating the hydrogen already in the reactor, on small-scale reformers, also using lpg and ethanol as fuel, and on on-board reformers in vehicles, mainly for auxiliary power applications.

Annex 1 describes the different reforming pathways in more detail, it gives the several reaction equations for the reforming processes. Also tables are given with the efficiencies of reformers, their energy input and the greenhouse gas emissions.

Coal gasification and Integrated Gasification Combined Cycle

In the past 'town gas' was normal in cities. It was made by gasifying coal what resulted into a mixture of mainly hydrogen and CO that was directly distributed to the residential areas. This method is still an option for hydrogen, with an efficiency between 60 and 70%.

Nowadays coal gasification is used to generate electricity by burning the coal-derived gas in a turbine and using the heat in a steam turbine: This is the meaning of 'integrated gasification combined cycle'. A new concept is that this type of plants produces both electricity and hydrogen (separated from the coal-derived gas) while capturing and sequestrating the formed CO_2. In Europe and the United States pre-feasibility studies are performed under the name Hypogen and FutureGen respectively. Both regions want to realise this concept in the next 10 years. Not many literature[1,2,3] exists currently about it. The expected efficiencies are around 25% for the electricity and 28% for the hydrogen. Carbon capture and sequestration will lower the total efficiency with 5 %.

Hydrogen from biomass

To produce hydrogen from biomass there are mainly two routes: production of gaseous hydrogen via gasification of woody biomass (residual wood or cultivated) and steam reforming of biogas. In the case of steam reforming of biogas organic waste from households (including sewage sludge), catering and food industry is converted to biogas by fermentation. The gasification and the steam reforming are principally the same as described in the previous paragraphs.

Research is carried out to produce directly hydrogen gas from organic waste with help of bacteria and algae, but this is far from real-scale implementation.

Annex 1 gives the results of two studies on hydrogen from biomass.

- **Customers of hydrogen**

Although the use of hydrogen as an energy carrier sounds new, in the past 'town gas' was popular as an energy carrier. This town gas was produced in gasworks by thermal gasification of coal and contained up to 50% hydrogen (see the previous paragraph). Currently hydrogen is almost exclusively used as chemical base material. Worldwide half of the hydrogen is used for the production of ammonia (base material for fertilisers), some 40% is used within the petrochemical industry and the remaining 10% is used in the food industry (as fat hardener), for the production of methanol, the production of glass, …

The demand for hydrogen will increase, especially by the refineries. Hydrogen is here used for desulphurising the oil. The demand for sulphur-poor transport fuels and the use of heavier oil stimulates this raise. Hydrogen is used if a controlled atmosphere is necessary like in glass manufacturing, the treatment of steel and the production of semiconductors. If hydrogen breaks through as an energy carrier it can be used in many ways: in piston engines, turbines, fuel cells, …

- **Hydrogen storage**

Like shown in Table 2-1 the specific energy content of hydrogen in terms of volume (10.8 MJ/Nm^3) is relatively low. This makes storing hydrogen in a compact way an challenge. We can divide three options: gaseous, liquid and metal hydride storage.

Hydrogen is mostly stored as a compressed gas, classically in bottles at 200 bar. Also the first vehicle prototypes used this pressure. However, car industry is aiming nowadays at 700 bar. This results in R&D for materials to be used for these systems in a safe way. Bringing hydrogen up to 700 bar needs 15 % of its energy content.

Hydrogen can be stored and transported as a liquid below -252 °C. The work pressure is, however, low, some bars. Off course a small part will continuously evaporate ('boil-off'). Liquefying hydrogen and keeping it liquid demands high investment costs and results into energy losses. Liquefying hydrogen needs 40% of its energy content while 0.4 – 1 % is lost per day by the boil-off.

In a metal hydride, hydrogen is chemically bounded to metal atoms (often alloys of Mg, Ni, Fe and Ti are applied). During the forming of a hydride heat is released, while for releasing the hydrogen heat must be supplied. Although the specific hydrogen energy content in terms of MJ/l can be higher than for liquid and gaseous storage, in terms of weight it is much less. For vehicles the weight of metal hydrides is a problem and also the heat release (up to 500 kW) during refuelling in a few minutes. Less safety measures for escape in case of an accident are needed while the hydrogen is bonded in the metal hydride.

New developments for hydrogen storage can be mentioned by way of nanotubes and complex alloys in order to try to increase the energy density and to make the hydrogen release easier.

The annex gives the different types of cylinders for the storage an their specific weights, the costs of storage and other techniques for storage. Also a description of the refuelling infrastructure is given.

- **Distribution of hydrogen**

Within the industry hydrogen is transported by truck and train or distributed by pipelines. Belgium has a remarking situation. As a result of the large chemical industry a wide underground hydrogen gas grid exists in Belgium. It is run by Air Liquide Industries. The gas grid, about 800 km, stretches from North France via Belgium (from the coast to Liège) up to the Rotterdam harbour in the Netherlands. Figure 2-2 shows the network.

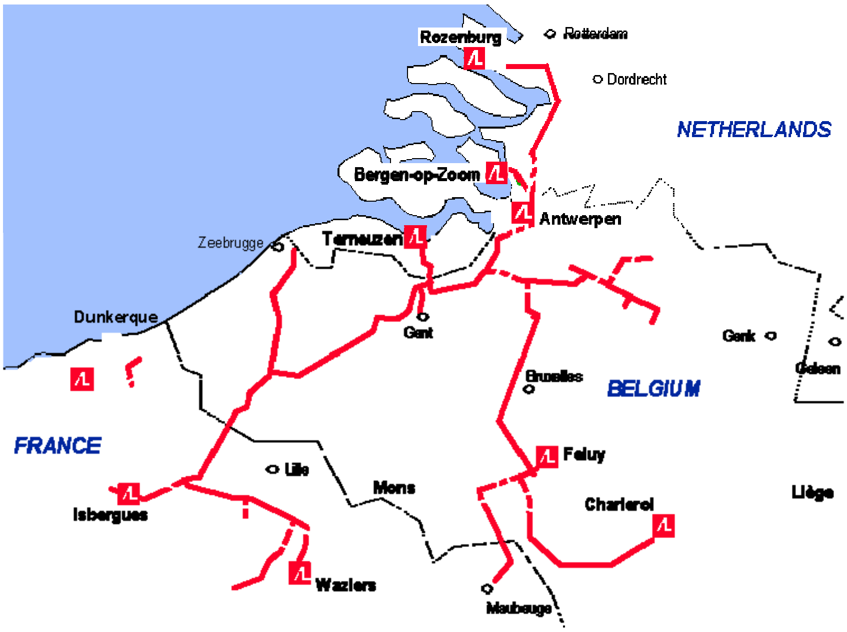


Figure 2-2: Underground hydrogen network of Air Liquide Industries in Belgium.

When hydrogen is distributed per truck it is done by a trailer loaded with gas bottles at 200 bar or by a super insulated cryostat trailer filled with liquid hydrogen. In both cases it is mostly steel that is moved. The truck with trailer can maximally weight 40 tons, of which only a bit more than 500 kg is hydrogen in case of gaseous hydrogen and somewhat more than 3000 kg in case of liquid hydrogen.

The annex gives more details about the pipeline network and the trailer distribution, including distances and costs.

- **Fuel cells**

Based on the availability of hydrogen, the use of hydrogen in fuel cells is interesting because of the potentially high efficiency compared to classical energy transformers.

Although it looks sometimes that fuel cells are a recent invention, this is not true. Sir William Grove discovered the fuel cell in 1837 (!). So, it is over one and a half century old. A fuel cell is an electrochemical system in which chemical energy is *directly* transformed into electricity. Figure 2-3 at the left shows the basic scheme of a fuel cell in which reactants (hydrogen and oxygen) are transformed into electricity, heat and water. The fuel cell itself consists of two electrodes (called anode and cathode) and an electrolyte. Figure 2-3 at the right depicts these components for a certain type of fuel cell. When oxygen is supplied at the cathode and hydrogen at the anode, naturally a voltage potential arises. At the anode oxidation of hydrogen occurs meaning that hydrogen molecules (H_2) are split into 2 ions (2 H^+ or protons) and 2 electrons. The protons move through the electrolyte (an ion conducting layer, that can be a solid membrane) towards the cathode, while the electrons move externally by the voltage potential to the cathode. At the cathode oxygen molecules are reduced into oxygen ions (O^{2-})

under reception of the electrons from the anode. The oxygen ions react with the hydrogen ions into water. In most of the fuel cells air is supplied at the cathode, of which only the oxygen is depleted. Looking at one cell, the resulting voltage is about 0.6 V at a current density of 400 mA/cm^2. To obtain 'useful' voltages and power, a number of cells are assembled together in series: a fuel cell stack. A stack of 50 cells with an active surface of 400 cm^2 per cell results into a power of 4.8 kW (30 V at 160 A).

- **Types of fuel cells**

Different types of fuel cells exist called after their electrolytes:
– AFC alkaline fuel cell: the electrolyte is a KOH solution
– PEM fuel cell: the electrolyte is a polymer membrane
– PAFC: the electrolyte is phosphoric acid
– SOFC: the electrolyte is a ceramic material
– MCFC: the electrolyte is a molten salt

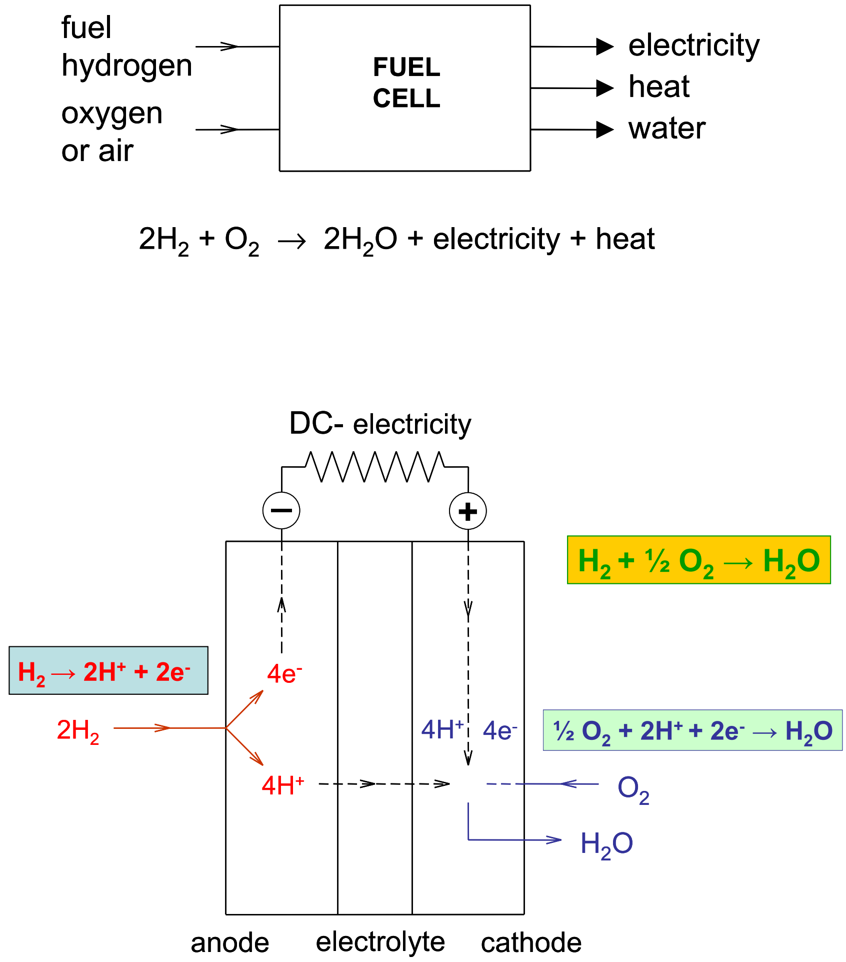


Figure 2-3: The basic scheme of a fuel cell and a specific example (PEM) showing the reactions.

Important in this enumeration is that the process temperatures are very different for each other resulting into consequences of the material technology and the application area, as will be illustrated later. The operation temperature for alkaline and PEM fuel cells is below 100 °C, mostly around 60-70 °C. The phosphoric acid PAFC fuel cell operates around 200 °C, while MCFC and SOFC function at much higher temperatures of 650 and 800 °C respectively.

Apart from the differences in temperature there are obvious variations in the reagents to be offered. For an alkaline fuel cell the air has to stripped from its CO_2, what is possible with nowadays technology. The PEM and PAFC fuel cell systems demand very pure hydrogen (especially for the PEM type some parts per million of CO is already disadvantageous). These fuel cell types can use conventional fuels as natural gas, but a reformer has to be connected in front. This reformer cracks the fuel into so-called reformate gas, containing a large part of hydrogen. High temperature fuel cells, SOFC and MCFC, have the benefit that classical fuels as natural gas can be directly supplied (internal reformation occurs). For MCFC this is the only way, it can not work on pure hydrogen while it needs CO_2, normally resulting from the reforming reaction.

Advantages

Fuel cells have the following benefits over classical prime movers as piston engines and turbines:

– high efficiency
– good partial load behaviour
– low emissions
– modular character
– low noise level
– few moving parts
– the heat produced can be used for cogeneration of heat and power

Due to its modular character the application range is very wide as will be described in the next paragraph.

In annex 1 a detailed description of each of the fuel cells is given including explanatory pictures and a comparative table.

- **Applications**

Above the different types of fuel cells have been described. In this paragraph we show their application. In the past fuel cells systems were mainly used in niche applications as aerospace and defence. Here performing systems could be used while the financial means were large. For large-scale application the range is wide. There are developments to replace the batteries in portable applications as laptops and mobile phones: fuel cells would result into a higher autonomy. It will take still a lot of effort to make them technologically and economically competitive with the current battery technology. Another important application area is the stationary power sector, discerning systems that produce electricity (mainly in the United States) and that cogenerate heat and power (CHP, mainly in Europe). Using a fuel cell for electricity production means often that the uncontrolled DC voltage output is transformed into stable AC electricity by means of power electronics. In case of CHP the heat released is used for space heating. Applying high temperature fuel cells the heat can be used also for steam generation. The third application domain is the transport sector where fuel cells can be the heart of vehicles with electric traction. Especially under the impulse of Californian legislation, car makers have built prototypes with fuel cells as driving force, both for cars and busses. In this segment mainly the PEM type of fuel cell is used with pure hydrogen. Figure 2-4 gives an overview in time for stationary and mobile applications.

In annex 1 a full description is given about applications. Vehicles are dealt with both on fuel cells as internal combustion engine with costs and efficiencies; the stationary applications are directed towards domestic applications, back-up power and industrial applications.

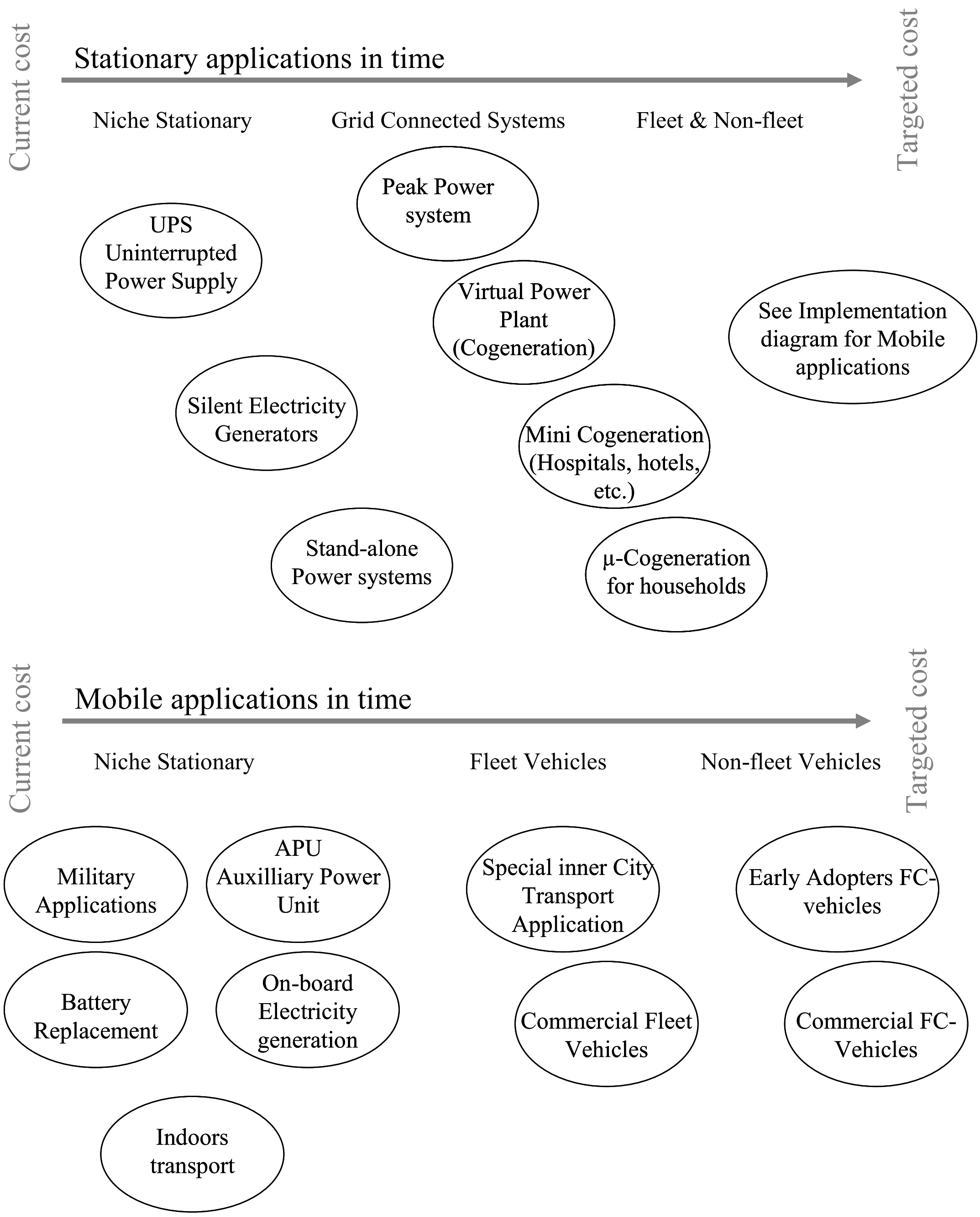


Figure 2-4: The applications for fuel cells as discerned in the HySociety study[4].

2.3.2 Demonstration projects

Since the beginning of the nineties research in fuel cells and hydrogen technology has been intensified, moving the accent from the academic area to industrial R&D. This reveals in prototypes that we can illustrate by some large-scale projects.

- **Stationary systems**

The American Department of Defense subsidized a project in which 30 American PAFC fuel cell systems including natural gas reformers of 200 $kW_{electric}$ are demonstrated in several army bases. In the mean time, a high number of working hours have been attained and a number of these systems has a high availability value. Problem is that the high investment cost has not been able to sink under 3500 €/$kW_{electric}$, making them economically less attractive.

Around 2000 a number of CHP systems based on Canadian PEM fuel cells with an electrical power of 200 kW have been tested in Europe and Japan. They were fuelled by natural gas and contained therefore a reformer. Such a system has been tested at the site of the university of Liège, proving that the efficiency is comparable to a classical gas piston engine. Being much more costly in this power segment, the development has been stopped. Nowadays most of the effort is directed towards systems with a power of less than 10 $kW_{electric}$. In this segment tests are done with alkaline, PEM and SOFC fuel cells. Recently a Flemish SME, E-Vision in Arendonk, built a CHP unit of 6 $kW_{electric}$ based on own alkaline technology. The module is already in its test stage (see Figure 2-5).

For systems with electrical power of several hundreds of kW the focus is on high temperature fuel cells (MCFC and SOFC). Most successful is the 200 $kW_{electric}$ MCFC system by the German MTU. It is tested currently at a dozen of locations. These systems reach an electrical efficiency over 46%: structurally higher than comparable gas engines. In future there are high expectations from SOFC technology in combination with gas turbines in the power segment of several MW, having a theoretical efficiency over 60%.

In Japan a stationary power demonstration project for residential housings started. In the first half of 2005 about 200 1 $kW_{electric}$ and 60°C hot water systems were installed at houses for combined heat and power (CHP). The systems come from different manufacturers like Ebara Ballard, Mitshubishi, Panasonic and Toyota. The units costs 10 M¥ (70,000 €) and are subsidized with 6 M¥ (40,000 €). The project continues up to 2007 installing new systems. Every year the subsidy lowers. The objective is to have a price of 1 to 2 M¥ in 2007.

Figure 2-5: A nowadays Belgian fuel cell system based on alkaline fuel cells of E-Vision.

- **Transport**

The demonstration projects that appeal mostly to the imagination are those with fuel cell vehicles. Every self-respecting car manufacturer has developed some prototypes and has them in a test programme. Only recently was thought that methanol would be an important fuel for fuel cell vehicles, but the tendency is towards hydrogen.

The most eye-catching project is the European CUTE-project: in 9 cities there are 3 busses each driving around with hydrogen and fuel cells on board. The fuel cell has a power of 200 $kW_{electric}$. The hydrogen is in every city generated in a different way (electrolysis, reforming, transport from a gas supplier,…) The project with a demonstration period of 2 years gives information about the state-of-the-art of fuel cell busses, but especially about regulations, approvals and permissions in the different cities. In chapter 5 this item is treated in detail. The project is extended so that the busses will drive around in 2006 as well.

In the United States, Japan and Canada currently large-scale demonstration programmes started with fleets of passenger cars coupled to the building of a hydrogen infrastructure. It is clear that in the transport sector the attention is not only directed to hydrogen cars but also to the development of infrastructure, including safety measures and logistics. To get an idea about the impact of hydrogen in the transport sector: if 5% of the European car fleet is replaced by hydrogen fuelled cars, the hydrogen needed equals 10% of the currently produced hydrogen worldwide.

Important is to stress that all fuel cell systems are in prototype stadium. The number of cars on the road increases every year, but with actual technology, regarding materials and systems, the cost price is too high to be commercially interesting. Also with the reliability and lifetime more experience must be obtained before guarantees can be given.

In annex 2 we are describing more than 10 demonstrations programmes in addition to those mentioned here. For Europe the transport vehicles at the München Airport are described, the cogeneration units of MTU and the virtual power plant project of Vaillant and PlugPower. For the United States the Californian Fuel Cell partnership is explained as well as the cogeneration units of Siemens-Westinghouse and the 75 fuel cell units at Long Island. In *addition to the above mentioned project in Japan, WE-NET is described and Japan Hydrogen & Fuel Cell Demonstration project.*

2.3.3 Regulation on hydrogen

- **Website**

The regulation has been published in this project in the form of a website (www.podopadd.be.tf). It contains direct links to the standardisation working groups and is in this way as exhaustive and up-to-date as possible. The website has a major split-up into:
– Code, Standard and Regulation on Hydrogen
– Permitting

The codes and standards part has been elaborated around a thematic classification:
1. Safety in general
2. Production/Product
3. Storage
4. Transport
5. Refuelling infrastructure
6. Use : Stationary
7. Use : Mobile
8. Use : Portable

This is represented by the first picture of Figure 2-6. The second picture shows the sub-classification and the division of standards in a standardised matrix. This discerns the EU, Belgium and international as geographic regions and makes a distinction between standards and regulation.

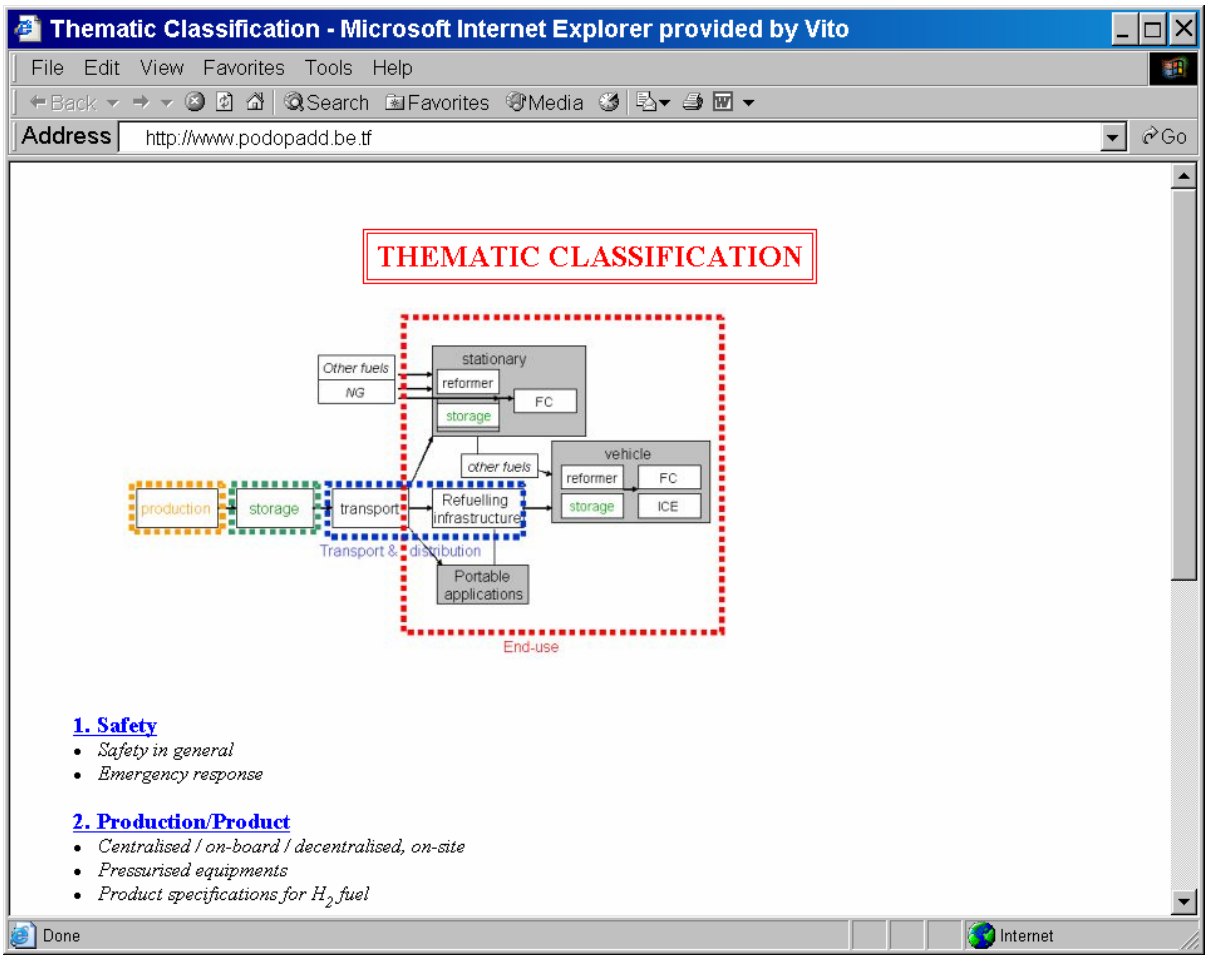
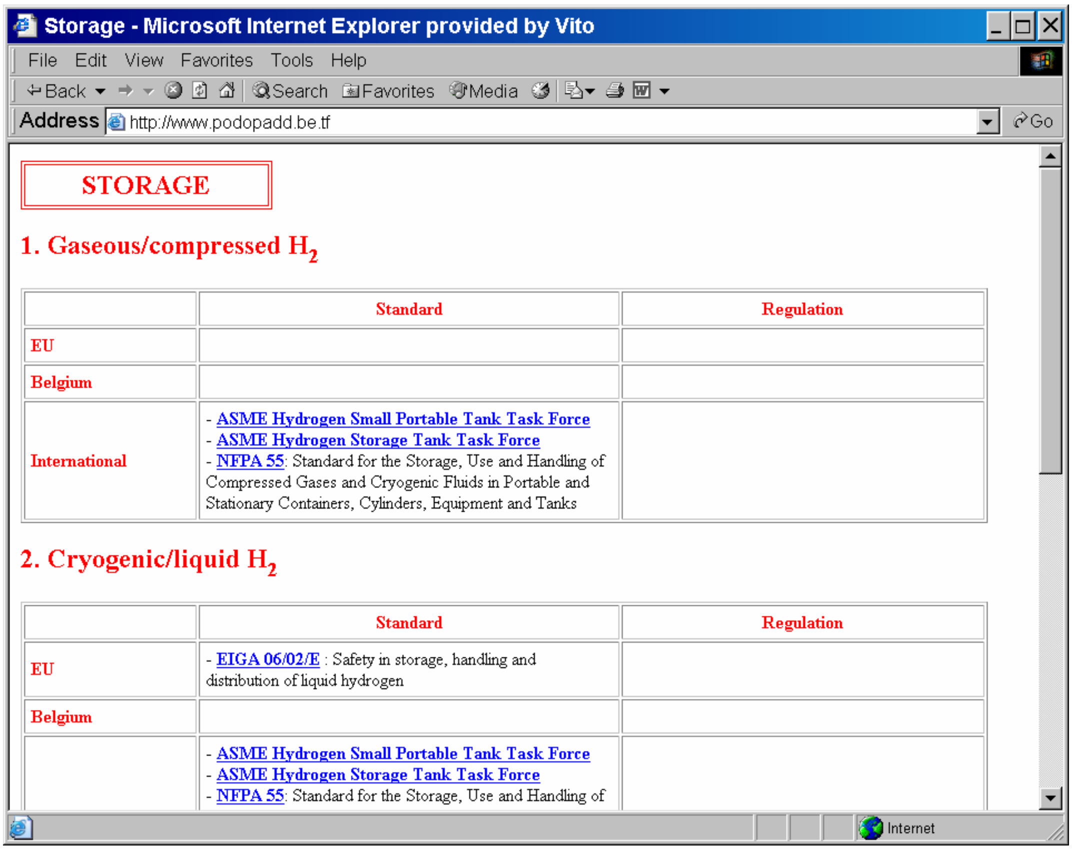


Figure 2-6 a: Screen shot of the web pages about regulation. It shows the thematic.


Storage - Microsoft Internet Explorer provided by Vito

File Edit View Favorites Tools Help

Address http://www.podopadd.be.tf

STORAGE

1. Gaseous/compressed H_2

	Standard	Regulation
EU		
Belgium		
International	- ASME Hydrogen Small Portable Tank Task Force - ASME Hydrogen Storage Tank Task Force - NFPA 55: Standard for the Storage, Use and Handling of Compressed Gases and Cryogenic Fluids in Portable and Stationary Containers, Cylinders, Equipment and Tanks	

2. Cryogenic/liquid H_2

	Standard	Regulation
EU	- EIGA 06/02/E : Safety in storage, handling and distribution of liquid hydrogen	
Belgium		
	- ASME Hydrogen Small Portable Tank Task Force - ASME Hydrogen Storage Tank Task Force - NFPA 55: Standard for the Storage, Use and Handling of	

Internet

Figure 2-6 b: Second screen shot of the web pages about regulation. It shows part of the standards for hydrogen storage.

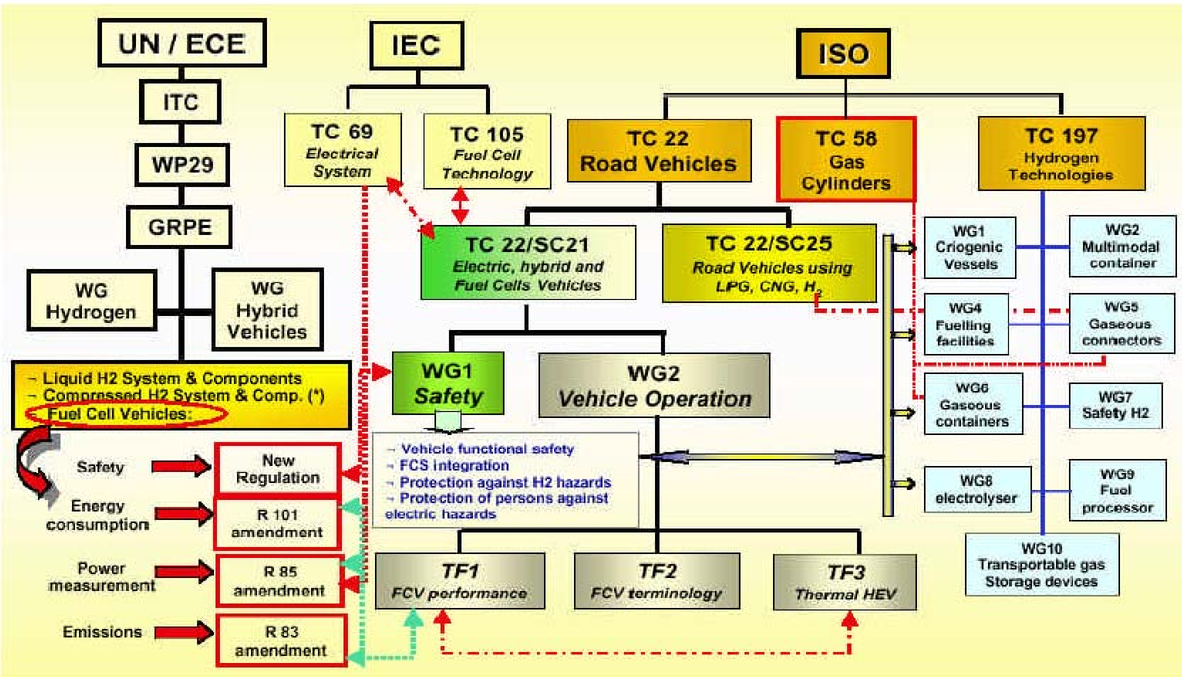


Figure 2-7: The international organisations working on standards and regulation for hydrogen and fuel cell applications.
The picture shows the working groups and their relationship.

- **International progress**

Figure 2-7 shows the international groups that work on standardisation for hydrogen and fuel cells. It shows also their relationship. The main organisations are UN/ECE, IEC and ISO. Their work is explained below.

The UN/ECE (United Nations Economic Commission for Europe) Transport Division formulates world-harmonised regulations for the type approval of vehicles. For hydrogen fuelled vehicles it started an ad hoc committee designated as UNECE/WP.29/GRPE *ad hoc working* group.

In this work the current situation is that although EU, Japan and USA are jointly and commonly working on this theme, they seem not to be able to agree yet on which kind of pathway they should follow. Specifically two proposals for a UNECE regulation on hydrogen vehicles have been proposed:

1. "Draft regulation on uniform provisions concerning the approval of
   - specific components of motor vehicles using compressed gaseous hydrogen
   - vehicles with regard to the installation of specific components for the use of compressed gaseous hydrogen"
2. "Draft regulation on uniform provisions concerning the approval of
   - specific components of motor vehicles using liquid hydrogen
   - vehicles with regard to the installation of specific components for the use of liquid hydrogen"

EU is promoting primarily the progress of work with the drafted ECE-R's for gaseous and liquid H_2 storage to a GTR (Global Technical Regulation), but neither U.S.A. nor Japan are willing to accept this at the moment. The regulation applies to the storage and the fuel system, excluding the propulsion system (ICE or Fuel cell) or any auxiliary power unit. Vehicles concerned are categories M (passenger transport) and N (goods transport), in practice cars, buses, vans and trucks. It is likely that the proposals will be implemented as European Directives. However there is no consensus yet on international level.

The fuel cell itself can be considered an electrical device since it generates electricity. This is why IEC (International Electrotechnical Commission) has been involved in its standardisation. Automotive applications on the other hand are covered by ISO (International Organization for Standardization), who considered the fuel cell system as a "black box" delivering electricity, to be compared with the battery on a battery-electric vehicle, and saw its job in the integration of the fuel cell into the vehicle. Therefore, a formal liaison between both committees (IEC TC105 and ISO TC22 SC21) as well as with the ISO committee specifically dealing with hydrogen (ISO TC197), was thus established.

IEC TC105 started its work on various aspects, grouped in 8 working groups (WG). The new standards on fuel cells to be drafted will form the IEC 62282 family of international standards, which comprises several parts. Part 2 deals with "fuel cell modules". This document intends to be the general standard for fuel cell modules, providing the minimum requirements for safety and performance of different types of fuel cell modules. As such the document is of course also relevant for automotive applications. Part 4 of IEC 62282 is aimed at performance, safety, electromagnetic compatibility (EMC), quality assurance and environmental aspects of fuel cell systems for propulsion and auxiliary power units in automotive applications.

ISO TC22 SC21 will deal with vehicle related aspects of fuel cell standardisation within in existing working group structure. WG 1 deals with "Vehicle operating conditions, safety and energy storage installation", and is thus also responsible for fuel cell vehicle safety. The standard will have 4 parts: (1) vehicle functional safety, (2) fuel cell system integration, (3) protection against hydrogen hazards, and (4), protection of persons against electrical hazards. WG 2 is working on performance standards and terminology.

ISO TC197 "Hydrogen technologies" is responsible for standardization in the field of systems and devices for the production, storage, transport, measurement and use of hydrogen. TC197 has established liaisons with several other TCs in ISO, such as TC58, which deals with "Gas Cylinders", but also with TC22 "Road Vehicles".
Up to now TC197 has produced two international standards: ISO 13984:1999 "Liquid hydrogen – Land vehicle fuelling system interface", and ISO 14687:1999 "Hydrogen fuel – Product specifications". TC197 has various running projects at various stages of evolution.

2.3.4 Foreign hydrogen experiences

Virtually all of the countries of the OECD reported investment in preparing policy studies[5]. In some cases, the policy work is detailed, setting out general goals and objectives for hydrogen and fuel cell work over the long run. In this chapter the main regions are reviewed indicating the major programmes and institutions.

- **Hydrogen Programs and policies in the United States**

Hydrogen Fuel Initiative
The President of the US has formulated several initiatives as part of his National Energy Policy, of which the Hydrogen Fuel Initiative is most explicit about hydrogen[6]. This initiative stems from the State of the Union in 2003 where it was announced that the United States will do research and develop infrastructure in order that a large number of Americans will choose for fuel cell vehicles by 2020. The initiative has to improve America's energy security by significantly reducing the need for imported oil. At the same time, it is a key component of the President's clean air and climate change strategies.

It builds on the FreedomCAR Partnership, launched in 2002 by the Energy Secretary, that is "a partnership with automakers to advance high-technology research needed to produce practical, affordable hydrogen fuel cell vehicles that American consumers will want to buy and drive". The President's Hydrogen Fuel Initiative and the FreedomCAR Partnership will develop, in parallel, technologies for hybrid components, fuel cells, and hydrogen production and distribution infrastructure needed to power fuel cell vehicles. The Hydrogen Fuel Initiative is sometimes also called FreedomFUEL.

To reduce the need for imported coal, the hydrogen has to come from renewables and nuclear energy as they offer the promise of zero emissions. With carbon capture and storage technologies, hydrogen production from America's abundant coal resources will also make a carbon emissions-free future possible. In this way the Hydrogen Fuel Initiative reduces the greenhouse gas emissions from transportation drastically. According to the initiative additional emissions reductions could be achieved by using fuel cells in other applications, such as generating electricity for residential or commercial uses.

The Department of Energy (DOE) published in March 2004 the Hydrogen Posture Plan in which it outlines the activities, milestones, and deliverables to support the shift to a hydrogen-based transportation energy system. The Posture Plan integrates research, development, and demonstration activities from the DOE renewable, nuclear, fossil, and science offices, and identifies milestones for technology development over the next decade, leading up to a commercialization decision by industry in 2015.

To fill in the Initiatives and the Posture Plan the Department of Energy launched the "Hydrogen, Fuel Cells and Infrastructure Technologies Program" that incorporates evaluation points through 2010. Success depends on fulfilling the following conditions (for the transport sector):

1. Hydrogen storage systems enabling a vehicle range more than 300 miles while meeting identified packaging, cost and performance requirements;
2. Hydrogen production to safely and efficiently deliver hydrogen to consumer at prices competitive to gasoline without adverse environmental impacts;
3. Fuel cells enabling engine cost less than $50 per kW while meeting performance and durability requirements.

Besides this programme it has set up an International Partnership for the Hydrogen Economy (IPHE) to connect international research.

International Partnership for the Hydrogen Economy

The IPHE is a partnership launched by the US Department of Energy[7,8]. The IPHE was signed in November 2003 by 15 countries and the European Union. Its goal is to efficiently organise, evaluate and coordinate multinational research, development and deployment programmes that advance the transition to a global hydrogen economy. Besides the RD&D it also provides a forum for advancing policies, and common codes and standards that can accelerate the cost-effective transition to a global hydrogen economy to enhance energy security and environmental protection.

Participants in the IPHE are: Australia, Brazil, Canada, China, European Commission, France, Germany, Iceland, India, Italy, Japan, Korea, Norway, Russia, United Kingdom, and United States.

The ultimate goal of the IPHE is to enable Partner countries' consumers to have by 2020 the practical option of purchasing a competitively priced hydrogen powered vehicle that can be refuelled conveniently. This goal can be realized by achieving the following benchmarks:

- Hydrogen powered vehicles are competitive with conventional vehicles.
- Hydrogen is safely and efficiently produced and delivered to consumers at prices and availability competitive with conventional fuels, without adverse environmental impacts.
- Fuelling and storage infrastructure enables ready access to fuel for hydrogen vehicles.
- Hydrogen fuel cells provide stationary and portable power.
- Storage technologies ensure hydrogen vehicle systems operate at the same levels of safety, performance and range as conventional vehicles.

– An internationally consistent system of safety codes and standards related to hydrogen utilization is developed and adopted.

- **Hydrogen Programs and policies in Japan**

Japan has high expectations of fuel cells[9,10]. It has few indigenous energy resources and very high energy import. For Japan hydrogen may offer an opportunity to achieve energy self-sufficiency. Japan has been an early leader in hydrogen and fuel cell technology development.

The Ministry of Economy, Trade and Industry (METI) is pushing forward hydrogen and fuel cell development by defining programmes and budgets. The important organisation is the New Energy and Industrial Technology Development Organization (NEDO). It is researching and developing hydrogen energy technologies in a joint industry-government-university effort, aiming at worldwide deployment by the year 2030.

In 1993 Japan launched the first major, national R&D programme on hydrogen and fuel cells. The METI has now launched the "New Hydrogen Project" for the commercialisation of hydrogen fuel cells in 2020. It integrates the development of fuel cells, hydrogen production, hydrogen transportation and storage technologies, together with demonstration programmes, vehicle sales, construction of refuelling infrastructure, establishment of codes and standards, and a general push to enlarge the consumer market for fuel cells and fuel cell vehicles.

- **Hydrogen Programs and policies in Europe**

Research and development on hydrogen at European level is mainly coordinated by the Directorate-General for Transport and Energy and the Directorate-General for Research. To get support and vision for their policies they launched a High Level Group on Hydrogen and Fuel Cells.

The reasons why Europe must work on developing and deploying hydrogen and fuel cell technologies are[11]:

– Sustainable Development – Hydrogen and electricity are expected to play an increasingly important role as interchangeable energy carriers in a future sustainable energy economy. Together they provide a promising transition pathway towards gradually becoming less dependent on fossil fuels, reducing greenhouse gas and pollutant emissions, and increasing the contribution of renewable energy sources. In the long term, hydrogen could play a key role in adapting energy supply to energy demand as it has the potential for large-scale, even seasonal, energy storage.

– Security and Reliability of Supply – The EU currently imports 50% of its coal, oil and gas; if nothing is done, this figure will rise to 70% in 20-30 years time. Hydrogen would open access to diversified primary energy sources and could therefore help us to reduce our dependence on imports of fossil fuels, thereby contributing to a dynamic and sustainable energy economy in Europe.

– International Competitiveness – Various market studies forecast that the potential market for hydrogen and fuel cell technologies in the future may be very large. At present the world leaders in the field are the US and Japan, where well financed, co-ordinated programmes to develop and market the necessary technologies are already in place. In contrast European hydrogen and fuel cell R&D is uncoordinated, under-funded and fragmented.

High Level Group on Hydrogen and Fuel Cells

The High Level Group on Hydrogen and Fuel Cells started on 10th October 2002[12]. It was launched by Vice President of the European Commission de Palacio, responsible for Energy and Transport, and Research Commissioner Busquin. The group is made up of 19 prominent stakeholders from a variety of backgrounds and from different countries, with the aim of formulating an integrated EU vision on the possible role that hydrogen and fuel cells could play in achieving sustainable energy. It will also address what would be required to achieve global leadership in this field in the next 20 to 30 years.

The first result of the group is a report "Hydrogen Energy and Fuel Cells - A vision of our future", supported by the Commission. The report aimed to capture a collective vision and agreed recommendations. It formulates five actions to a hydrogen energy future:

- A political framework that enables new technologies to gain market entry within the broader context of future transport and energy strategies and policies.
- A Strategic Research Agenda, at European level, guiding community and national programmes in a concerted way.
- A Deployment Strategy to move technology from the prototype stage through demonstration to commercialisation, by means of prestigious 'lighthouse' projects which would integrate stationary power and transport systems and form the backbone of a trans-European hydrogen infrastructure, enabling hydrogen vehicles to travel and refuel between Edinburgh and Athens, Lisbon and Helsinki.
- A European roadmap for hydrogen and fuel cells which guides the transition to a hydrogen future, considering options, and setting targets and decision points for research, demonstration, investment and commercialisation.
- A European Hydrogen and Fuel Cell Technology Partnership, steered by an Advisory Council, to provide advice, stimulate initiatives and monitor progress – as a means of guiding and implementing the above, based on consensus between stakeholders.

European Hydrogen and Fuel Cell Technology Platform

The European Commission has facilitated the establishment of a European Hydrogen and Fuel Cell Technology Platform aimed at accelerating the development and deployment of these key technologies in Europe[1]. The platform should assist in the efficient co-ordination of European, national, regional and local research, development and deployment programmes and initiatives and ensure a balanced and active participation of the major stakeholders (i.e. industry, scientific community, public authorities, users, civil society). It should help to develop awareness of fuel cell and hydrogen market opportunities and energy scenarios and foster future co-operation, both within the EU and at global scale. The technology platform and all its activities should contribute to an integrated strategy to accelerate the realisation of a sustainable hydrogen economy in Europe. Regular annual or bi-annual meetings of platform participants will ensure shared ownership and a common vision. In thus platform there is a Member State's Mirror Group, actively involving the EU Member States as regards furthering the European Research Area in hydrogen and fuel cells. This Group will aim to ensure closer coordination and co-operation between Member States, regional research programmes, high-level representatives within administrations of Member States and the platform.

Deployment Strategy

The European Hydrogen & Fuel Cell Platform prepared a strategy for developing and exploiting a hydrogen-oriented energy economy for the period up to 2050[13].For this purpose it developed an intermediate milestone: 'Snapshot 2020', it identified milestones for the Strategic Research Agenda for 2015 to enable a mass-market implementation in 2020 and proposed a Development Strategy.

The Snapshot 2020 is a target setting and coordination of the development of hydrogen and fuel cells. Figure 2-8 gives the deployment status for applications in 2020. It is expected that fuel cells in portable applications, especially in computers and in generators, will be an established market in 2020. The market for stationary fuel cells will be growing and road transport applications will be at the threshold of mass market implementation. To reach the targets a considerable cost reduction of the fuel cell system and a significant improvement in lifetime are needed.

The deployment strategy focuses on short-term (2010) actions. These include:

- 'Light-house Projects'
- Programmes for market introduction and cost reduction
- Regulation, codes and standards
- Policy framework to encourage hydrogen and fuel cell deployment
- Development of early niche markets.

The 'Light-house Projects' will be integrated research and demonstration projects towards commercialisation and the public framework (regulations and sustainability criteria). They have to be in line with carbon-lean energy sources. The Light-house Projects will be developed in certain pilot regions across the EU. The Light-house resemble at a proposal from the European Initiative for Growth: HYCOM & HYPOGEN. HYCOM will be pilot areas to demonstrate fuel cell applications, while HYPOGEN will be combined plants for electricity and hydrogen generation from fossil fuels (mainly coal and natural gas) with carbon capture and sequestration[14].

Key Assumptions on Hydrogen & Fuel Cell Applications for a 2020 Scenario[3]

	Portable Fuel Cells For handheld electronic devices	**Portable Generators & Early Markets**	**Stationary Fuel Cells** Combined Heat and Power (CHP)	**Road Transport**
EU H2/FC Units Sold per Year projection 2020	~ 250 million	~ 100,000 (~ 1 GW_e)	100,000 to 200,000 (2-4 GW_e)	0.4 million to 1,8 million
EU Cumulative Sales projections until 2020	n.a.	~ 600,000 (~ 6 GW_e)	400,000 to 800,000 (8-16 GW_e)	1- 5 million
EU Expected 2020 Market Status	**Established**	**Established**	**Growth**	**Mass market roll-out**
Average Power Fuel Cell System	15 W	10 kW	<100 kW (Micro CHP) >100 kW (industrial CHP)	80 kW
Fuel Cell System Cost Target[4]	1-2 €/ W	500 €/kW	2.000 €/kW (Micro CHP) 1.000-1.500 €/kW (industrial CHP)	< 100 €/kW (for 150.000 units per year)

[3] These projections are discussed in detail in the DS Foundation report.
[4] The primary reasons that automotive fuel cells are expected to be produced at a significantly lower cost than stationary fuel cells are discussed in detail in this Foundation report.

Figure 2-8: Deployment status for applications in 2020 according to the Deployment Strategy

For the Light-house Projects the Deployment Strategy steering panel gives the following recommendations:

– Focusing on a limited number of large-scale projects, primarily addressing transport applications, plus other relevant applications for maximum synergy
– In addition, establishing selected "hydrogen communities" with early markets and stationary fuel cell applications as the main driver
– Networking and co-ordinating activities in different regions and clusters in order to demonstrate and comprehensively benchmark "real world behaviour"
– Including appropriate existing demonstration sites that support the above targets and allow a quick start and expansion
– Fostering progressive growth and expansion to other European regions
– Designing appropriate financial mechanisms and instruments to facilitate this key development
– Building co-operation with complementary initiatives, such as the International Partnership for the Hydrogen Economy (IPHE).

The total of plans, from deployment strategy focuses on short-term, together with the foreseen market development and policy framework has been graphically represented as shown in Figure 2-9.

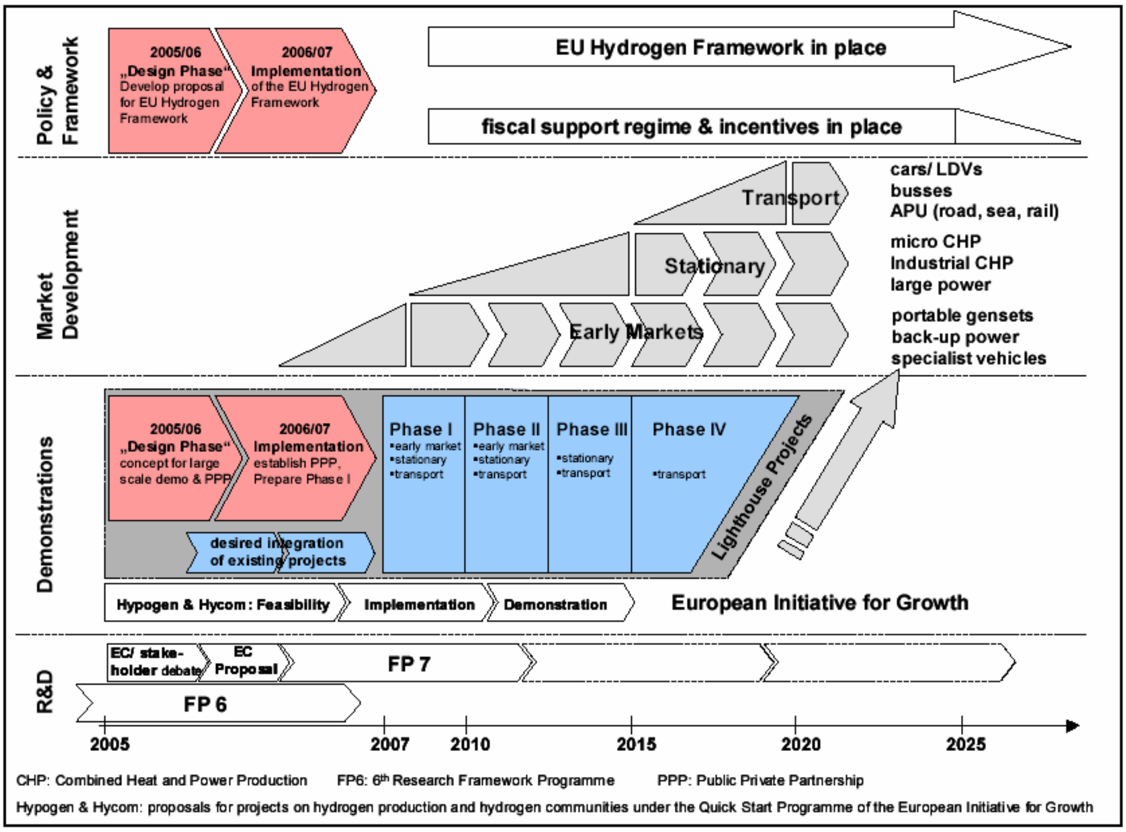


Figure 2-9: The schedule for the Deployment Strategy on Hydrogen & Fuel Cells.

Strategic Research Agenda

Together with the Deployment Strategy a Strategic Research Agenda has been defined by the European Hydrogen & Fuel Cell Platform (the cover is shown in Figure 2-10)[15]. The Strategic Research Agenda proposes an aligned, prioritised and benchmarked technology development plan for the period 2005- 2015 in line with the market penetration levels envisaged in 'Snapshot 2020' from the Deployment Strategy.

The long-term outlook is the basic motivation for the R&D initiative: "In 2050, oil will very likely no longer be cheap and, certainly, Europe's internal reserves will be exhausted. It is inferred from today's stock assessments that an increasing proportion of primary energy production will be drawn from CO_2 lean resources.
Hydrogen will be one of the three energy vectors, besides electric power and liquid biofuels. As it can be produced from a great variety of primary energies and consumed by an even greater variety of applications, it will form an energy hub – much like electric power today.
By 2050, hydrogen is expected to be widely available in industrial nations, at competitive cost. Indeed, it can realistically be expected to serve as a major transport fuel for vehicles, with a share of up to 50%."

The document touches all issues on hydrogen and fuel cells. For every aspect a research budget has been defined, benchmarks given and targets set up to 2015. Table 2-2 gives an overview of the research areas and the proposed budget shares. In the document each area has been worked out regarding actual status, benchmarks and research budget priorities.

Figure 2-10: Cover page of the "Strategic Research Agenda" from the European Hydrogen & Fuel Cell Technology Platform.

Table 1: Proposed Budget Shares for Hydrogen & Fuel Cell Targeted R&D

Research Area	Budget Share	Key Considerations
Transport applications	27%	Technologically crucial for environmentally friendly transport solutions and the driving force for fuel cell development
Hydrogen production	22%	Essential for the technological development of the entire sector. Increase of CO_2-lean production is targeted. Carbon capture and sequestration are of the essence, yet are expected to be covered within other European R&D programmes
Stationary applications	20%	Important for CO_2 reduction via highly efficient cogeneration. Provides an opportunity for early markets
Hydrogen storage & distribution	18%	Storage density is crucial for effective storage – particularly for transport and portable applications
Portable applications	10%	Important for early markets. Fit ever increasing market needs to fuel gadgets and small transport applications
Socio-economics	3%	Long-term guidance for technological development
Total Hydrogen & Fuel Cells	100%	

Table 2-2: Proposed budget shares in the Strategic Research Agenda for the different research areas.

2.4 Conclusions

Hydrogen is traditionally used by the chemical industry in Belgium. Using hydrogen as an energy vector is however new. The advantage of hydrogen as an energy vector is that it is clean (no greenhouse gases are formed at oxidation) and that it can be stored (this is an advantage over electricity).

Hydrogen in its free form does not just exist on earth. It has to be generated. However, it can be made from every primary energy source (section 2.3.1, annex 1). The main pathways for carbonaceous fuels are reforming (especially for natural gas) and gasification (in particular for coal) into hydrogen and carbon dioxide. Other energy sources like the sun and wind can be transformed into hydrogen by means of electrolysis. For electrolysis electricity is needed.
The property that hydrogen can be made from all sources makes it a versatile energy carrier able to help the security of energy supply. Hydrogen obtained from the pathway wind/sun – electricity – electrolysis – end use is free from GHG emission. The pathway natural gas – hydrogen – fuel cell car is more efficient than natural gas – internal combustion engine car (annex 3). If hydrogen production from fossil fuels is combined with carbon capture and sequestration the emission of greenhouse gases could be drastically reduced.

Based on the availability of hydrogen, the use of hydrogen in fuel cells is interesting because of the potentially high efficiency compared to classical energy transformers. There exists five types of fuel cells. High temperature fuel cells can also use natural gas or biogas directly as fuel.

An actual problem is the cost level of hydrogen production and fuel cells. An important explication is the small amount of fuel cells and hydrogen production units that are assembled per year. At the turning of the millennium governments started with demonstration projects, like the CUTE buses in 9 European cities (section 2.3.2, annex 2). This stimulates learning by doing. The scale will increase towards complete hydrogen regions. This is the way that automated assembly can start leading to lower costs.

For Europe the desired progress in hydrogen and fuel cells from demonstration programmes towards market introduction is described in the Deployment Strategy, made by the European Hydrogen and Fuel Cells Platform (section 2.3.4, annex 2). This strategy is assisted by a Strategic Research Agenda, filling in future performance and costs.

The demonstrations programmes lead to a demand for regulations. The three worldwide standardisation organisations – IEC, ISO and UN/ECE – have specific working groups for fuel cells and hydrogen (see section 2.3.2). They work in close connection. The countries make their own standards too and rules for permitting. An overview of all regulation and standards has been published in this project as a website with direct links to the organisations behind it: www.podopadd.be.tf.

2.5 References

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3 TECHNIC-ECONOMIC EVALUATION

3.1 Objective

It is the objective of this chapter to illustrate how the MARKAL-TIMES model can be used to evaluate the role of hydrogen in the Belgian energy system. On the basis of the output of work package 1, the hydrogen part of the MARKAL-TIMES database has been revised and completed. Data on hydrogen production technologies and on hydrogen applications in the transport sector have been added or updated. The purpose of this chapter is now to *illustrate* the use of the updated model and database with some scenario runs. It is important to keep in mind that these scenario runs are not based on any kind of concrete or planned policy decision.

Section 3.2 gives a short survey of the MARKAL-TIMES model and describes the scenarios that will be evaluated with the model. In section 3.3 we discuss the results. Section 3.3.1 gives an overview of some static cost calculations and section 3.3.2 discusses the simulation results. Section 3.3.3 then explains how the hydrogen is produced, while section 3.3.4 focuses on some sensitivity analysis exercises. Finally, section 3.4 concludes.

3.2 Methodology

3.2.1 The MARKAL-TIMES model

The MARKAL-TIMES model is well suited for the economic evaluation of energy scenarios as it captures energy flows from the stage of mining, production or import of primary energy sources up to the stage of the delivery of energy services to the demand sectors. The main energy transformation and energy use processes that lie in between this first and last stage are modeled in detail. Also, emissions of global and local pollutants, such as the greenhouse gasses CO_2, N_2O, CH_4 and more local pollutants like CO, NO_x, SO_2, VOC and particulates, all related to the use of energy, are included. In this chapter, the focus of the discussion will be on hydrogen and on the impact of using hydrogen on the emissions of CO_2.

The MARKAL-TIMES model incorporates a detailed database containing different existing and future types of technologies as they are or will be available in Belgium. The old database also contained a small number of hydrogen technologies. Each of these technologies is characterized by information on technical parameters (efficiency of the process, links between inputs and outputs, joint output ratios,...), capacity parameters (earliest investment date for new technologies, lifetime of the technology, maximum growth ratio or maximum capacity addition per period, residual installed capacity,...), cost parameters (investment cost per unit of capacity, fixed maintenance cost, variable costs, delivery costs,…), availability parameters (forced outage, maintenance etc.) and environmental characteristics (emission ratios per type of process used)[a].

[a] For a more detailed description of the MARKAL-TIMES model, we refer to Loulou, Goldstein et al. (2004)[1]. This document can be downloaded via the documentation link on www.etsap.org.

3.2.2 The scenarios

In order to evaluate the impact of a policy measure in terms of hydrogen usage, at least two scenarios should be simulated. The first scenario (the reference scenario) evaluates the role of hydrogen in the provision of energy services, taking into account *existing* energy policy measures (nuclear phase out, existing excise taxes,…) and constraints on emissions (GHG emission caps). This scenario takes as given the technological state of knowledge concerning hydrogen as it comes from work package 1.

The alternative scenarios start from the reference scenario but add an additional constraint or target to the model, such as, for example, a harsher post-Kyoto constraint. Such an additional constraint can have an impact on the use of hydrogen technologies but also on the use of many other technologies. For example, an emission reduction target can be achieved in many different ways, each with different cost implications. Usually this also implies that efforts are spread differently over the energy system. In general, when different efforts are required from different sectors and actors, there is a need for an instrument to evaluate the role of these sectors and technologies in a verifiable and consistent manner. The MARKAL-TIMES model is a valuable tool for such evaluations.

- **The reference scenario**

The base case scenario includes the (post)-Kyoto target and the nuclear phase-out decision. Clearly, there currently is no international agreement on a post-Kyoto target, but in the reference scenario it is assumed that an agreement will emerge. For 2050, a post-Kyoto target is set at – 22,5% relative to the 1990 emission level. The emission reduction effort is imposed linearly, i.e. in 2030 CO_2-equivalent emissions should be 15% below the 1990 level. The Kyoto target is imposed for 2010. In that year a reduction of CO_2-equivalent emissions with 7,5% relative to the 1990 level is to be achieved.

The nuclear phase-out decision states that new nuclear generation plants cannot be build any more. Existing plants can continue to operate until they reach the end of their lifetime.
Furthermore, in the context of this project the following additions or changes have been made to the database:

- Recent data on hydrogen production technologies have been added, both for already existing technologies, but also for new technologies. These data were collected and provided by VITO.
- The delivery costs of hydrogen have been reviewed and updated. These delivery costs contain the transport of hydrogen, either via pipelines or via trucks, liquefying, storage and the cost for refuelling.
- Some new carbon sequestration technologies have been added that might be combined with hydrogen production units.

It is also important to keep in mind that the focus of the model is on Belgium. The model assumes no international trade in electricity or in emission permits. This implies that measures to achieve the Kyoto target have to be taken domestically. No emission permits can be bought or sold abroad.

- **Scenario 1**

In scenario 1 we assume that the transport sector is required to reduce its CO_2-equivalent emissions with 40% relative to the emissions that occur in the transport sector in the reference scenario. This target is to be achieved for all periods from 2010 to 2050. For the country as a whole, the post-Kyoto target as defined in the reference scenario still applies.

- **Scenario 2**

In scenario 2, we assume a more stringent Post-Kyoto emission reduction target. The target is assumed to change linearly between 2010 and 2050. Emissions in 2030 should now be 30% lower than the emissions in 1990. In 2050 emissions should be 52,5% below the 1990 level. In the reference scenario, the post-Kyoto target for 2030 and 2050 was -15% and -22,5%, respectively.

3.3 Results

Before discussing the MARKAL-TIMES simulation results in section 3.3.2, we first focus on a static cost comparison of some hydrogen production technologies and of (hydrogen) vehicles. Having insight in these static cost numbers helps to understand the choices made by the MARKAL-TIMES model.

3.3.1 A static cost analysis

3.3.1.1 A comparison of end-user prices for H_2

In order to get a feeling for the relative costs of different hydrogen fuelled cars, we first discuss the static costs of these cars. With a static cost analysis, we look at a technology separately from other technologies. As an example, we calculate in Table 3-1 the cost per unit of output (output is measured in GJ or in vehicle-kilometer, depending on the technology) over the lifetime of the technology, taking into account investment costs, variable costs, efficiency and availability of the technology. The costs exclude taxes, subsidies and external cost. A 10% discount rate is used. Each column contains the levelised cost of a reforming unit that is installed in the indicated year, assuming that at the time of the investment all cost (future) elements can be locked in via for example long term contracts.

In Figure 3-1 a static comparison of the production costs for H_2 shows that large scale *coal gasification* and *reforming* have a competitive advantage over large scale electrolysis. Small scale production of hydrogen seems for the moment not to be competitive, even when the delivery costs are taken into account.

NG Reformer (large)	**2010**	**2020**	**2030**	**2040**	**2050**
Cost of Gas (€ per GJ)	4.085	4.458	5.395	5.503	5.614
Delivery of Gas (€ per GJ)	0.562	0.562	0.562	0.562	0.562
Investment cost (€ per GJ)	9.513	9.513	7.927	7.927	6.342
Fixed annual cost (€ per GJ)	0.476	0.476	0.396	0.396	0.317
Lifetime (years)	30	30	30	30	30
Output (per GJ input)	0.750	0.750	0.780	0.780	0.780
Availability factor	0.950	0.950	0.950	0.950	0.950
Annual variable cost (€ per GJ output)	6.196	6.693	7.637	7.776	7.917
Annual fixed cost (€ per GJ output)	1.563	1.563	1.302	1.302	1.042
Total cost (€ per GJ output)	7.759	8.256	8.939	9.078	8.959
Delivery cost (€ per GJ output)	6.728	6.728	6.728	6.728	6.728
Total cost H_2 (€ per GJ output)	**14.487**	**14.984**	**15.667**	**15.806**	**15.687**

Table 3-1: Static cost for a large scale reformer (€2000).

One can expect that delivery cost for decentralised (small scale) production of hydrogen will be (much) lower, when this production takes place 'on site'. The bars in Figure 3-1 all indicate cost figures including delivery costs. If small scale production units do not need to take account of delivery costs, then this component can be subtracted. The size of this delivery cost is also shown in Figure 3-1 with the green bar. It is clear from the figure that the larger production costs linked to decentralised production cannot be compensated by potential savings in delivery costs. Therefore, we have assumed for the simulations presented in this document that centralised and decentralised production (i.e. large scale and small scale production) of H_2 both involve a delivery cost as this makes the modelling of H_2 in MARKAL-TIMES somewhat simpler.

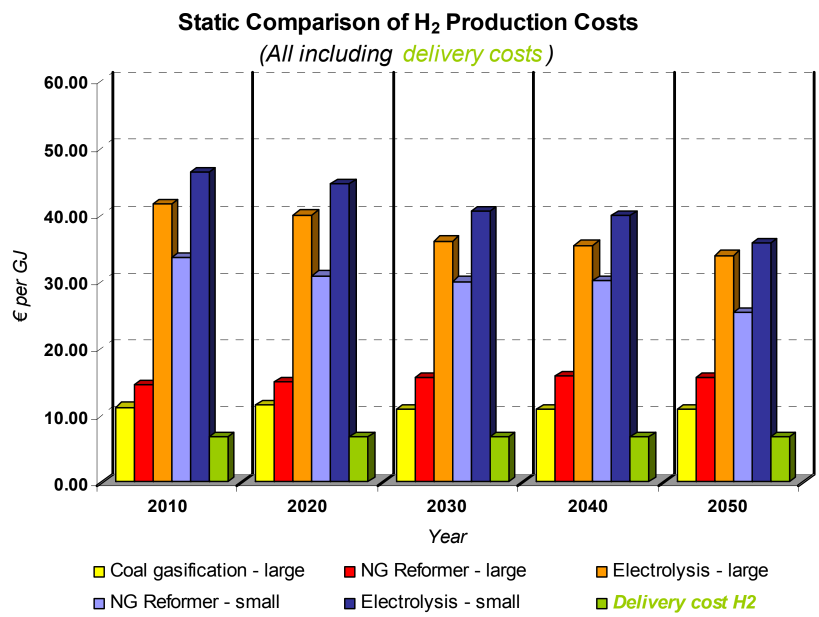

Figure 3-1: Static comparison of H_2 production costs.

3.3.1.2 A comparison of fuel costs excluding excise tax

In Figure 3-2, we show the fuel cost of hydrogen for two production technologies, large scale reforming and large scale gasification. As illustrated in section 3.3.1.1, these technologies are among the most competitive options for hydrogen production. Comparing fuel prices (including delivery costs and excluding taxes, subsidies and external costs) learns that in 2010, diesel, gasoline and hydrogen via gasification have comparable costs per GJ. The cost of electricity and hydrogen via reforming is significantly higher.

In contrast to the cost of the other fuel types, the unit cost of hydrogen produced with gasification is reducing over time. One of the main drivers for this result is the *relative* evolution of the primary fuel prices.
Note that all fuel costs are calculated *excluding* taxes, subsidies and external costs related to the use of these fuels. This is important to keep in mind when analysing the MARKAL-TIMES results. We also observe that the ranking of the fuels in terms of cost per GJ remains unchanged over time.

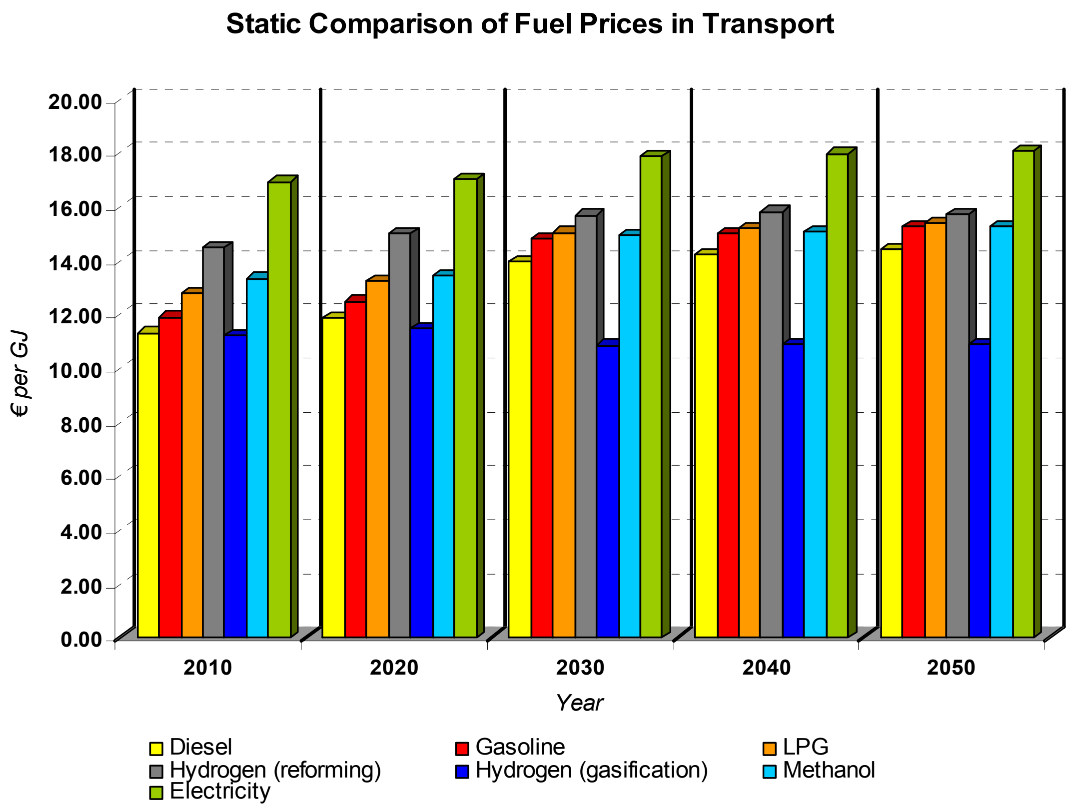

Figure 3-2: A static comparison of fuel prices in transport.

3.3.1.3 A comparison of static costs for vehicles

This section takes a closer look at the static costs of using hydrogen vehicles as they are described in the MARKAL-TIMES database. This model distinguishes short distance from long distance transport. Short distance implies that on an annual basis, each 'technology' produces about 13.832 vehicle-kilometers. Long distance implies a production of about 22.092 vehicle-kilometers. Long distance vehicles are assumed to have a better efficiency than short distance vehicles. Other vehicle parameters are assumed to be identical for both distances. These assumptions hold for all fuel type vehicles.

A static cost analysis for H_2 vehicles

Figure 3-3 contains information for both distances. For each period (horizontal axis) the first four bars indicate the per vehicle-km cost when the vehicle is used for short distance transport. The last four bars indicate the cost for long distance transport. On the basis of the previous assumptions, we can expect that the vehicle cost is lower for long distance vehicles, because the same investment outlay is spread over a larger number of kilometers.

In 2010, we see that for both distances the Hydrogen ICE car and the Hybrid ICE car have the lowest cost per vehicle-kilometer. The cost difference with the (hybrid) fuel cell car is very large. This latter observation only holds until 2020. From 2030 onwards, the (hybrid) fuel cell cars have a vehicle-kilometer cost that is comparable to that of the Hydrogen ICE cars. This latter evolution is due to the larger decrease in investment cost that is expected to occur in the segment of fuel cell vehicles.

The same evolutions also appear for the short distance cars. Until 2020 and per vehicle-kilometer, fuel cell cars are more expensive than Hydrogen ICE cars while the hybrid versions of each technology are somewhat more expensive than the non-hybrid ones.
Once again, note that these static costs do not reflect taxes, subsidies or external costs.

Making the same analysis for buses (Figure 3-4) shows that fuel cell buses are more expensive per vehicle-kilometer than the Hydrogen ICE buses. For buses, the difference in per vehicle-km costs for urban and intercity buses is due to the larger fuel efficiency of the intercity buses. Both the urban and the intercity buses are assumed to produce 23.209 km per year.
The cost difference decreases over time because of the larger economies of scale that are expected for the production of fuel cell buses.

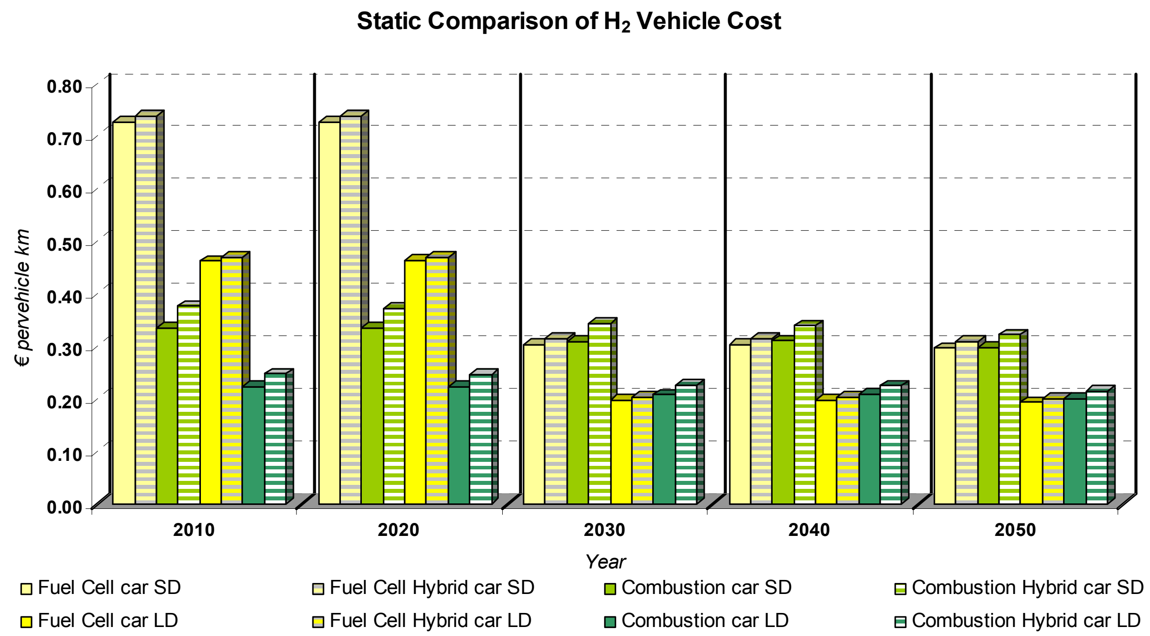

Figure 3-3: A static cost comparison of H_2 vehicles for short and long distance.

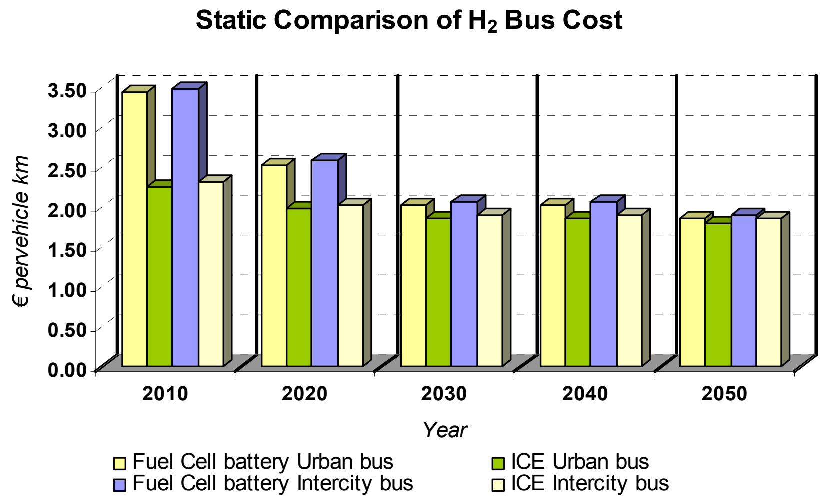

Figure 3-4: A static cost comparison of H_2 buses for urban and intercity transport.

A static cost analysis of vehicles of different fuel type

Figure 3-5 shows a comparison of the short distance vehicle-kilometer cost for a *(hybrid) fuel cell car*, a (*hybrid) hydrogen ICE car*, a *euro 4 diesel car* and a *euro 4 (hybrid) gasoline car*. It is clear that the diesel as well as the gasoline car performs better than the hydrogen cars in terms of vehicle-kilometer costs, although the difference reduces over time. The latter evolution is due to assumed economies of scale that will occur in the production of hydrogen cars.

Also note that gasoline cars have a lower per vehicle-km cost (net of taxes, subsidies and external costs) than diesel cars.

The same type of evolution can be observed for the long distance cars (Figure 3-6). Here, the per vehicle-km cost of the LPG car has also been included.

These static cost results will now be used in the following section when we explain the MARKAL-TIMES simulation results.

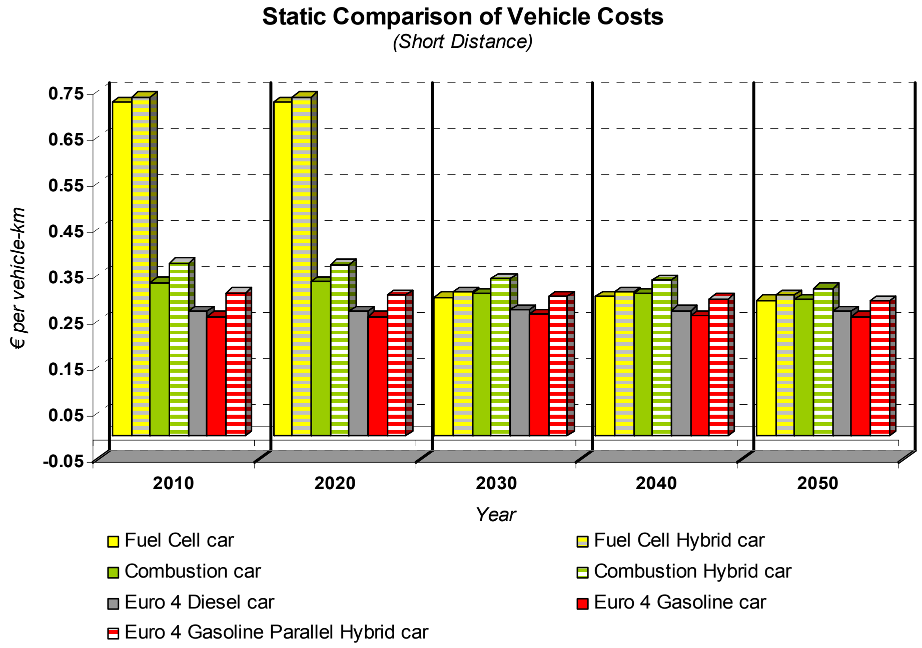

Figure 3-5: A static cost comparison of short distance vehicles for different fuel types.

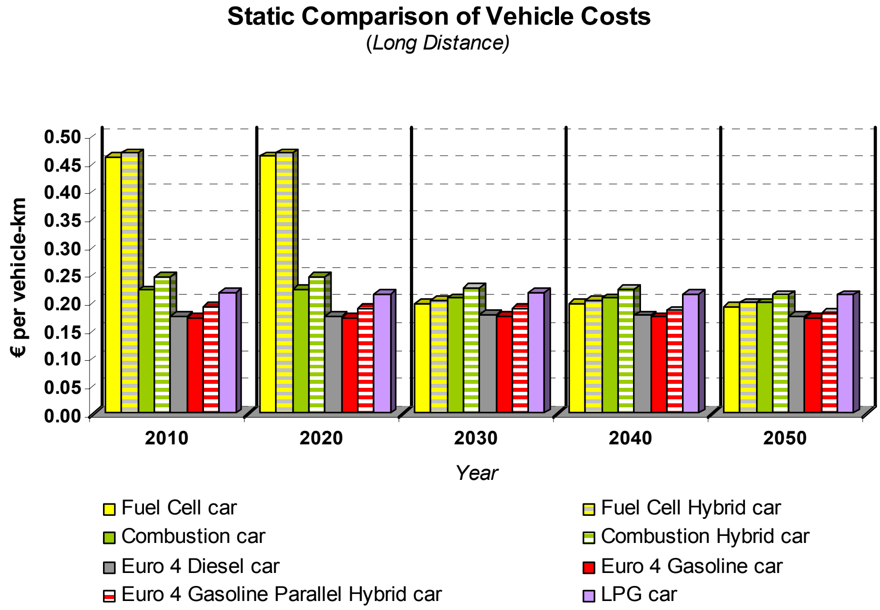

Figure 3-6: A static cost comparison of long distance vehicles for different fuel types.

3.3.2 The scenarios

The scenarios that will be discussed in this section are described in section 3.2.2. The discussion will focus on the evolution of the market shares of the different vehicle types. We will distinguish short-distance and long-distance transport and output in each market is measured by the number of vehicle-km produced. Section 3.3.2.1 concentrates on car transport. Section 3.3.2.2 focuses on buses. The results will as much as possible be explained by referring to the static costs calculations that were discussed in the previous section.

3.3.2.1 Car transport

Figure 3-7 and Figure 3-8 summarize the results for the three simulation runs that have been made. The left part of each figure presents the results for the reference case, the middle part for scenario 1 (additional emission constraint for the transport sector) and the right hand part for scenario 2 (harsher post-Kyoto). Figure 3-7 shows the results for the short distance segment, Figure 3-8 for the long distance segment.

In both figures, the red colored bars indicate gasoline fuelled cars, green and yellow bars indicate hydrogen fuelled cars. Green bars represent hydrogen combustion cars, yellow bars represent hydrogen fuel cell cars. Striped bars indicate the hybrid version of the car type of the same main color.

Note that the figures in this report show results with a 5 year interval, except for the period 2030-2050, where a 10-year interval is used.

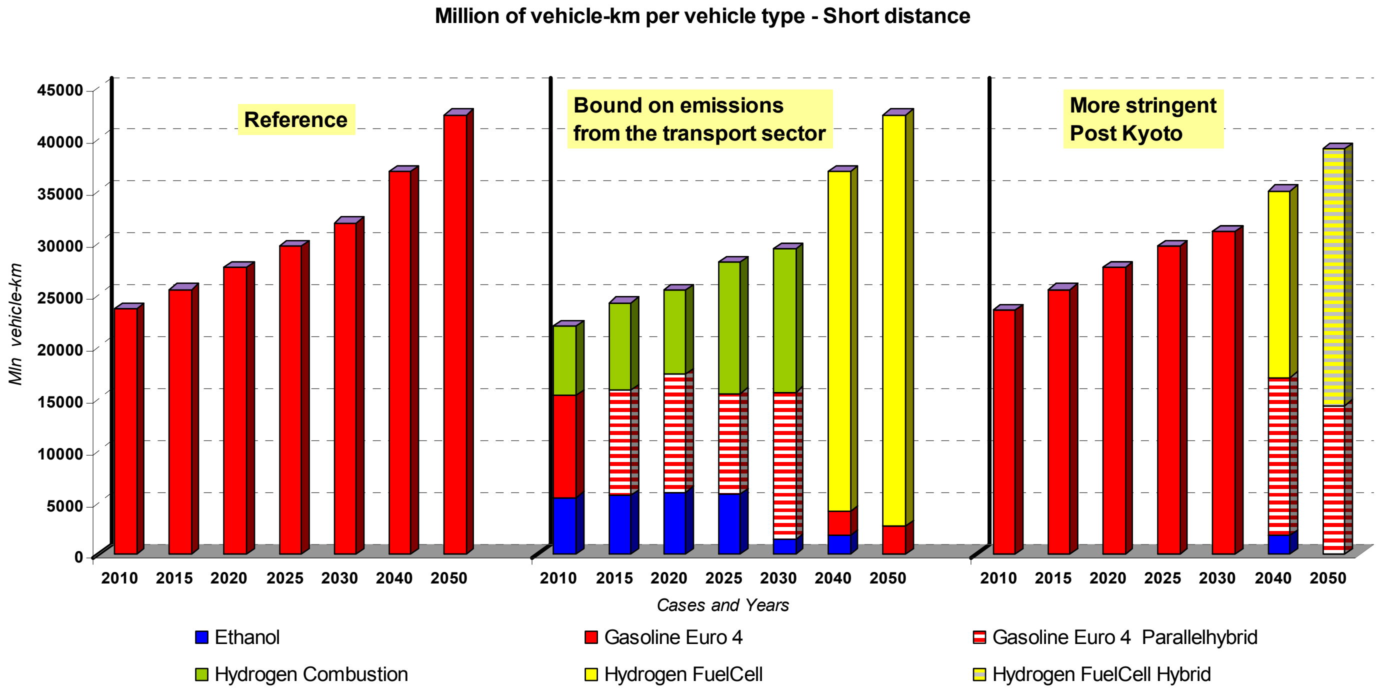

Figure 3-7: Number of vehicles – short distance.

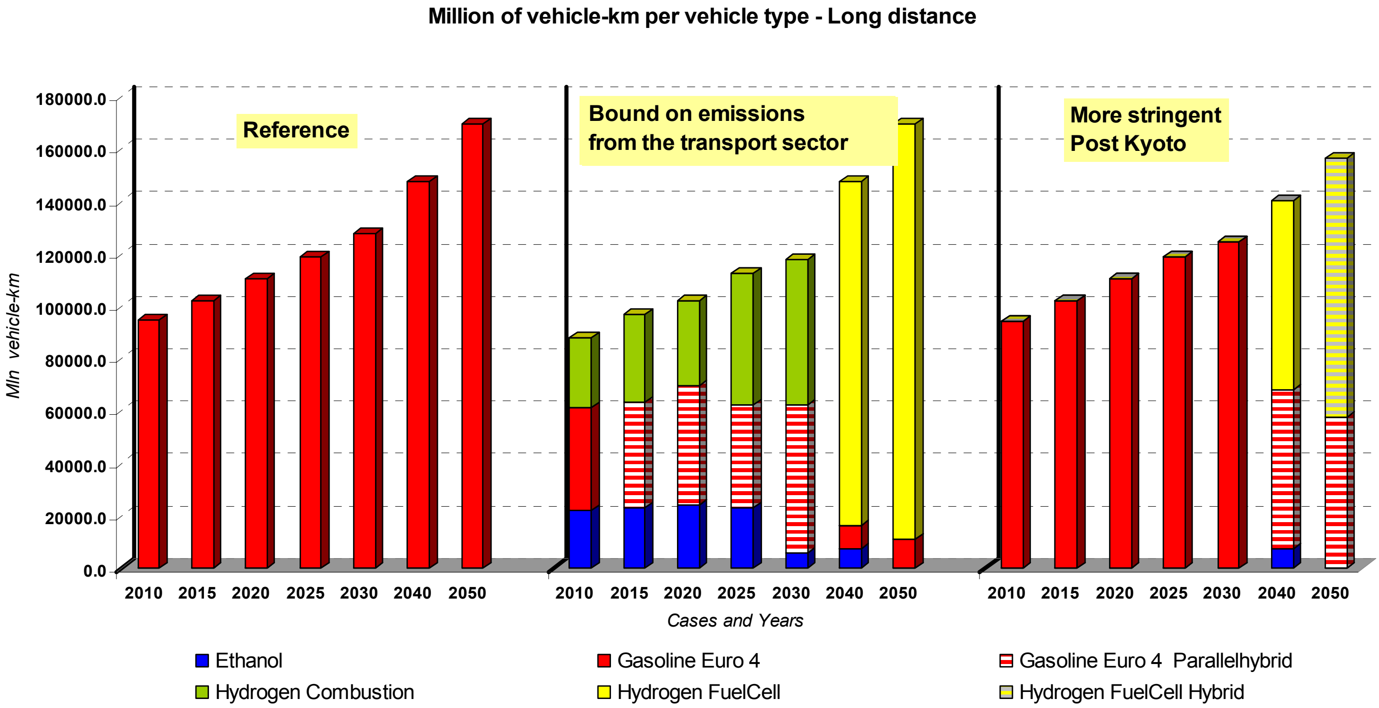

Figure 3-8: Number of vehicles – long distance.

- **The reference scenario**

In the reference scenario, hydrogen cars do not enter the market before 2050. In this scenario, we only find gasoline cars in the market[b]. This finding holds for the short as well as for the long distance market segment and the result can be explained by looking at the static cost figures that are shown in Figure 3-5 and Figure 3-6. Some of the numbers behind these figures are summarised in Table 3-2.

	Short distance			Long distance		
	2030	**2040**	**2050**	**2030**	**2040**	**2050**
Diesel Euro 4	0.275	0.273	0.271	0.177	0.176	0.175
Gasoline Euro 4	***0.263***	***0.262***	***0.260***	***0.175***	***0.173***	***0.172***
Gasoline Parallel Hybrid	0.304	0.299	0.293	0.188	0.185	0.181
LPG				0.217	0.215	0.213
Fuel cell	0.302	0.302	0.295	0.197	0.197	0.193
Hybrid fuel cell	0.314	0.314	0.308	0.203	0.203	0.199
ICE	0.309	0.310	0.296	0.207	0.208	0.199
Hybrid ICE	0.342	0.338	0.321	0.226	0.224	0.213

Table 3-2: A selection of static costs for hydrogen vehicles (€ per vehicle-km).

Comparing the static costs of cars reveals that for all future periods and for both distance markets, the gasoline fueled car has a cost advantage. This explains why the MARKAL-

[b] Note that in the simulations a societal point of view is taken, implying that taxes and subsidies are not taken into account. This explains why we do not find diesel cars in the solution for the reference scenario.

TIMES model advances the gasoline fuelled car as the best option for all future periods and markets.

In 2030, the hydrogen combustion (ICE) engines have a clear cost advantage on fuel cell cars in the short as well as in the long distance segment. For that year, the *hybrid* combustion type enters the market, because of its better environmental characteristics (i.e. fewer emissions per vehicle-kilometer) that compensate for the small cost disadvantage relative to the ordinary combustion cars.

In 2030, this cost advantage for combustion cars has almost fully disappeared. Now the fuel cell cars gain market share because their small remaining cost disadvantage (in the short distance market) is more than compensated by the relative environmental benefits of the fuel cell technology.

In the reference scenario the CO_2 reduction is realized mostly by industry and the electricity sector.

- **Scenario 1 – Harsher CO_2-target for the transport sector**

This first alternative scenario considers the effect on the market penetration of hydrogen cars when a harsher CO_2-emission reduction target is imposed *in the transport sector*. It is assumed that emissions in this sector must be reduced with 40% relative to the emissions level of the transport sector in the reference case. Figure 3-9 shows the required additional effort that is needed.

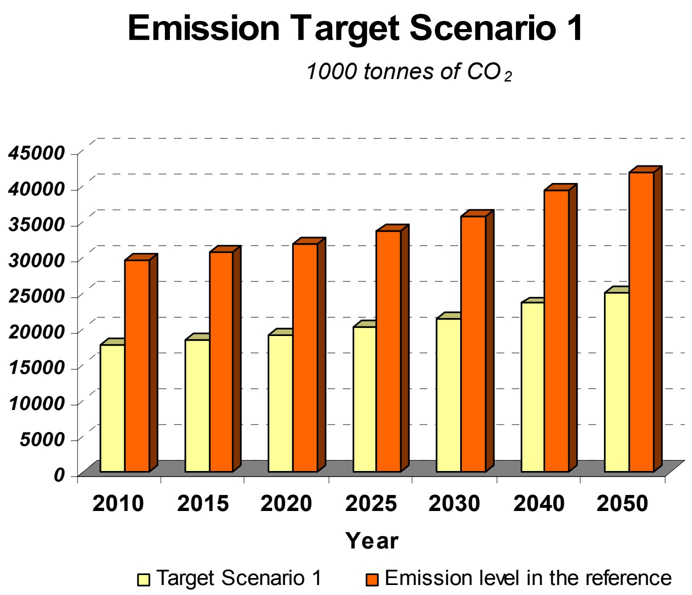

Figure 3-9: A harsher CO_2-emission reduction target for the transport sector.

General assessment of the effects

In the reference scenario, emission reduction efforts are made in a cost effective way, i.e. marginal abatement costs are equalised over all sectors in the energy system. This is a condition that will necessarily be satisfied when the cost of achieving the (post)-Kyoto targets is minimised[c]. By imposing an emission reduction constraint on the transport sector that goes beyond the 'reference-case' emissions of that sector, one will necessarily increase the cost of achieving the (post)-Kyoto emission reduction target. This harsher emission reduction target for the transport sector implies that emission reduction efforts are made in that sector even if these emission reductions can be achieved at a lower cost in other sectors.

Also note that, for the energy system as a whole, the Kyoto constraint still applies in scenario 1. Thus, the additional emission reduction efforts required from the transport sector create room for the non-transport sectors to increase their emissions. From the point of view of the country, emissions will not be lower than the emissions that we have in the reference scenario. Only the *distribution* of emissions over the different sectors will change.

Effects on the transport sector
First, it should be noted that looking at Figure 3-7 and Figure 3-8 reveals that in both markets the same technologies appear with the same market shares. This is due to the MARKAL-TIMES assumption that one car is used to produce short distance as well as long distance transport[d]. However, the output produced in both markets is different, which can easily be seen by looking at the scale of the vertical axis. For that reason, we will, in the discussion that follows, not make the distinction between short and long distance.

In order to reduce emissions in the transport sector, investments in that sector will need to shift from CO_2 emitting technologies to less or even zero-emitting technologies. Several options are available to achieve this and, according to our results, investing in hydrogen combustion, ethanol and gasoline parallel hybrid fueled cars will provide the major contribution to the reduction of CO_2 emissions. In the available list of options, these are indeed the cheapest ones (see static cost analysis).

In 2040, we see the fuel cell car entering the market. This result can be explained as follows. Scenario 1 imposes an additional constraint on the transport sector. The model solves for the cheapest way to satisfy the demand for transport services, given the set of available technologies and the constraints on emissions. The demand for transport services is expressed in vehicle-kilometers and thus the cost per vehicle-kilometer will play an important role in the choices made by the model. In section 3.3.1.3 these costs were discussed and it was observed that the hydrogen combustion car has a lower cost per km than the fuel cell cars. Therefore, combustion cars are selected from 2010 onwards. In 2040 the cost difference with the fuel cell car reduced sufficiently for the latter to enter the market.

Finally, note that the fuel efficiency of fuel cell cars, expressed in kilometers per GJ of hydrogen input, is almost twice the fuel efficiency of hydrogen combustion cars. This observation is important to understand the difference with the results under scenario 2.

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[c] Note that the MARKAL-TIMES model assumes that emission reduction efforts are made domestically. It does not consider the possibility of emission trading, clean development or joint implementation. Allowing for international trade in emission permits would allow marginal abatement costs to be equalised for all participating countries. This would ensure that the aggregate cost for these countries to achieve their aggregate emission reduction target is minimised.

[d] In the old MARKAL model, different cars were used to produce short distance and long distance transport services. This would then typically result in different market shares for the different technologies.

- **Scenario 2 – Harsher Post-Kyoto target for Belgium**

In scenario 2, we assume a harsher post-Kyoto constraint than the one imposed in the reference case. In the latter, it is assumed that in 2030 (2050) emissions must be reduced to a level that is 15% (22,5%) below the 1990 emission level. Scenario 2 now assumes that in 2030 (2050) emissions must be at 30% (52,5%) below the emissions in 1990. The required emission reduction efforts increase linearly between 2010 and 2050. Figure 3-10 shows the constraints graphically.

This emission reduction is imposed 'globally', i.e. it applies to the global Belgian energy system. Because of the latter feature, it is possible to reach the emission reduction target in a cost efficient way (at the country level), i.e. the marginal abatement costs will be equalised over all sectors[e].

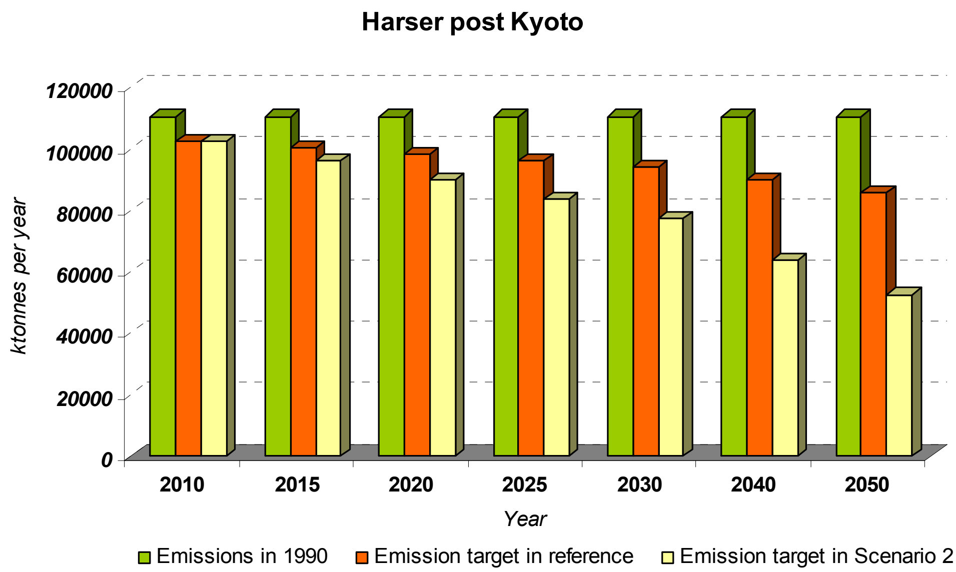


Figure 3-10: The emission reduction target in scenario 2.

Effects on the transport sector

The results for scenario 2 are similar to the results for the reference case up to 2030. Then a large number of fuel cell cars enter and hybrid gasoline cars enter at the expense of gasoline cars. A small market share is also reserved for ethanol cars. The fuel cell cars only stay in the market for about 10 years. Then they are replaced by hybrid fuel cell cars.

By 2040, the static costs of the fuel cell cars is lower than that of the hydrogen combustion cars (see Figure 3-6). It is therefore quite obvious that the fuel cell car is preferred to the hydrogen combustion car.

An additional effect, less present in the other scenarios, is due to the difference in fuel efficiency of the hydrogen car types and the shadow costs coming from the emission constraints. As indicated before, the fuel cell car has a larger fuel efficiency, which means that

[e] Keeping in mind the qualification in footnoteC.

less hydrogen is needed to drive a given number of kilometers. The sector producing the hydrogen is now also subject to a harsher post-Kyoto constraint and, therefore, the shadow cost of hydrogen will also include a component reflecting the shadow cost of CO_2-emissions related to the use of the car. This provides an additional incentive to car users to buy fuel cell cars.

In section 3.3.4 we will show and discuss some sensitivity analysis results with respect to the investment cost. These will probably also shed some light on the robustness of the results for some changed assumptions.

3.3.2.2 Bus transport

If asked, most hydrogen experts would predict that the first hydrogen applications with a significant market share would be found in the bus transport sector. This prediction is not confirmed by the simulations; on the contrary. Until 2050 we see no hydrogen buses entering the market, as can be seen in Figure 3-11. Diesel and Electric Trolleys for urban bus transport dominate the market in all three scenarios. Essentially, the bus sector is not influenced by either a harsher post Kyoto constraint or a harsher emission constraint on the transport sector.

Figure 3-12 provides an explanation for this result. The per bus-kilometer cost of using a hydrogen fuelled bus is about two times as high as the same type of cost for a diesel bus or an Electric trolley bus. Hydrogen will remain the most expensive option until 2050.

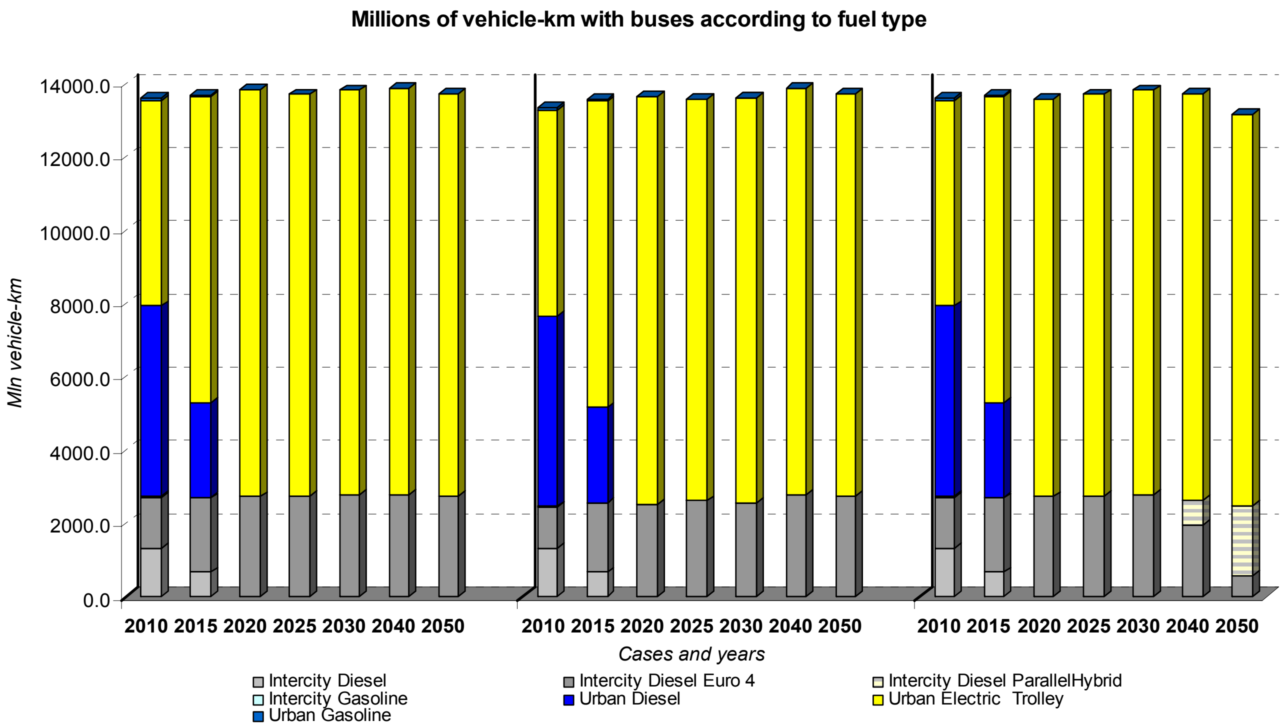


Figure 3-11: Millions of vehicle-km in the market for bus transport.

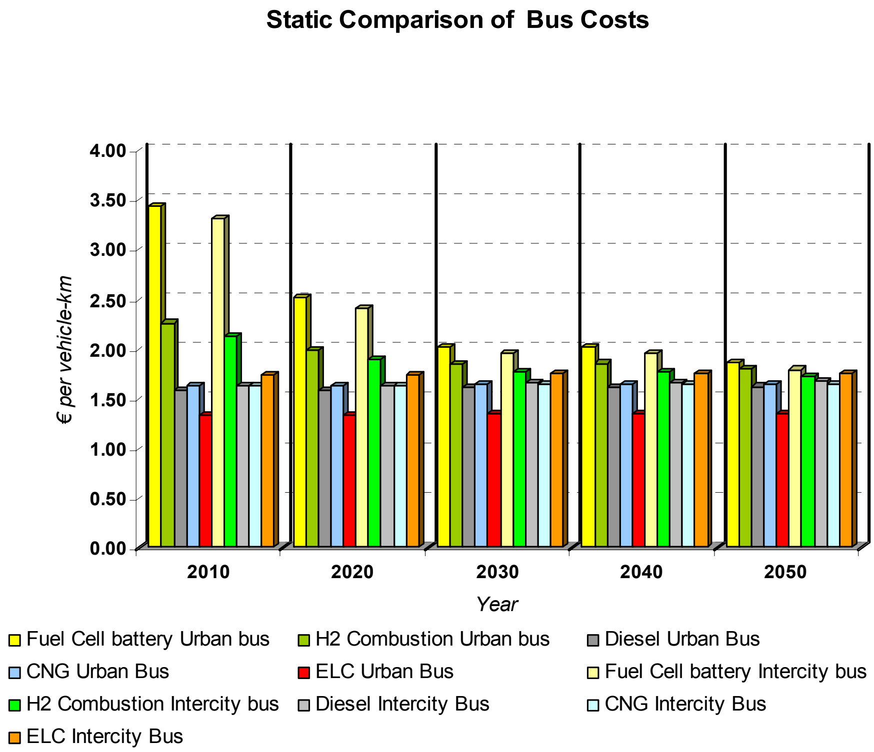


Figure 3-12: A static cost comparison of buses for different fuel types.

Within the class of hydrogen fuelled buses, the combustion engine bus performs best in terms of vehicle cost per kilometer. The difference reduces sharply over the years and by 2050 these technologies will have cost figures that are comparable with those of the other technologies.

3.3.3 Where does the hydrogen come from?

In the previous sections, the focus was on the use of hydrogen vehicles to satisfy the demand for energy services. The results suggest that hydrogen fuelled vehicles will be used in the next decades. In this section we discuss where the hydrogen comes from.

In the MARKAL-TIMES database, a number of hydrogen production technologies have been added and static hydrogen production costs for the cheapest technologies are presented in Figure 3-1. From that figure, we can predict that only large reformer plants and large gasification plants, possibly in combination with carbon capture, are real candidates to produce hydrogen.

Description
Biomass gasification (centralized)
Biomass gasification (centralized) with CCS
Biogas reforming (decentralized)
IGCC (centralized)
IGCC (centralized) with CCS
Coal gasification (centralized)
Coal gasification (centralized) with CCS
NG Reforming (centralized)
NG Reforming (centralized) with CCS
NG reforming (decentralized)
Electrolyzing (centralized)
Electrolyzing (decentralized)

Table 3-3: The hydrogen production technologies in the MARKAL-TIMES database.

This prediction is supported by the MARKAL-TIMES results. MARKAL-TIMES produces the hydrogen via large scale reforming without sequestration. Based on a simple static cost comparison, this is not the cheapest option to produce hydrogen. However, taking into account the environmental effects of the hydrogen producing technologies (reforming uses gas, gasification uses coal) and the CO_2-emission constraint already present in the reference scenario, the reforming technology (without sequestration) is preferred.

3.3.4 Sensitivity analysis

This section discusses some sensitivity analysis results. We look at the effect of 20% lower investment costs for hydrogen cars as well as for hydrogen buses. This analysis provides insight in the sensitivity of the results for errors in projected investment costs.

Discussion of the results

Generally speaking, one can say that the qualitative results do not change very much. Hydrogen fuelled vehicles penetrate the market earlier and with larger market shares. In the reference scenario, fuel cell cars now enter in 2040, with a 100% market share. We also observe that, when an additional emission constraint is imposed on the transport sector, ethanol cars do not enter the market any more. Their place is now taken by the hydrogen fuelled cars.

Qualitatively speaking, the results in scenario 2 are the same as in Figure 3-7.

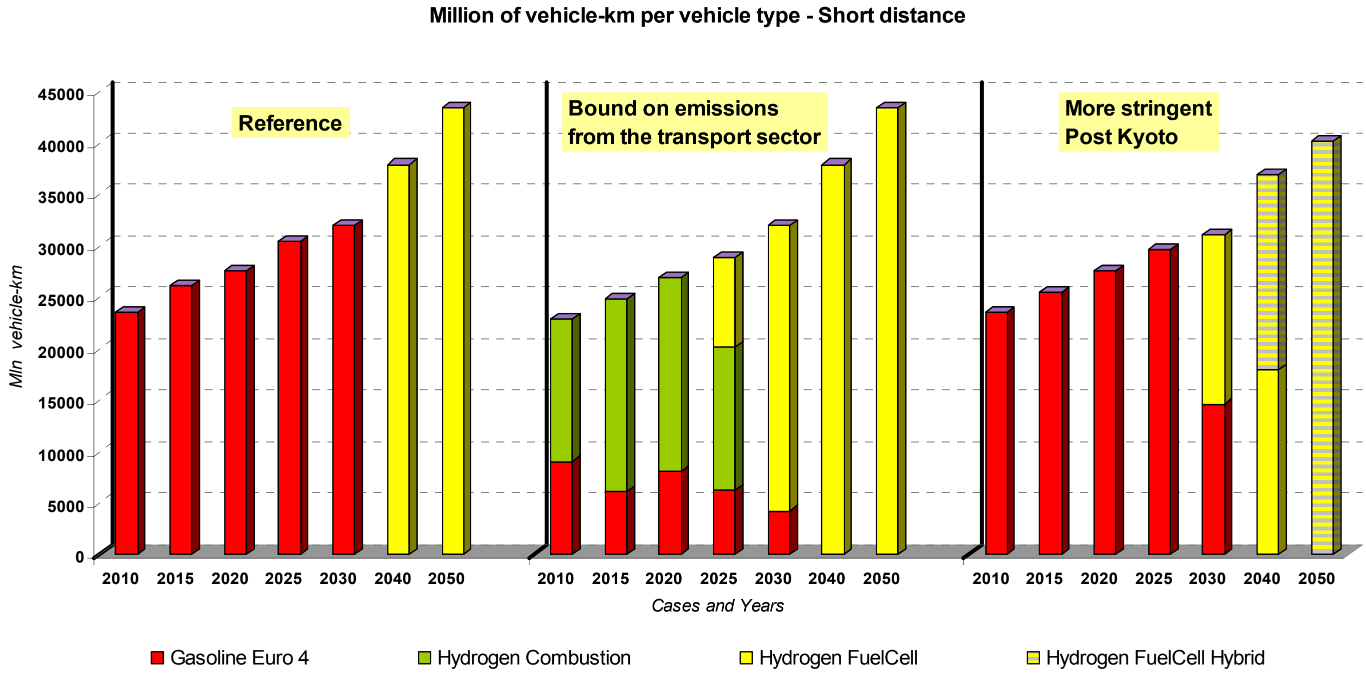


Figure 3-13: 20%Lower investment costs for Hydrogen vehicles – short distance.

For the reasons explained before, the results for the long distance market are similar to the results for the short distance market. Like in the short distance market, we do not have ethanol cars entering any more.

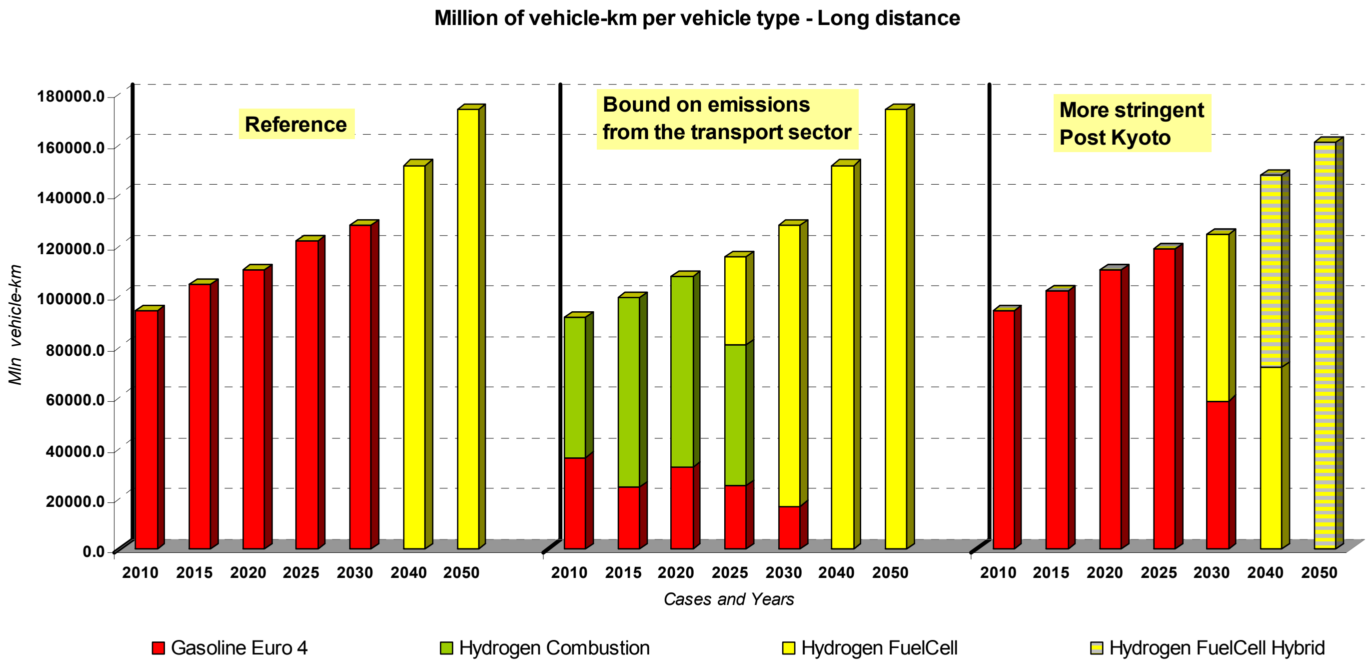


Figure 3-14: 20% lower investment costs for Hydrogen vehicles – long distance.

Buses

For buses, no change is observed despite the reduced investment costs. See Figure 3-15.

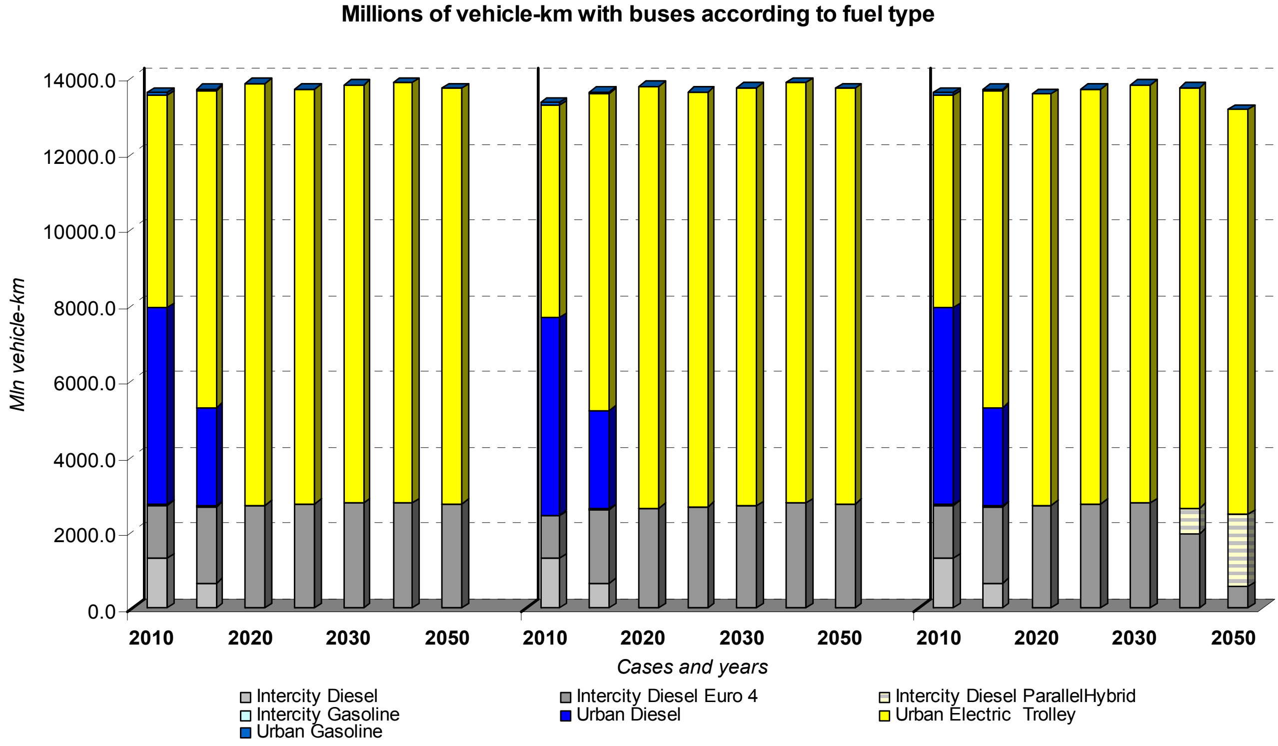


Figure 3-15: 20% lower investment costs for Hydrogen vehicles – buses.

3.4 Conclusions

The purpose of this chapter is to illustrate the use of the MARKAL-TIMES model for the evaluation of hydrogen use in the energy system. In a fist step, the MARKAL-TIMES technology database was updated to take account of the recent state of knowledge about hydrogen technologies on the production as well as on the consumption side.

In a second step, we then made some scenario runs with the model. These were compared with a reference run that includes the current Kyoto target and the nuclear phase-out decision. Two scenarios were considered. In a first scenario, we assume that the transport sector is forced to reduce its CO_2-emissions below the emissions of the sector in the reference scenario. The second scenario then assumes a harsher post-Kyoto constraint compared to the post-Kyoto target that was assumed in the reference scenario.

The simulation results suggest that hydrogen fuelled cars will enter the market in any of these two alternative scenarios, but not in the reference scenario. These results seem to be fairly robust, even when considering a sensitivity analysis with reduced investment costs for hydrogen technologies. In that case hydrogen technologies would from 2040 onwards enter the market in the reference scenario.

However, the scenario runs provide no consensus on the *type* of hydrogen vehicles that will enter. Depending on the scenario and on the market segment that is considered, it will either be hydrogen combustion or fuel cell cars. The results are also rather sensitive for the assumed investment costs. It is therefore best not to draw firm conclusions for as far as the car type is concerned.

Finally, we also found the robust result that hydrogen buses are not to be expected in the time horizon considered by the MARKAL-TIMES model. This result stands opposite to the conjecture by hydrogen experts that one of the first and most important applications of hydrogen would be found in the bus segment.

3.5 References

[1]R. Loulou, G. Goldstein and K. Noble, (2004), 'Documentation for the MARKAL Family of Models', p. 389

4 TECHNOLOGY ASSESSMENT

Within the technology assessment Belgian experts and stakeholders on hydrogen gave their opinion on how to implement hydrogen as an energy carrier in the typical Belgian case.

4.1 Objective

To create in Belgium a social basis for a specific trajectory for the introduction of hydrogen as an energy vector, the commitment of relevant stakeholders is crucial. This work package aims to get more insight in the perceptions that different experts and stakeholders have on hydrogen and to create a feasible and probable introduction of hydrogen in Belgium.

4.2 Methodology

Knowledge of the perceptions and visions of key stakeholders is a basic requisite to build a policy that is feasible. Vision assessment is a technique to get an overview of these perceptions and visions. By using this technique, insight into the existing perceptions and visions was gained in a systematic way. Via comparison of the visions in an interactive discussion, several ideas on how to come to a feasible and probable vision on sustainable hydrogen were collected.
As method to realize this vision assessment we opted for the expert panel.

4.2.1 Expert panel

The main task of an expert panel is to synthesize a variety of inputs – testimonies, research reports, outputs of forecasting methods, etc., and in our project, it is about a variety of perceptions and visions – resulting in a report that provides a vision and recommendations for future possibilities and needs for the topics under analysis or, in our project, to get an overview of and insight into the existing visions and perceptions on the introduction of hydrogen in Belgium.

Expert panels are particularly appropriate for issues that require highly technical knowledge and/or are highly complex and require the synthesis of experts from different disciplines.

4.2.2 Approach: workshop

In a half day workshop 16 stakeholders explored on a structured manner each others perceptions with respect to hydrogen and their visions on a feasible and probable introduction of hydrogen in Belgium.

The objectives of this workshop were:
- bringing together the Belgian hydrogen experts;
- exploration of the future possibilities of hydrogen in Belgium within the framework of the European ambitions;
- possible points of interest with regard to the introduction of hydrogen in Belgium;

- proposals to the government in order to support the introduction of hydrogen.

Since the different stakeholders play different roles in the hydrogen scenario it was important that they get acquainted with each other's assumptions and opinions.
An open dialogue was stimulated in order to achieve that assumptions were adjusted, that insights changed and that the mutual harmony between actors improved.

Starting point for the workshop were following 4 statements:

1. *"In my opinion the major strong points of hydrogen in Belgium are …"*

2. *"Within 20 years the most likely chance of application of hydrogen in Belgium is in …*
   " I estimate the market share of hydrogen in Belgium for this application within 20 years at about …"

3. *"In my opinion the major impediment to the introduction of hydrogen in Belgium is …"*

4. *"In order to give a chance to the introduction of hydrogen in Belgium the government should …"*

The workshop was divided into 3 phases:

1. <u>Exploration of the statements by means of interviews</u>

Objective
- To get response of each participant to each of the 4 statements.

Process
- Everybody had to feel free to express themselves without being pushed in a certain direction.
- The approach should participants help to adopt an attentive attitude in order to understand the position of others and to improve their own insights.
- The approach should also maximize the interaction between the participants.

Approach
- The expert group was split up in 4 small groups of 4 people.
- In each group each participant had to give his reaction on the 4 statements by means of face to face interviews in which alternately each participant took place across another participant.

Roles
- Each group was supported by one of the project team members.

2. <u>Synthesis of the reactions on the statements</u>

Objective
- To come to a complete overview of the reactions of all participants to the 4 statements.

Process
- To get acquainted with the positions of the participants in the other groups.

– To give the opportunity to the participants to come loose of their own positions and to understand the ideas and positions of other participants.

Approach

– In 4 groups, each group concerning one of the 4 statements, a summary was made of all reactions to the particular statements.
  All responses to each statement were brought together and sorted out:
  – positions that are agreed on,
  – positions that are not agreed on,
  – more information needed.
– Each group had its own rapporteur.

Roles

– The supporting project team member led the discussions and made notes on the flip-chart.

3. Plenary session

Objective

– To get informed on the diversity of positions and assumptions regarding the different aspects of the issue.

Process

– The participants could give feedback to their own reactions and see how their reactions related to the others' reactions.

Approach

– In a plenary session with all participants each group commented its synthesis of the reactions.
– An exchange of opinions, assumptions, reactions, etc., took place, not with the intention to reach a consensus on the 4 statements, but to understand well the arguments and positions of the other participants.

4.2.3 Moderator

In order to moderate the discussions between the experts and not to influence them, we opted for a professional facilitator, not an hydrogen expert. We choose for an organization advisor, with a psychological background, with 17 years of experience in organization matters and human resources.
Being not an hydrogen expert the facilitator was not involved in any technical discussion and was able to moderate the discussion in an impartial and unbiased way, paying attention to the right methodological approach.

4.2.4 Selection of experts

The success of a workshop depends upon the number of participants as well as their up-to-date knowledge of, and interest in, the workshop subject. Too many participants tend to suppress active discussions. On the other hand, too few participants tend to limit the overall scope and acceptance of results. The number of participants should typically be less than 20, excluding observers.

We tried to identify the market players by the means of social mapping.

1. First, we made an inventory of the different sectors:
   - H2 producers,
   - production systems,
   - users,
   - utilities,
   - automotive industry,
   - fuel producers,
   - chemical industry,
   - research,
   - government.

2. In these sectors we identified more than 50 market players.

3. From that long list, after discussion in the project team, we selected a short list of 16 key experts and stakeholders having in mind an adequate representativeness from each of the different sectors and ensuring a reliable mix of expert knowledge and experience needed for the panel to understand, analyze and draw sound conclusions on the presented issues.
   Sixteen participants seemed to be an ideal number. It gave the possibility to work in small groups of four people, but it also allowed to have a good and interactive discussion with a broad scope in the plenary session.

4. The selected participants were contacted by telephone by the team members and informed on the overall project and on the goals, the place and the role of the workshop in it.
   After confirmation of their participation they received a written invitation explaining the objectives and the approach of the workshop. In annex a description of the project 'Development of tools to evaluate the potential of sustainable hydrogen in Belgium' was added.

   16 experts and stakeholders from following organizations were invited to the workshop on 13 April 2005:
   - Advanced Energy Technologies,
   - Air Liquide,
   - Belgian Petroleum Federation,
   - E- vision,
   - Fedichem,
   - General Motors,
   - De Lijn,
   - MIVB,
   - Solvay,
   - Tractebel,
   - Ghent University,
   - Liège University,
   - Van Hool,
   - VITO,
   - Flemish government: AWI,
   - 3E.

The workshop took place in the centre of Leuven in a building of the Catholic University, one of the project team members. Leuven is centrally located and quite well to reach by car and by public transport.

4.3 Results

Based on a very efficient way of collecting 16 individual answers on the 4 above mentioned questions, following results can be summarized.

For every topic the opinions are catalogued into categories:

* positions that are agreed on: …
* positions that are not agreed on: …
* information needed on: …

4.3.1 The major strong points of hydrogen

Discussions on this question resulted in two different approaches:

* general advantages of hydrogen as energy vector
* specific advantages of hydrogen in Belgium

Below the main conclusions on both are presented.

4.3.1.1 Positions that are agreed on:

* A lot of competence and experience on hydrogen is available in Belgium. We have strong industrial players and research. We have important hydrogen producers. We have fuel cells producers. And particularly in the chemical industry wide experience exists in the reforming of natural gas into hydrogen.

* An extensive hydrogen and natural gas distribution network in Belgium for large industrial consumers already exists. If pilot applications can be based on existing infrastructure it will accelerate developments and make them more cost effective.

* The size of the country, the dense population and road network and consequently the high concentration of potential consumers result in lower costs for distribution of hydrogen to end-users.

* The existing natural gas network can be used for new projects for a mixture of natural gas/hydrogen.

* There is a real opportunity for meeting CO2 and other greenhouse gas reduction requirements by production of hydrogen via:
  – nuclear energy: the intensive use of nuclear energy in Belgium allows an efficient large scale production of hydrogen,
  – renewables: by hydrolysis of H2O by electricity based renewable energy sources (bio fuels, off shore wind, photovoltaic, …),

- conversion of hydrocarbons linked with carbon capture and storage (sequestration),
- biotechnological processes, e.g. by use of bacteria.

This CO2 issue gives an important economic drive to many players.

* Hydrogen is able to produce/generate useful energy for a variety of applications, this means less dependence on fossil fuels.

* Efficient energy use by fuel cells: a fuel cell has a potentially high efficiency compared to conventional energy converters.

* Reduction of local pollution (e.g. cities), since energy produced from hydrogen is cleaner than of any other energy-rich fuel. By using centralized production sites pollution can be concentrated. It allows to choose for sustainable (carbon free or low carbon) energy production, based on renewable energy sources.

* Hydrogen as storage capacity can result in a more efficient use of renewable energy and nuclear energy.

4.3.1.2 Positions that are not agreed on:

* Research on hydrogen is fragmentized: universities, companies, research centres, etc., carry out R&D work on hydrogen without sufficient coordination and harmonization of the research efforts.
  The government should play a stimulating role in this issue: a supportive R&D climate needs to be created.

* Opposite visions exist on the efficiency of internal combustion engine on hydrogen.

* The sustainability of the conversion of hydro-carbons with CO2 sequestration:
  - fossil fuels are needed for the conversion of hydro-carbons into hydrogen;
  - direct burning of fossil fuels is more efficient.

4.3.1.3 More information needed on:

* Actual figures on hydrogen production and consumption with distinction between hydrogen as resource in chemical industry and as an energy carrier.

* The application areas of hydrogen (information to be provided by the government).

* The characteristics of the Belgian hydrogen network in order to assess the real applicability of the network in a future hydrogen supply.

4.3.2 The most likely chance of application of hydrogen in Belgium within 20 years The market share of hydrogen in Belgium for this application within 20 years

4.3.2.1 Positions that are agreed on:

* The most likely chance of application of hydrogen in Belgium within 20 years is in public transport, because central refueling point and in UPS (Uninterruptible Power Supply), because its good reliability and its cost is less important.
  The production of hydrogen has to be based on rational energy use and greenhouse gas reduction.

4.3.2.2 Positions that are not agreed on:

* Discussion is ongoing on the efficiency of technologies for transport applications: internal combustion engine versus fuel cells.

* The market shares of application of hydrogen in transport in 2020 vary from a few % up to 40 %.

* Will the end-users for transport applications be only government fleets or all users and related to this will it result in a centralized or decentralized refuel infrastructure?

* UPS is an interesting market, but discussion exists on the capacity of a very fast start-up of the system.

* There is discussion on the most appropriate stationary applications of hydrogen:
  - in government buildings, hospitals, …
  - or as storage capacity for renewable and nuclear energy.

* The portable application of the fuel cell is considered as a possible first market, but the fuel is discussed: will it be hydrogen or methanol?

* There is no agreement to which policy level (EU or national level) following activities belong: R&D, demonstration programmes, financial initiatives, taxes, market introduction, etc…

4.3.2.3 More information needed on:

* Actual figures on non-energy related hydrogen production and consumption and influence on availability of hydrogen as energy carrier.

4.3.2.4 Important reflections on:

* There are a lot of uncertainties about the cost of hydrogen production and storage. But, also the evolution of the prices of the traditional fuels remains difficult to predict.

* Will hydrogen have a small share in the total energy supply or will it become the major energy carrier in the future?

* Hydrogen production has to be based on rational energy use and greenhouse gas reduction.

* There is a possibility to opt for a mixture of hydrogen and natural gas instead of using pure hydrogen.

4.3.3 The major barriers of hydrogen in Belgium

4.3.3.1 Positions that are agreed on:

* Cost
  The major impediment to the introduction on hydrogen in Belgium as energetic vector is the cost of it.

  The price to produce it (from well to wheel), to store it, the price of the application using it (e.g. fuel cells) and the cost to change all infrastructures in industries to adapt them to this new energy source is still very high.

  The cost to produce it from a carbon free source (or to associate it with carbon capture and storage) would further increase the production price.
  The production by electrolysis through electric energy produced by nuclear way would not be accepted by population (cfr. nuclear withdrawal in Belgium).

  The lack of knowledge on hydrogen technologies is still to important to be able to ensure low price technology products and applications.

  A major problem is the scale factor. To lower the price sufficiently, it would be necessary to reach a scale large enough. But the problem is "cyclic": to impose hydrogen at a larger scale, its price should be attractive. So, there is a need to have government incentives to favour hydrogen systems (see statement nr.4).

* Lack of Belgian roadmap
  A the present time, there is still no clear roadmap to hydrogen in Belgium.

  Moreover, Belgium is too small to impose a new energy vector and its technology, we need to include our effort into a European level.

  A real impediment is the Belgian mentality to stand as "followers" and to practice a "wait and see" position. We just let other nations try new things and jump into the train once it has prove worth of interest. The same attitude can be noticed in government, there is still no roadmap contrary to other (European) countries such as France or Germany.

  It is a fact that the complexity of Belgian policy and its numerous levels of decision (federal, community and regional) is not in favour of a simple implementation of a new technology or energy.

* Lack of coordination
The lack of coordination in the research. A lot of small teams work on the same subjects without collaboration. While respecting the diversity of skills of all labs and teams, it would be desirable that a better collaboration would exist, between all the universities or centres of the country, and between the different regions, in order to reach "critical size" of teams to ensure a better efficiency.

* Lack of acceptance by public and industry
Another problem that hydrogen will have to face is the "psychological" aspect, both for the public and the industrials.

In the public's mind, hydrogen is associated with the Hindenburg explosion and considered as "highly dangerous". There is nothing rational in this fear, but it is powerful enough to have already hindered the implementation of LPG, despite its very interesting cost and the huge security precautions imposed on tanks and fitters and regular obligatory control of them.
To be accepted by public in houses, it will also need to imply as less as possible changes in the way people use it at home. To be as user-friendly as natural gas is.

A great need of communication will have to be taken in account if Belgium wants to implement hydrogen in "personal use". To reassure the public of the safety of systems using hydrogen, by announcement campaigns on television and demonstration of the security of tanks in cars in case of crash or fire, for instance.

A first step could be made by using hydrogen in public buildings, in administration, etc. It would allow people to get familiar with the use of hydrogen and to help to overcome their apprehensions.

In industries, it is more the habits than the fear of this gas that will have to be bypassed. When "good practices" are established since a long time, the change of a lot of procedures always encounters some resistance. People have to be convinced of the improvements and advantages of hydrogen.

4.3.3.2 Positions that are not agreed on:

* Opposition by oil-lobby and strength of this sector
The opposition of the "Oil Lobby" and its strength to hinder new technologies that would take some of its market share.

* Infrastructure:
  – is not sufficient, but some large-scale network already exists:
    – it is not sufficient to ensure a good availability of hydrogen everywhere in Belgium (some parts of the country are not served by those pipelines);
    – but it exists : existence of some networks but not at retail level (unlike natural gas).
  – There is no network for end-use (compared to natural gas).

* Practical difficulty to handle hydrogen in cars

Some experts say there are practical difficulties to handle hydrogen (in cars). Others reply that is not different from LPG (cars) or natural gas (home). The equipment should be adapted to a user-friendly handling, such as other systems already are. It is more an "acceptance matter" than a real technological point.

* Size of Belgium
  Belgium is too small to be able to force the introduction of hydrogen:
  - we have no industry to force introduction in the market (e.g. car manufacturer that would impose a fuel cell powered engine in their cars)
  - side of end-user: cars, engine, components
  - we are waiting for developments of industries abroad
  - but, it is the same problem for everything: we don't make cars or engines but we drive!

* No coordination in training, school, university
  There is no coordination in training on hydrogen in schools and at universities. At the universities teaching on hydrogen exists as a part of other courses (more general). Some universities started specific courses on hydrogen. Some European projects include training related to hydrogen.

4.3.4 Government's measures to give a chance to the introduction of hydrogen in Belgium

4.3.4.1 Positions that are agreed on:

* Apply favourable taxation on hydrogen as energy carrier, based on positive contribution to energy/environment/CO2 requirements.
  The market price of hydrogen and energy using products cannot be influenced at the end by the government. But taxes are government issue.

* Active participation in international (EU and UN) organizations:
  - push for EU wide, or better worldwide, certification standards for products (e.g.) vehicles using hydrogen,
  - promote the development and implementation of consistent standards and regulations in accordance with EU standardization and legislation.

  The introduction of a new energy vector in the Belgian economy can only succeed and have impact if it is in line with a broad EU and even worldwide public and industrial consensus (type of applications, technological choices).

* Play an active role in the definition of a European R&D agenda (7th Framework programme). Use it for one's own applications (e.g. tender UPS – H2).

* Harmonize regional and federal efforts on legislation and licenses before implementation. The governments should avoid to tackle obstacles; they have to start with a cooperation agreement between the federal and regional level on e.g. permitting for infrastructure, R&D funds, etc.

* Initiate large-scale demonstration projects
  - integrated projects: cooperation within European Framework-programmes,

- industrial participation: support pilot projects in public sector (schools, public transport, hospitals) with industrial partnerships,
- based as much as possible on existing infrastructure.

* Support public acceptance of hydrogen:
  - show interest in hydrogen, including projects in public service (e.g. fuel cell buses),
  - communication and education: inform the public upon the advantages of the use of hydrogen as a clean energy source; reassure the public of the safety measures.

4.3.4.2 Positions that are not agreed on:

* "Hydrogen is the solution"
  Hydrogen is not the solution for all energy related problems. It has a lot of advantages, but it has also its limitations.

* "Hydrogen = fuel cell technology"
  The application of hydrogen in fuel cells is a logical step because of the high efficiency of fuel cells, and thus the optimum use of hydrogen. However, hydrogen can also been used as fuel for internal combustion engines.

4.3.4.3 More information needed on:

* Hydrogen from biomass: assessment is needed of the biomass potential for hydrogen purposes.

4.3.5 Two scenarios came from the assessment that were agreed on:

- Public transport because central refuelling point.
- UPS (Uninterruptible Power Supply) because its good reliability and its cost is less important.

Scenario 'public transport' was selected as input for the Markal model.

In terms of total energy consumption the UPS application is limited. This makes this scenario of less interest for hydrogen as energy carrier and makes it impossible for a Markal assessment.

4.4 Conclusions

Methodology: evaluation of the technology assessment

1. The workshop approach proved to be an efficient tool to collect information from the experts.

On a structured and interactive manner the different experts could explore each others perceptions and assumptions. It was not the intention to reach a consensus on the four statements. It resulted in an overview of, sometimes differing, visions on how to realize a feasible and probable introduction of hydrogen in Belgium.
The outcomes of the workshop were very valuable and turned out to be decisive for the further development of the project.

2. The well-balanced selection of experts resulted in a very productive discussion in which a variety of perspectives was covered. Sixteen participants was an ideal number: it gave the possibility to work in small groups of four people, but it also allowed to have a good and interactive discussion with a broad scope in the plenary session.

3. The face to face interviews were very crucial to the success of the workshop. They allowed each participant to make more explicit his own position on the 4 statements in a very fast and efficient way.
The reactions of the participants after the workshop confirmed this positive conclusion.

4. The choice of a professional facilitator seemed to be a good decision. Being not an hydrogen expert, the facilitator was not involved in any technical discussion, and so, he was able to moderate the discussion in a impartial and unbiased way, paying attention to the right methodological approach.

Results

1. The major strong points of hydrogen in Belgium

* A lot of competence and experience on industrial hydrogen is available in Belgium.
* An extensive hydrogen and natural gas distribution network in Belgium for large industrial consumers already exists.
* The size of the country, the dense population and road network and consequently the high concentration of potential consumers result in lower costs for distribution of hydrogen to end-users.
* The existing natural gas network can be used for new projects for a mixture of natural gas/hydrogen.
* There is a real opportunity for meeting CO2 and other greenhouse gas reduction requirements by production of hydrogen.
* Hydrogen is able to produce/generate useful energy for a variety of applications, this means less dependence on fossil fuels.
* Efficient energy use by fuel cells: a fuel cell has a potentially high efficiency compared to conventional energy converters.
* Hydrogen as storage capacity can result in a more efficient use of renewable energy and nuclear energy.

2. The most likely chances of application of hydrogen in Belgium within 20 years

The most likely chance of application of hydrogen in Belgium within 20 years is in public transport, because central refuelling point and in UPS (Uninterruptible Power Supply), because its good reliability and its cost is less important.
The production of hydrogen has to be based on rational energy use and greenhouse gas reduction

3. The major impediments to the introduction of hydrogen in Belgium

* High costs
* Lack of Belgian roadmap
* Lack of coordination of R&D
* Lack of acceptance by public and industry

4. Suggestions for the government to introduce hydrogen in Belgium

* Apply favourable taxation on hydrogen as energy carrier, based on positive contribution to energy/environment/CO2 requirements.
* Active participation in international (EU and UN) organizations:
  – push for EU wide, or better worldwide, certification standards for products (e.g.) vehicles using hydrogen,
  – promote the development and implementation of consistent standards and regulations in accordance with EU standardization and legislation.

The introduction of a new energy vector in the Belgian economy can only succeed and have impact if it is in line with a broad EU and even worldwide public and industrial consensus (type of applications, technological choices).

* Play an active role in the definition of a European R&D agenda (7th Framework programme).
* Harmonize regional and federal efforts on legislation and licenses before implementation.
* Initiate large-scale demonstration projects.
* Support public acceptance of hydrogen.

5 TRANSLATION OF FOREIGN PROGRESS IN LEGISLATION

5.1 Objective

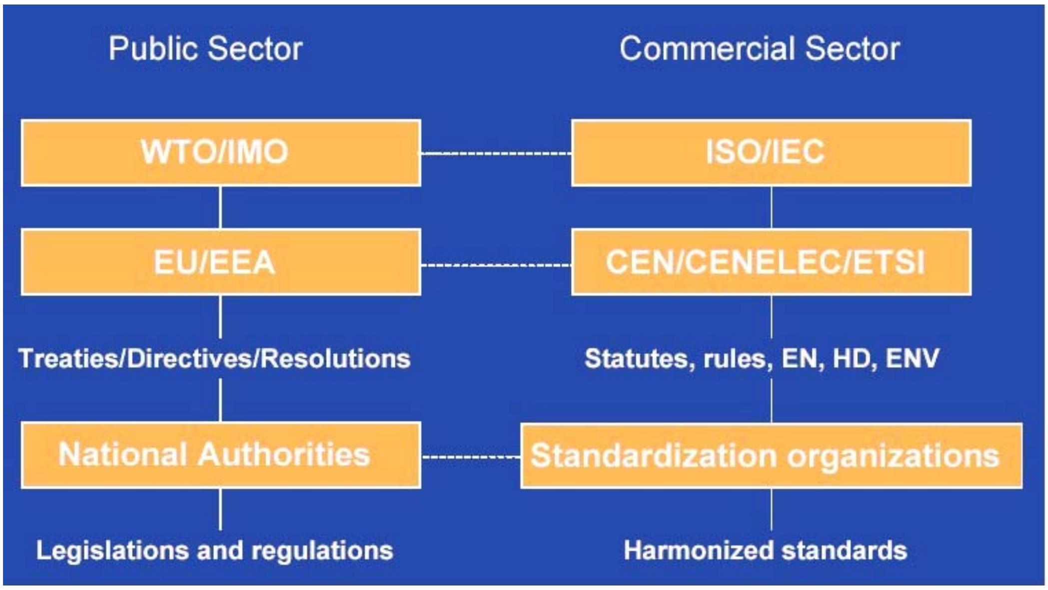
Legislation and building permit procedures exist of course in Belgium. By lack of public hydrogen projects in the frame of energy supply, it was not worked out specifically for this aim. A translation, in three steps, of foreign experiences with demonstration projects is proposed on the Belgian background.

- Links to legislation database and scenario.
- Attention has been paid to the demonstration projects in other countries.
- Lessons for Belgian situation.

5.2 Methodology

Regarding the database on regulation, we opted for an internet-site, being http://www.podopadd.be.tf/. A combination of Belgian and international information has been compiled and integrated in this web-site. Based upon the scenario calculations this part will be worked out more in detail.

In the legislation field , some definitions are useful :
Code: any system or collection of rules and regulations
Standard: 1.) an object, considered by an authority or by general consent as a basis of comparison; 2.) anything as a rule or principle that is used as a basis of comparison (=norm) enough for business
Regulation: a rule or order prescribed by authority, as to regulate conduct needed to ensure human safety & environmental compatibility



The scenario to be dealt with in Work Package 4 will focus on busses and fuelling stations. From the expert discussion on market share, we put forward a target of 10% hydrogen busses.

This represents that about 600 busses will be in use in Belgium. More or less 100 depots exist at the moment. According to different hypothesis (chose will be done to put into service only some large depots or all depots), between 20 to 50 depots should be implemented with H2 facilities (supply infrastructure, workshops,…).

Centralized production of H2 (reforming from NG in a first step) will be preferred in a first stage. The first choice for transport to depots is by pipelines from centralized production.

Concerning demonstration projects and foreign experiences, attention has been paid to CUTE-ECTOS (30 busses in 10 European cities). The experience from the CUTE project is very important with regard to development of regulations, codes and standards for hydrogen applications in the transport sector.

5.3 Results

5.3.1 Inventorisation of legislation

5.3.1.1 Classification

Hydrogen has several classifications according to different codes, standards or Royal Decrees. The main ones are given here.

According to the Arrêté Royal of January 11th, 1993 concerning classification, packing and labelling of hazardous preparations with a view to put them on market or their use, (MB 17.05.1993), hydrogen is classified as:

- F+ , R12 : highly flammable
- S9 : "keep the tank in a well ventilated place"
- S16 : "keep away from any source of flame or spark - do not smoke"
- S33 : "avoid the accumulation of static charges"

The American NFPA (National Fire Protection Agency) codes for hydrogen are 0-4-0 for gaseous hydrogen, 3-4-0 for liquid hydrogen.

Concerning zoning, hydrogen is a gas of IIC group, class of temperature T1 (according to standard EN 50.014 / NBN C23-001 : electrical material for atmospheres presenting a danger of explosion - general rules).

Concerning transport, hydrogen is referred as :

- Compressed hydrogen. It belongs to the class/division 2.1, rubric ADR/RID 2, 1°F, danger n° ADR/RID 23 and labelling ADR is label 3 : flammable gas. The ADR is the European agreement on international transport of dangerous goods on the road (Accord Européen relatif au transport international des marchandises Dangereuses par Route). The RID is the same but for rail transport (Règlement concernant le transport International ferroviaire des marchandises Dangereuses).
- Liquid hydrogen is referred as Refrigerated liquid hydrogen. It belongs to the class/division 2.1, rubric ADR/RID 2, 3°F, danger n° ARD/RID 223 and labelling ADR is the same.

Related to legislation, we can make two categories of subject matter. The first one is related to fixed installations. "Industrial installations" encompass hydrogen production, transport, refuelling stations, workshops,…The fact that there is no public access means that permit procedure should be in "classic" form.

The second point is related to transport by road (passengers but also hydrogen transport by truck). In this case, the homologation of vehicles is the point and it is the use of CE certified equipment and legislation compliance is usually needed to obtain the licences.

5.3.1.2 Permit procedure

Institutional Belgium complexity leads to three different permit procedures for fixed installations. The establishment and operation usually require permissions from local and regional authorities : environment, fire and explosion, building and operation Authorities.

Approval process typically took several months. Several steps are included:

- Application for authorisation
- Response from authorities : permission document with detailed description of all requirements
- Public hearing of permission document
- Permission to build/establish facilities
- Inspection of facilities by public authorities body
- Approval and permission to operate

In the Walloon Region the situation is a little different; the steps are :

- Public hearing comes before the application for authorisation
- Dialogue with authorities : detailed description of all requirements
- Single Permit to build and establish facilities and to operate
- Inspection of facilities by public authorities body

European project EIHP2 has not finalized the code of practice to allow refuelling station. Another European project «HYAPPROVAL» has the objective to elaborate an EU-uniform «handbook» for approval of Hydrogen refuelling stations throughout Europe. One could think that "there is an urgent need to start working on a common procedure to be followed, and start discussions with all the related parties and stakeholders on regional, national and international level". This has not neen started yet in Belgium and its regions.

The permit procedures for fixed installations does not implicate Seveso II regulation if hydrogen stocks are under 5 tons, but consultation of specialized teams of authorities is plausible (for example : Cellule "Risques d'accidents majeurs" (R.A.M.) in the Walloon Region).

If the directive "Seveso II" may not be relevant for current stations, it should however be noted that it is the total amount of hazardous substances that should be considered related to the area of application. Thus, if at the station also other hazardous substances are handled or stored in significant amounts, such as ammonia, LPG, methanol etc. the relevance of this directive should be considered.

A special legislation is related to gas products transport by pipelines on the responsibility of Federal Authorities.

5.3.1.3 Homologation of vehicles

Homologated vehicles in a Belgian Region (or in another Member State) should be accepted anywhere. The use of CE certified equipment, and a third party inspection document/certificate are usually needed to obtain the licences. Notified or competent bodies, such as Det Norske Veritas and TÜV, may be authorised by the local authorities to assist in the process.

For ATEX, EMC (Electromagnetic compatibility) and Machinery Directives subcontractors of equipment have to issue a declaration of conformity before CE-marking can take place and to state to which directives that their equipment is comprised. For equipment appurtenant to PED (Pressurised Equipment Directive), an authorized notified body has to assist in declaration of Conformity and CE-marking.

When marking a product with CE, the producer states that all safety requirements relevant for the product are met. CE marking is dependent on risk analysis, inspection, testing and operation experience.
Work is in progress under the auspices of UNECE/WP.29/GRPE ad hoc working group. EU is promoting primarily the progress of work with the drafted ECE-R's for gaseous and liquid hydrogen storage.

5.3.2 Experiences from CUTE project

The experience from the CUTE (Clean Urban Transport for Europe) project is very important with regard to development of regulations, codes and standards for hydrogen applications in the transport sector.

It appears that in many cases approval procedures for installing and operating refuelling stations have been extremely painful and there have been as many approaches and safety requirements as projects. For example, it has taken a year to approve a hydrogen filling station in Hornchurch (London) for the project. This was mainly due to the resistance of local residents who were concerned about a lack of information on hydrogen safety.
The use of CE certified equipment and a third party inspection document or certificate are usually needed to obtain the licences. Notified bodies, such as TÜV, may be authorised by the local authorities to assist in the certification process.
The authorities have guided the CUTE city project groups in how to apply and how to approach the approval process, but interpretation of mandatory regulations and requirements has not been straight forward. The technical and safety related documentation needed for the approval process has been subject to discussion. In most cases the authorities and the city project groups have developed a mutual understanding of how to interpret and comply with the regulations, but the approval process has been a time consuming activity for the city project groups.

5.3.2.1 Madrid CUTE station

The production method of hydrogen for the Madrid station is on-site natural gas reforming. Critical point is that this hydrogen refuelling infrastructure has been considered as an industrial installation instead of a public service (as for conventional gasoline stations), so this has affected all the regulations to comply.

Thus for the filling station, a lot of requirements were made :

- Environmental License (Regional Government); this license was the hardest to get in time and effort.
- Activity and Civil Work License (Local Authorities)
- Start-up License (Local Authorities)
- Industry License (Regional Government)
- Natural Gas License (Regional Government)
- Fire Protection Maintenance Plan
- Emergency Plan

An Hydrogen Storage and Transport License had to be obtained from National Government. For the garage and workshop, an Activity and Civil Work License from the Local Authorities and a Start-up License from Local Authorities were needed.

5.3.2.2 CUTE project Amsterdam. Nimby reaction.

The Cute project in Amsterdam knew a reflex of fear relayed by a particular type of media. The statements (which are in the following box) from different individuals and persons presented as experts are a succession of items to be addressed with.

Statements by hosts and "independent" experts :

- permits are full of mistakes or are missing
- emergency services are not notified
- hydrogen is the most explosive gas
- "…with all reason I don't understand that one chooses this fuel to perform experiments with…"
- hydrogen explodes with just one spark
- escaping hydrogen self-ignites
- extinguishing is not allowed
- means of extinguishing automatically lead to explosions
- so the consequences are that the fire brigade won't stand a chance and should only remain at a long distance from the fire
- "Ignition of the high explosive hydrogen can lead to a chain of exploding hydrogen cylinders, and will be launched as cruise missiles"

These actions caused only very few months of delay to obtain operation permit. But among the lessons to be learnt, there is the fact that every city has its own "independent" experts and it is important to make use of professional spokespersons. However, the communication between partners is crucial and must act as one. It is essential to be always honest and remain consequent and close to the facts. Crucial information should be established by third independent parties.

5.3.2.3 CUTE project London

Cute project in London should demonstrate external supply of liquid hydrogen and its storage, for a capacity of 3,2 tons, on site at the station. The resistance of local residents who were concerned about a lack of information on hydrogen safety has involved a year to approve the hydrogen filling station for the project.

Several reasons could explain this large implementation delay : practitioners were all trapped in administration process. BP, partner of Cute project and promoting hydrogen refuelling demo in London, did not have the right resources in place. The main actors of opposition to site were local residents; they expected answers but did not trust the messenger. Media carried out adverse comment and the broader political community were interacting through press and public presentations.
Some lessons can be learnt out of London experience. Very little UK public were exposed to hydrogen projects and even experts were quite ignorant. For the future, there is a need for proactive campaign of awareness. No UK political body took the lead in fixing the process, it is the reason why political contacts should be managed very actively. A strong hands-on project management will impede that, like in London, communication consultants have no hydrogen experience and hydrogen provider (BOC) have no public access experience. Attention will be paid to select a site with no pre-existing negative reputation.

5.4 Conclusions

Concerning the database on regulation we opted for an internet-site, being currently http://www.podopadd.be.tf/. A combination of Belgian and international information has been compiled and integrated in this web-site. The regulation database was checked with good success : however some legislation texts and links were added in the web site.

An important way to make hydrogen penetration easier should be to establish dialogue between Belgian Regional permitting bodies in order to avoid that the requiring company or public agency have to collect and organise different information to obtain permit. It should be stranger enough that, for example, the filling station requirements should be different in the three different Regions of Belgium.

We hold on to items (from experts) to be managed : it is important to carry out an active involvement in international (EU and international) organizations on product certification and standardization and to harmonize regional and federal legislation and licenses.

In order to apply the development of regulations, codes and standards for hydrogen applications in the transport sector, large attention has been paid to CUTE-ECTOS project (30 busses in 10 European cities). One major challenge, from the project, related to obtaining licences or approval from the authorities was :

- the lack of experience in handling hydrogen for non-industrial or public applications, and
- the absence of regulations explicitly expressing the safety requirements for such applications.

Regarding these foreign experiences, it is important to gain experience and to build competence within Federal and Regional administrations to achieve an effective approval process and in order to avoid Nimby reaction, we recommend to join legal procedure and population information in a complete and coherent mode.

6 POLICY ISSUES

6.1 Objective

At the moment a lot of countries are developing an energy policy for introduction of hydrogen in the energy system.
In this chapter the first ideas concerning the development of an energy policy for the introduction of hydrogen into the Belgian energy system will be presented.
As an hydrogen policy will be based on international energy policies (especially the European view on hydrogen) and on the results of this study, the starting points of developing an energy policy on hydrogen will be explained in paragraph 6.2.
Based upon these starting points possible objectives will be presented, as well as possible instruments that can be developed in paragraph 6.3. It is important to realize that the introduction of hydrogen as an energy carrier will be competing with other policy driven evolutions, e.g. renewable energy. Therefore within paragraph 6.4 attention will be paid to this issue.

6.2 Methodology

The methodology to derive policy issues in a systematic way is first to look in the following three issues:

* Europe: highlights of the European energy policy on hydrogen
* Belgium: responsibilities of federal and regional authorities on energy policy
* Belgium: actual hydrogen situation

Based on this reference frame it is possible to define policy items. These items can be divided into:

* Possible policy objectives
* Possible policy actions/ instruments

This will be the result of this chapter.

6.2.1 European energy policy on hydrogen and fuel cells

As stated in paragraph 1.3 of this study the European Union is active in developing an energy policy on the introduction of hydrogen. It is important to remark that the American, Japanese and Korean energy policies on the introduction of hydrogen are much more 'aggressive' compared to the European ambitions.
For Belgium it is not useful to directly copy the European policy, as the specific Belgian situation differs from the overall European context. However, it is necessary to develop a Belgian hydrogen policy that can run parallel to the European hydrogen policy.

In August 2005 the 'European Hydrogen & Fuel Cell Technology Platform' presented a report on the 'Deployment Strategy' of hydrogen and fuel cells. Figure 6-1 shows the European schedule for a deployment strategy on hydrogen and fuel cells.

In this figure following different areas are defined for the period 2005 – 2025:

- policy & framework
- market development
- demonstrations
- research & development

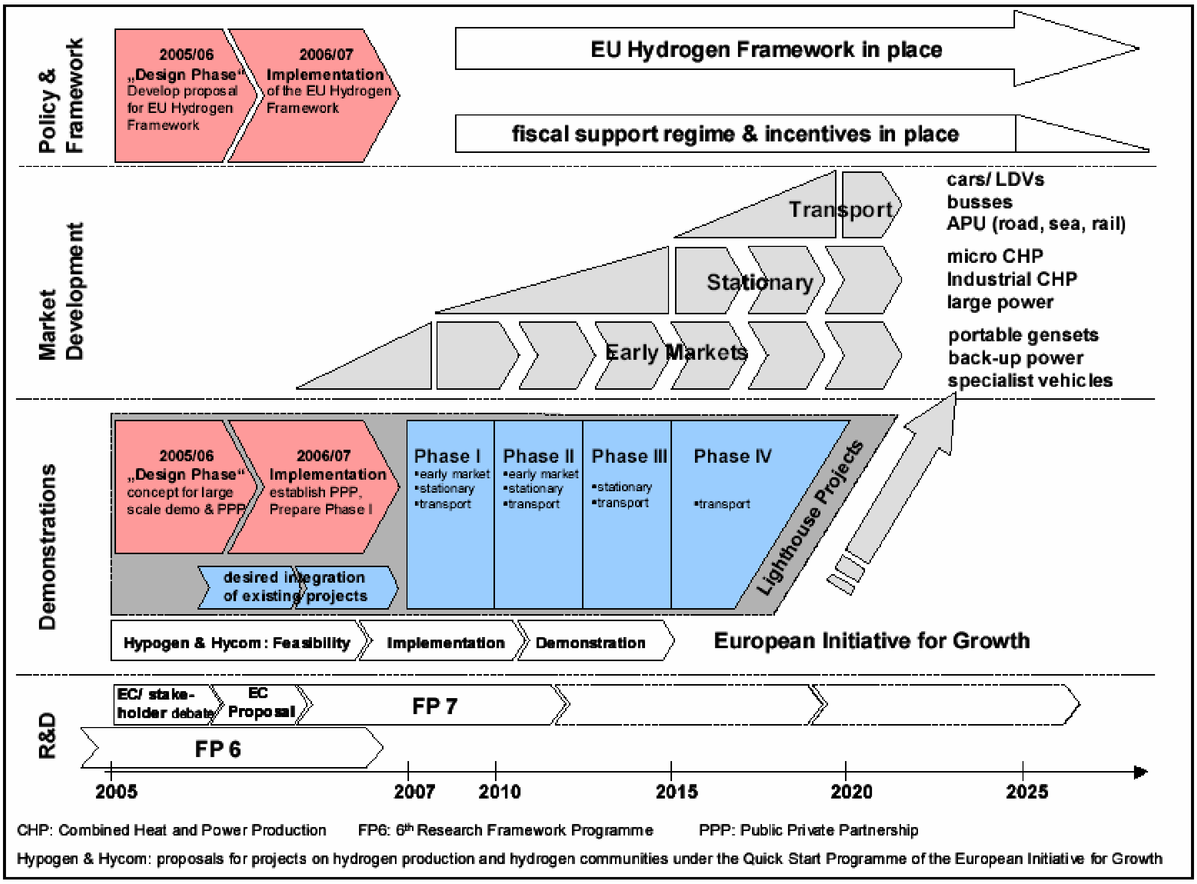


Figure 6-1: Schedule for a deployment strategy on hydrogen and fuel cells [Deployment strategy Europe]

In this deployment strategy a list of phases and areas of the European policy framework are well described. As it is important to run the Belgian policy framework parallel to this European policy framework, the European policy framework will be explained in this paragraph. See also paragraph 2.3 for an introduction into the deployment strategy and annex 2 for a wider description of the European activities.

The main phases and areas of actions carried out by public bodies, authorities and governments are summarized in the deployment strategy as follows:

1. the different phases and areas of the policy framework
2. the basic conditions for an effective public support to the deployment

3. the role of energy and environment strategies of governments
4. the public funding policies
5. the fiscal incentives policies
6. the role of public-private partnerships at different levels
7. the effects of actions directly performed by public authorities and governments in hydrogen and fuel cells related projects
8. the impact on education and public awareness
9. the need for a governance of the system

For these policy areas the most important issues will be summarized according the deployment strategy document.

1. phases and areas of the policy framework
    a. strategies in the fields of energy and environment, with evaluation of socio-economic effects of build-up of a hydrogen economy in the relevant context
    b. laws and rules at national and at regional level
    c. direct support to research and pre-commercial development
    d. support to facilitate market development
    e. participation in demonstration projects
    f. policies on the creation of new districts and of new jobs
    g. definition of codes and standards
    h. education and dissemination of knowledge about hydrogen to improve public awareness

2. basic conditions for public support
    a. regarding commitment:
        i. a general long-term vision of the government is much helpful
        ii. the consciousness of the need for a sustainable development
        iii. the capacity of evaluating potential socio-economic impacts
        iv. the capacity of building networks at national and regional levels
        v. the visibility of the action supporting the development of hydrogen and fuel cells
    b. regarding most adequate government level and dimension:
        i. member states are the natural reference points
        ii. regions are important political actors
        iii. regions can facilitate regional or local communities for hydrogen
        iv. implementation of 'light-house projects' or even 'light-house regions'
        v. direct links between the European Commission and European Regions are recommended

3. energy and environment strategies
    a. <u>energy</u> policies suitable to support economic development
    b. <u>environment</u> policies particularly attentive to sustainability
    c. <u>innovation</u> policies oriented to promote medium-to-long term research as well as short term demonstration projects
    d. <u>industry</u> policies able to recognize the possibility of development of new opportunities in terms of market evolution and job creation

4. public funding policies
    a. maximize the efficiency and effectiveness

            i. minimize overlapping or duplications of projects
            ii. avoid leaving significant gaps which are not covered by proper funding
            iii. evaluate the priorities and relationships between the funded projects
            iv. concentrate resources on 'strong' strategic projects
    b. increase of resources for research and technological development:
        i. public funding of demonstration projects
        ii. creation of new financial support strategies and instruments
        iii. use of European structural funds
        iv. state aid will be carefully considered by the European Commission
        v. include external costs in the cost of energy produced

5. fiscal incentives policies
    a. de-taxation of hydrogen production
    b. fiscal incentives for development of hydrogen distribution networks
    c. additional pricing of energy itself
    d. short term: grants or fiscal benefits
    e. fiscal incentives for research and precommercial development of fuel cells
    f. fiscal incentives for first generations of hydrogen powered vehicles as well as the realization of first fleets (public services, taxis,…)
    g. fiscal policies should be adopted on a coherent basis inside the European Union
    h. kinds of taxes affecting hydrogen and fuel cells:
        i. excise duties such as taxes on energy consumption
        ii. income taxes:
            1. modification of depreciation regimes regarding investment in hydrogen and fuel cells
            2. straightforward fiscal incentives for private consumers
            3. technology risk guarantees for project financing are required
        iii. property tax such as motor vehicle tax
        iv. value added tax
        v. revenue roll-over of emission certificates such as ROC's (renewable obligations certificates)

6. actions of public administrations
    a. direct involvement in national/regional demonstration projects:
        i. public transportation prototypes, such as hydrogen buses
        ii. public fleets, such as vehicles for waste management or light duty vehicles including passenger cars and taxis
        iii. fuelling stations for such fleets and prototypes
        iv. hydrogen and fuel cells based applications for cogeneration and tri-generation in public buildings or for district heat and power supply
    b. public procurement of hydrogen and fuel cells related products
    c. facilitate infrastructures for hydrogen distribution systems by direct involvement of the public authorities
    d. pursuing European alternative fuels strategy, including hydrogen

7. public-private partnership
    a. needs a strong commitment on the side of the public sector
    b. several possibilities:

   i. stimulate joint initiatives between public administration and private companies in the field of demonstration projects
   ii. build synergies between the research efforts and activities of universities, public research centres and private companies
   iii. create consortia between private companies and public authorities
   iv. develop public/private initiatives for the creation of industrial districts
   v. joint realization of infrastructure networks

8. education and public awareness
   a. introduce hydrogen and fuel cells in education programs
   b. dissemination of information to the public
   c. lighthouse projects

9. governance
   a. coordination of the strategies at national, regional and local levels
   b. activation of a monitoring process of projects
   c. creation of the conditions for an efficient integration of projects
   d. adequate policies to allow funding for industrialization

6.2.2 Belgium: different responsibilities on federal and regional level on energy policy

In order to define a clear and effective energy policy on hydrogen for Belgium it is important to take into account that federal and regional authorities have different responsibilities on the issue 'energy policy'.

Federal responsibility on energy policy:

- national program on the equipment of the electricity sector
- nuclear energy
- large infrastructures for storage
- transport of electricity > 70 kV
- production of energy
- electricity and gas tariffs

Besides these energy issues, the federal government is responsible for definition of product norms, having indirectly an impact on the energy systems.

Regional responsibility on energy policy:

- distribution of local transport of electricity ≤ 70 kV
- public distribution of natural gas
- use of mine gas and gas blast furnaces gas
- transport systems for district heating
- valorisation of stone-pits
- new energy sources, excluding nuclear systems
- recovery of energy by industry and other users
- rational use of energy

6.2.3 Belgium: actual hydrogen situation

Currently there is no policy defined on the use of hydrogen and fuel cells in Belgium: the different authorities/governments do not have programs on hydrogen or fuel cells.

However this lack of policy, Belgium has undoubtedly some strong industrial players and unique positions in hydrogen and fuel cells.

The most remarkable fact regarding hydrogen in Belgium is that Belgium is the centre of the largest hydrogen transport system in the world (see chapter 2). Air Liquide owns and operates this largest hydrogen distribution network in the world. The network, consisting of pipelines with a total length of more than 800 km, crosses Belgium and reaches from the Northern part of France to the Rotterdam port area.
It is important to state that this hydrogen is used as feedstock in industrial processes, so this network is only used for transport of hydrogen between industries (chemical, steel,…). Industries involved in this network are steam reforming, chlor-alkali-industry, refineries,…. This means that the quality of the hydrogen and infrastructure specifications (e.g. pressure) do not allow direct use of this hydrogen for residential or transport applications.
On the other hand building and operating large hydrogen infrastructures in Belgium, means that some companies as well as authorities are familiar with the industrial production and distribution of hydrogen.

Regarding the use of hydrogen as an energy carrier, several companies in Belgium play a major role in research and development.
Besides the very large steam-reforming plants for producing hydrogen out of natural gas (as built in Antwerp), Belgium has a key-player regarding on-site hydrogen production of hydrogen via electrolysis. The company, originally known as Vandenborre Technologies, is now part of world-leader Hydrogenics (Canada), and produces half of all water electrolysers world wide.

On fuel cells Solvay is a major developer of components for PEM and DMFC fuel cell technology. Recently Umicore has acquired an important PEM-fuel cell developer in Germany, making Umicore also involved in fuel cell technology.
The Flemish SME E-Vision is world leader on alkaline fuel cell technology. Autobus company Van Hool delivered 3 fuel cell buses in the United States of America and is building an new fuel cell bus in Belgium at the moment. Other companies are delivering parts of complete systems.

In Flanders in 2002 the "Flemish Cooperative on Fuel Cells" has been founded (Vlaams Samenwerkingsverband Brandstofcellen vzw). This network brings research and industry together; frequently the members have meetings to exchange information on the recent development of fuel cells and hydrogen technology. Besides this information element, also joint projects between partners are initiated. The network is for 20% financed by the members and for 80% by IWT (Flemish government).
Actual members of VSB vzw are: Umicore (chairman), VITO (project coordinator), E-Vision, Tractebel, Electrabel, Distrigas, Aspiravi, SPE, Sustainable Energy Ventures, Solvay, Vrije Universiteit Brussel, Université Libre de Bruxelles, Universiteit Gent, Katholieke Hogeschool Limburg, Linde, Tech2bizz consulting, Atlas Copco, Laborelec, Microtherm, Energo, Emrol.
This group is an interesting platform to discuss the future of hydrogen and fuel cells in Belgium.

6.3 Results

Nowadays no concrete projects on hydrogen as energy carrier are in operation. Most industries focus their efforts in cooperation with international partners abroad, while limited research and development take place at universities and research institutes.

In order to introduce hydrogen as an energy carrier in Belgium in this paragraph possible objectives and instruments are suggested in the areas of:

* Market development
* Demonstrations
* Research & Development
* Policy & Framework

6.3.1 Market development

Generally speaking, the introduction of a new energy vector is driven by economic characteristics by which services can be supplied using this new energy vector, and that it is supported by an infrastructural and institutional framework allowing for the development of such service supply.
Regarding hydrogen as energy carrier some large demonstration projects are realised, but the economics of hydrogen technology do not meet the requirements of the market for the moment. Therefore a dedicated policy regarding market introduction has to been defined.

6.3.1.1 Possible policy objectives

Talking about hydrogen and fuel cells, following applications are treated here:

- portable applications
- transport applications
- stationary applications

In this chapter these possible markets will be discussed more in detail.
Before going into details it is very important to realise that a successful market introduction of hydrogen requires that hydrogen technologies are superior to the competing (conventional) technologies: a 'blind' introduction of hydrogen without assessing the 'competitors' of hydrogen is by definition a mistake.

Portable applications
Portable applications of hydrogen and fuel cells (e.g. laptops, mobile phones, cameras,….) are considered to be an 'early market' for application of fuel cell technology (see figure 6.1).
The High Level Group on Hydrogen and Fuel Cells expects that in 2020 every year about 250 million portable H_2 fuelled Fuel cell systems will be sold.
Introducing fuel cell technology in this kind of applications is very important for the global acceptance for fuel cell and hydrogen technology, but this has almost no effect on the national and regional energy supply systems, CO_2- emissions and local air pollution. Therefore, this application will not be discussed here.

Transport applications
Based upon the vision assessment (chapter 4) and the European activities and focus on hydrogen and fuel cell technology, transport is an important market application for hydrogen as energy carrier.
This is mainly based on the fact that almost 70% of EU's final oil demand is used for transportation of which the majority is for road transport. Therefore, alternative fuels and technologies for road transport that meet the requirements of security of energy supply and reduction of greenhouse gas emissions are urgently needed.
The High Level Group on Hydrogen and Fuel Cells estimates for 2020 that annually 0,4 – 1,8 million hydrogen fuelled fuel cell vehicles will be sold in the EU. Even at the lower end of this estimate, a few thousand hydrogen filling stations will be required, probably in clusters around the most populated European cities.

The vision assessment of the Belgian experts (chapter 4) expects a market share of hydrogen vehicles in transport in Belgium in 2020 ranging from a few % up to 40%.

In chapter 3 results of MARKAL-calculations show an introduction of fuel cell vehicles between 2010 and 2030, regarding the type of vehicle and the scenario definition. Important in these calculations is the level of investment cost and 'total cost per vehicle-kilometre'.

Stationary applications
The Belgian experts as well as the vision of the European Union expect the first stationary market to be the market of UPS (uninterruptible power supply) system, e.g. for telecommunication infrastructure. As these UPS-systems run a limited number of hours per year the energy saving and emissions decreasing impact of these systems is very limited.

Stationary markets with a large impact are:

* residential CHP systems	(1 kW – 10 kW)
* CHP-systems for buildings	(10 kW – 1 MW)
* large industrial CHP-systems	(> 1 MW)

Although several large scale demonstration programs on residential CHP-systems are being carried out in the United States of America, Europe (Germany, The Netherlands, Switzerland) and Japan, the experts don't expect an early large scale introduction of these systems in Belgium.

At the moment the largest CHP-systems tested on-site have an electric power of about 200 kW (see annex 2), fuelled by natural gas. These CHP-systems are tested on-site in several tens of places (mostly high-temperature systems). The first market applications will be expected in the valorisation of waste gases (landfill gas, biogas,...). The Belgian experts didn't expect an introduction of these systems on the short term.

Large systems for stationary systems (> 1 MW) are only built on a few places in the world and the experience with this technology is not sufficient to estimate a time horizon of introduction.

The European Union estimates that in 2020 yearly about 100.000 to 200.000 stationary CHP-systems will be sold (total power 2 – 4 GW); in this figure small scale residential systems (1 – 5 kW) as well as larger CHP-modules (200 – 500 kW) are covered.

These European estimations have to be in line with already determined targets on the introduction of renewable energy (e.g. EU directive 2001/77/EC share of electricity from renewable energy sources within EU-15 shall reach 22% (EU-25: 21%)).

Although experience with stationary systems is rather limited and the Belgian experts didn't expect a large introduction, it will be probable that introduction of this technology in Belgium will be in parallel with introduction in other European member states.

An important issue regarding the introduction of hydrogen as energy carrier is that markets can compete: will available hydrogen be used in transport or in stationary applications? This competition between application areas is already the case for biomass. The limited availability of biomass results in a competition between stationary and transport applications; in practice the success of using biomass in a specific market is determined by policy actions/instruments (guaranteed tariffs, exemption from taxation).

6.3.1.2 Possible policy actions/instruments

The strongest factor influencing the choice of use of hydrogen is the economic attractiveness. As hydrogen as energy carrier has no economic attractiveness for the moment it is necessary to define policy actions/instruments to influence the economics or certain options changing/correcting the market forces.

Portable applications
From the point of view of the government no specific actions are needed regarding the introduction of this technology, besides checking the confirmation with existing codes and standards on product norms. In practice this means the correct and in time implementation of European guidelines in Belgian and regional legislation.

Transport applications
The development of hydrogen fuelled vehicles is mostly carried out in other countries. However, as Belgium is an important car manufacturer (General Motors, Volvo, Ford, Volkswagen), it is useful to be well informed about the status of hydrogen fuelled vehicles. It will also be useful to show that the Belgian government is interested in innovative vehicle technology.
Regarding the hydrogen fuelled buses, Belgium has some companies active in development and manufacturing of buses. So, in this part of the transport applications more effort can be spend on well defined R&D programs with the industry and the research world.

From a policy point of view the transport market has some important issues:

- taxation of fuel and vehicles
- hydrogen infrastructure

As a large part of the actual fuel price a consumer pays, consists of taxes and excises, it is important to define the cost structure of 'alternative fuels', such as biofuels and hydrogen. The production, storage and distribution of hydrogen is expensive compared to the 'conventional oil', a de-taxation of hydrogen production and distribution is an important issue the government has to discuss.
Regarding the investment costs of hydrogen fuelled cars the government can give grants or fiscal benefits to hydrogen cars in the short term. Such an action exists in Belgium already for environmentally interesting cars.

Also on the property tax such as motor vehicle tax the government can grant advantages to hydrogen vehicles.
Within the European deployment strategy fiscal incentives for first generations of hydrogen powered vehicles as well as the realization of first fleets (public services, taxis,…) have been proposed.

Another very important issue in the transport applications is the hydrogen infrastructure. Regarding infrastructure, hydrogen, needing a new infrastructure, has to compete with liquid biofuels that are able to use the existing infrastructure.
At the moment almost all vehicle developers state that one has to have hydrogen on board of the vehicle (in the '90's methanol as fuel on board was more popular).
The absence of hydrogen fuelled vehicles and a hydrogen infrastructure is often characterized as a chicken-and-egg problem: it is not useful to develop very performing hydrogen vehicles as there is no hydrogen infrastructure; it is not useful to build a hydrogen infrastructure if you don't have good hydrogen vehicles.
Of course it is not possible to ask consumers to build an hydrogen infrastructure (although some ideas of home-fuellers are being tested now), so the government has an important role to play in building the hydrogen infrastructure.

One of the major lessons learned of the CUTE-project (27 busses in 9 European cities) is that implementation of a limited hydrogen tank infrastructure for public transport (so a well defined amount of people will use this) is not simple.
Starting thinking of a hydrogen station, a lot of discussions start between vehicle developers, hydrogen producers and local authorities. One of the problems is that the different actors have a different background in hydrogen. Besides this the public opinion about hydrogen is a key-element for local authorities to take into account.
So, the major role of policy makers regarding hydrogen infrastructure is that the government plays a very clear and straightforward role of coordinating and communicating this process between partners and all citizens involved.
Building a new hydrogen infrastructure implies also that new regulations and legislation have to be developed. One major issue is the lack of experience in handling hydrogen for non-industrial or public applications. Government must play a catalyzing role and not a delaying role in this process.

Specific for Belgium it is useful to dialogue from the beginning between the Belgian and regional permitting bodies in order to avoid regional differences.

In order to introduce hydrogen vehicles in Belgium on a large scale, several visual demonstration projects hydrogen infrastructure have to be realized to gain experience.

In the future the hydrogen safety issue will become even more severe than now: nowadays in the vehicles hydrogen is stored at about 350 bar, while in the future it is expected that an hydrogen storage pressure in a vehicle should be about 700 bar (because of reaching a sufficient action-radius).

Stationary applications
Nowadays most systems in stationary applications run on natural gas: PEM-and PAFC-systems use a natural gas reformer, while the high temperature fuel cells have an internal reformer. Using conventional fuels, makes the introduction of fuel cell systems easier from the viewpoint of safety and regulations.

However in the future conventional fuels will become more scarce, so an increasing amount of systems will use directly hydrogen as fuel. In that case the same important discussion on hydrogen infrastructure will arise.
A large scale introduction of an hydrogen network will require the similar activities as the introduction of a natural gas network in Belgium. A major decision will be if hydrogen production will be centralized and a pipeline network will be built, or the production of hydrogen will be decentralized. At the moment some companies promote hydrogen production at home.
It will be clear that within a large scale introduction of stationary hydrogen systems the government has to play an important role regarding regulation/legislation, communication, financing, licensing,….

6.3.2 Demonstrations

6.3.2.1 Possible policy objectives

Before a large scale integration of hydrogen systems will be reality a lot of demonstration projects in different applications, with different technologies, on different places have to be realized. The experience gained in these demonstration projects is necessary to be able to introduce large scale hydrogen systems in a proper way.

A possible objective for the government is to make a good selection of some large scale, visible demonstration projects, showing know-how and possibilities of hydrogen in Belgium, in line with the European ambitions.

As large scale demonstration projects are expensive, it is important that the federal/regional government proposes concrete demonstration projects, based upon promising markets for the Belgian situation. It is also important to use as much Belgian know-how as possible in these large scale demonstration projects, so that the demonstration projects can be used as a show-window for the Belgian industry.

Regarding defining demonstration projects in Belgium it is useful to analyse if the existing network on industrial hydrogen can be used in a demonstration project.

6.3.2.2 Possible policy actions/instruments

Large demonstration projects require a lot of money and are usually not profitable. Therefore the federal and regional governments have to reserve financial means for realizing these projects. Experience from existing large scale demonstration projects shows that the budget for these projects vary between 5 and 20 million euro. That is way it is very useful to define demonstration projects that can count upon interest form regional, federal as well as European governments, so that financial support from these three governments can be used in funding demonstration projects. From Europe the use of European structural funds should be maximized.

An important task of the government in realizing a demonstration project is to communicate the project very clearly and directly to the citizens involved, so that the people are positive on the project and the NIMBY-effect can be minimized.

The government should encourage people to create consortia between private companies and public authorities.

Another stimulating action for large scale demonstration project is to develop public/private initiatives for the creation of industrial districts or the joint realization of infrastructure hydrogen networks.

Important regarding policy is that the government coordinates and communicates all issues regarding safety, regulation, licensing and legislation.

6.3.3 Research and development

6.3.3.1 Possible policy objectives

Within Belgium no specific research and development program of hydrogen and fuel cells exists. For specific individual projects hydrogen and fuel cell developers can get grants from the government.
This makes that R&D activities in Belgium are very fragmentized, making R&D on high level not easy. The consequence of such an inefficient structure of hydrogen R&D is that on international podia hardly any Belgian players are present.
The poor visibility of hydrogen and fuel cell R&D in Belgium makes that international partners don't ask frequently Belgian partners in international consortia. Result is that in the European Energy research, focusing more and more on hydrogen and fuel cells, the Belgian participation becomes lower and lower.

A possible objective of the government should be the definition of a clear R&D program on hydrogen and fuel cells on a Belgian level; regionalization of this kind of international R&D is conflicting with the international character of hydrogen and fuel cell research.

Another objective could be an increasing participation of Belgian actors in international (European) high level R&D.

6.3.3.2 Possible policy actions/instruments

A Belgian R&D program on hydrogen and fuel cell technology requires funding. To maximize the efficiency and effectiveness of such an R&D-program one needs to:

- minimize overlapping or duplications of projects
- evaluate the priorities and relationships between the funded projects
- concentrate resources on 'strong' strategic projects

It is important to define this program together with the Belgian industrial R&D-world. Such a program should have a clear structure and well defined targets.
A clear example of an efficient organization of R&D on hydrogen and fuel cells is Japan. In Japan some large industrial companies have to make progress in hydrogen and fuel cell technology in order to introduce their systems at world level. To solve technological issues regarding fuel cells, the Japanese government opened a National Laboratory on fuel cells in April 2005; in April 2006 a National Laboratory on hydrogen technology will be opened.

Not only within the definition of a R&D-program industry, scientific world and government should work together: also in concrete projects good mixed R&D-teams (industry, research institutes, universities) are essential to have results at the end of the project.

As hydrogen and fuel cell technology is an international theme, it is very important that the presence of Belgian R&D in the European R&D-area increases. A way to realize this is that industry and government play an active role in the definition of European R&D-programs.
At this moment the structure and contents of the 7^{th} Framework program and of the Joint Technology Initiatives are defined within Europe. An active participation of Belgian actors in this definition phase is very important.

6.3.4 Policy & Framework

6.3.4.1 Possible objectives

Following objectives can be defined for policy makers:

- dissemination of information to the public
- coordination of the strategies at Europe, national, regional and local levels
- introduction of hydrogen and fuel cells in education programs
- facilitating clearly defined codes, standards, licensing, permits, …

6.3.4.2 Possible policy actions/instruments

Dissemination of information to the public
In case that hydrogen and fuel cells become a large success in the future, it is necessary to involve as much as possible people in this world-wide change.
Last years a lot of non-information on hydrogen and fuel cells has been published all over the world; in order to estimate the possibilities and the threads of hydrogen and fuel cell technology it is necessary to have a clear and objective view on the real status of technology and economics.
Therefore the government has to develop channels to obtain crucial information on hydrogen and fuel cell technology. As most R&D and projects are abroad, a good networking with high level international organizations is necessary.

A way to start this networking is joining Implementing Agreements within the International Energy Agency. An active role of Belgian representatives in the relevant IEA-annexes is important to start international networking. The federal government, partly supporting these activities financially, should ask and spread information in exchange for the money they give.

In Flanders a network (Vlaams Samenwerkingsverband Brandstofcellen), consisting of about 25 members, is partly supported by the Flemish government. This cooperative organizes every 3 months a workshop in which the most important developments are discussed and important international hydrogen actors are invited to present their vision and targets. It would be useful to extend this network to a Belgian network.

Beside information exchange between government and industry, it is very important to communicate hydrogen issues with the public. This communication can be made concrete as soon as clear R&D-projects and large scale demonstration projects have been started up.

Coordination of the strategies at Europe, national, regional and local levels
Within the Belgian context it is not that easy to coordinate the different levels in a proper and efficient way: a lot of R&D in Belgium is spread over the whole country.
However, hydrogen and fuel cell technology is an international item and the R&D has just started.
This means that a more coordinated R&D program on hydrogen and fuel cells could be an interesting option to communicate with the European level. Such a visible Belgian program fits in the philosophy of the EU, as the EU wants to work closely together with programs of member states.

Introduction of hydrogen and fuel cells in education programs
In order to have enough capable people in the industry and scientific world, it is important that people at school will get a basic know-how on this technology.
By introduction of specific programs in the secondary school more pupils can become interested in this new technology.
Besides interest, it is also very important for a large scale introduction of hydrogen and fuel cell technology, that as much as possible people are familiar with this technology: specific education programs can play a major role to achieve this.

Facilitating clearly defined codes, standards, licensing, permits, …
The few large-scale demonstration projects have shown that a lot of energy and frustration has to be put into issues as 'codes, permits, standards, licenses,…'.
Most important is to tackle all these questions/problems as soon as possible on a proper way.
Therefore a clear coordination of all these activities should be done by the government.
On the international scene several organizations are active in defining codes and standards for hydrogen and fuel cell technology: it would be very interesting if in some important networks, Belgium should be represented in these meetings. Being member of these organizations results in first-hand information and allows to discuss directly problems in Belgian projects with international experts.

6.4 Interaction with the policy on biofuelmarkets in the EU

6.4.1 Introduction

The introduction of hydrogen will be competing with other policy driven evolutions. The most direct and short to medium term evident case is the one of biofuels. Biofuels are an alternative fuel for transport and promoted to lower the dependence of imported fossil fuel, and to lower CO_2 emissions of the transport sector.

6.4.2 Competing uses of biomass

In fact, three different uses of biomass are competing:

- Production of food
- Production of materials from biomass (e.g. fibres for the production of insulation materials, lubricants etc.)
- Production of energy carriers, both for stationary and for transport purposes

On the other hand, the agricultural land area is limited. In addition, there are certain restrictions such as protected areas for nature conservation (national parks, bird migration areas etc.), areas restricted to military use etc.

The three different biomass uses mentioned above are only to a certain extent integrated into national or regional value chains. Those sectors representing a world market, such as certain agricultural food products (soy beans especially as animal feed, cerials etc.), are flexible to adapt to changing economic environments such as new competing land uses. It has to be taken into account here that the agricultural sector is a strongly regulated sector in Europe with a complex structure of subsidies and regulations.

Analysing the potential for biomass availability for energy purposes in general requires certain assumptions on the future agricultural policies in Europe. On this basis, the land area available to alternative uses is calculated, taking into account nature protection goals and other restrictions. In addition, residual biomass from agricultural and industrial processes is assessed. The next step of the analysis is then the assessment of the actual use of biomass for energy purposes resulting in the potential for additional use. The production of primary materials from biomass is in general not assessed quantitatively as this is a very complex sector with a very large number of potential products, economic structures, competition etc. Thus, assessments of biomass potential depend on assumptions on the development of the agricultural sector, and in general do not take into account a potential land use for the production of primary materials (except already existing production of primary materials).
Taking this as a starting point, the competition between stationary uses of biomass energy, and transport fuel production from biomass can be analysed.

6.4.3 Present situation

Traditionally, biomass is used for heating purposes in the form of firewood. Since a number of years, the use of biomass in combined heat and power plants (CHP), in the production of bio-gas through a fermentation process and the use of wood pellets in pellet fuelled boilers for space heating is increasing.
The following table shows that about 20%-30% of the entire solid biofuel potential in EU-25 is already used presently. Industrial wood and scrap wood is used for heat and power production to a large extent and will thus most probably not be available for transport fuel production.

Potential for residual wood	1.8 – 2.9 EJ/yr
Potential for other lignocellulosic biomass	0.6 – 1.4 EJ/yr
Total potential for lignocellulosic biomass	2.4 – 4.3 EJ/yr
Potential for wood from fast growing trees	1.9 EJ/yr
Total potential for lignocellulosic biomass	*4.3 – 6.2 EJ/yr*
Dedicated harvesting of timber for domestic firewood (not included in the potential)	0.6 EJ/yr
Use of solid biofuels from residual biomass	1.5 EJ/yr
Total solid biofuel use 25[1,2]	*2.1 EJ/yr*
Share of biofuel potential used presently	20% - 30%

Table 6-1 : Biomass potential and present use in EU-25

The total solid biofuel use includes about 1.0 EJ/yr for residential buildings in EU-25 in the year 2002.
Replacing heating oil and liquefied petroleum gas used for space heating would require about 2.5 EJ/yr of biomass. Together with the already used 2.1 EJ/yr this represents 4.6 EJ/yr, or about the lower limit of the available potential.
Improved insulation of buildings and efficiency increases in biomass combustion could significantly reduce energy requirements without compromising the services delivered, and would thus increase the biomass availability potential.

This analysis of availability potential and current use of biofuels as well as the energy consumption for space heating shows how limited the biomass potentials are, even if power generation and transport fuels are not included.

6.4.4 Factors influencing the competition

Several factors influence the balance between stationary use of biomass and the production of transport fuels:

- Political targets
- Political framework and support programmes
- Market forces
- Infrastructure aspects
- Availability of technology.

These boundary conditions on different levels make it a very dynamic balance between stationary and mobile biomass uses. The following chapters describe qualitatively the different influencing factors. A quantitative analysis and prediction is beyond the scope of the present report.

6.4.4.1 Political targets

Quantitative political targets have been set at EU level for the share of renewable sources for power production and for the share of alternative transport fuels. Main motivation for these targets are the goals for greenhouse gas emission reductions for climate protection and concern of a secure energy supply. The transport sector depending to more than 90% on crude oil and the increasing energy import dependency of the EU are a matter of growing concern.
In accordance with the Kyoto protocol the EU has committed to reduce the GHG emissions by 8% until 2008-2012.

According to EU Directive 2001/77/EC the share of electricity from renewable energy sources within EU-15 shall reach 22% (EU-25: 21%) and the share of renewable energy sources of the primary energy consumption should be increased from 6% to 12% until 2010.
In 2000 the share of electricity from renewable energy sources within EU-25 was about 13.8% and the share of renewable energy sources of the primary energy consumption was about 5.8%[3,4].
For the proposed alternative transport fuel shares see chapter 2.2.1.

The European Commission has agreed with ACEA , the umbrella association of the European car industry, a self commitment to reduce the CO2 emissions of the fleet of new cars to 140 g/km by 2008. This value is equivalent to a fuel consumption of about 6.0 l gasoline or 5.3 l diesel per 100 km. A further reduction to 120 g/km which is equivalent to a fuel consumption of 5.1 l gasoline or 4.5 l diesel per 100 km is included as an option.

6.4.4.2 Political framework and support programs

The political framework for the support of renewable power generation is probably the most important factor at present.
There are fixed feed-in tariffs for electricity from renewable energy sources in Belgium (only Flanders and only for photovoltaics), Germany (for all renewable energy sources), Estonia, Finland, France (wind power), Greece, Latvia, Luxembourg, Austria (all renewable energy sources), Portugal, Slovenia, Spain (all renewable energy sources), Czech Republic, Hungary and Cyprus. These fixed tariffs provide good conditions for commercial development guaranteeing a profitable operation of the installations. Without similar regulations for transport fuels, this is a strong factor pushing towards stationary applications of renewable energy including biomass.

At the same time, an exemption of biofuels from mineral oil tax effective in Germany since February 2004[5] opens the competition between stationary and mobile applications of biomass. At present, both biofuels production plants and biogas power plants are on the increase in Germany, which indicates that both political framework conditions result in similar economic advantages.

On the other hand, natural gas as transport fuel also takes advantage from a significant reduction of mineral oil tax. As a consequence, biogas (purified and compressed) is not offered as a transport fuel as the support for natural gas makes this an unattractive option.

6.4.4.3 Market forces

The strongest factor influencing the choice of use of biomass is the economic attractiveness.
The two preceding chapters have demonstrated though, that political choices can strongly influence the economics or certain options changing / correcting the market forces.

Important market forces in the energy area are the prices of the different energies. The present high oil, natural gas, coal and uranium prices influence all uses of energy.
A relative increase in the price of fossil energy sources does not automatically favour mobile uses of renewable energies versus stationary uses, but road transport is highly dependent on mineral oil, which shows the strongest price fluctuations. But there are certain indications that consumers are probably more prepared to pay higher prices for energy to secure their "auto-mobility" than for other energy uses.

Another factor to be taken into account here is the fact that the potential to reduce the energy consumption of cars is relatively limited compared to stationary energy uses. Especially the large energy savings potentials in space heating will be tapped, even more so as they are to a significant extent already economical.
It should be noted that the transport sector becoming a new customer of renewable energies will significantly change the market situation as the quantities involved are enormous.

6.4.4.4 Infrastructure aspects

The infrastructure for the production, distribution and refuelling of hydrogen as transport fuel is not available and has to be built up. This is a big challenge which will require time and significant investment.
Liquid biofuels on the other hand can make use of the existing infrastructure, i.e. road tanker trucks and refuelling stations. They can even be blended into the conventional fuels.
Consequently, liquid biofuels have a higher chance to be competitive to stationary biomass uses.

6.4.4.5 Availability of technology

The commercial availability of technologies for energy conversion, e.g. fuel production or power generation, is an important factor. Biomass gasification to hydrogen or to BTL fuels is not yet commercially available, nor are hydrogen vehicles. By the time these technologies are available on the market, the biomass potentials may be used to a large extent for stationary applications. Once established, there are certain constraints on immediate changes to other applications even if they are more profitable, as investments have to be depreciated.

6.4.5 Conclusion

The competition between the use of biomass for stationary applications or for the production of liquid biofuels with the production of hydrogen fuel depends on a multitude of factors. A number of them can be influenced by political decisions.

Nonetheless it is clear that transport fuels produced from biomass (be it hydrogen or liquid biofuels) cannot cover the energy needs of the transport sector entirely, even if the entire biomass potential not yet used would be reserved for this and if the fuel consumption of road transport would be reduced significantly.

On the other hand it is expected that the transport fuel sector, given the anticipated worldwide peak of mineral oil production, the continued growth of the global demand, and the climate protection efforts, will become a big additional consumer of renewable energy, both biomass and electricity.

In contrast to the biomass potentials, the renewable electricity potentials in Europe are large enough to supply both the stationary sector and the transport sector. The potential is multiplied by considering the renewable power potential outside the EU, e.g. Northern Africa.

6.5 Conclusions

At the moment a lot of countries (Europe, United States of America, Japan, Canada,….) are developing an energy policy for introduction of hydrogen in the energy system. In Belgium for the moment no energy policy on hydrogen and fuel cells exists. Therefore the suggestions for developing a Belgian policy on hydrogen and fuel cells is based on the current European policy.

The main conclusions for Belgian policy makers can be summarized in following statements:

* start thinking/acting on hydrogen
* participate actively in the development of an European Vision
* dialogue with Belgian experts (industry, research,….)
* introduce hydrogen and fuel cells in education programs
* network with high level international organisations
* define relevant Belgian vision and targets within policies on environment, energy and innovation… and compatible with the European vision
* define a Belgian action plan (demonstration, R&D,…)

Start acting on hydrogen

Before Belgium can decide to implement the introduction of hydrogen in the energy policy, it is necessary to assess the impact (ecological, economic, innovation, technology development,….) of this on the Belgian society.
Therefore a program has to be defined to calculate/map this impact in an objective way. (calculating specific scenario studies, discussions with international policy makers, discussion with Belgian industry and research,…).

Participate actively in the development of an European Vision

Last years Europe has been very active in defining a hydrogen road map for Europe and recently an European discussion platform has been installed to discuss hydrogen and fuel cells in Europe. Since august 2005 two important European reports on hydrogen and fuel cells are available: 'Strategic Research Agenda' and 'Deployment Strategy'.
Both reports are essential to define a Belgian policy on hydrogen and fuel cells being compatible with the European Vision.
Therefore is it strongly suggested that the Belgian policy makers participate actively in the European platform.

Dialogue with Belgian experts (industry, research,..)

As every country has its own background and ambitions on hydrogen, it is not possible to copy the complete European vision to each country. Therefore Belgian policy makers need to have a clear view on the possibilities/ambitions of industry and R&D in Belgium, in order to synchronise the Belgian efforts to the European targets as efficient as possible.
Presenting specific Belgian possibilities and targets of Belgian industry and R&D to Europe will give a high visibility of Belgium with respect to the development of an European hydrogen and fuel cell policy.

Introduce hydrogen and fuel cells in education programs

Hydrogen and fuel cells are a rather new technology and in order to be able to work within an international scientific world, it is necessary that at least at universities education on hydrogen and fuel cells will be started up or extended. This is crucial for making Belgian scientists becoming more involved in international R&D projects.

Network with high level international organisations

The European platform is the most important international organisation with respect to the development of a Belgian hydrogen policy.

But an active participating in the International Energy Agency is also a necessity to be able to assess the international context (technological, economics, ecological, policies,…) of hydrogen and fuel cells. Within IEA the implementing agreements 'Advanced Fuel cells' and 'Hydrogen' are most important for this issue. Since several years Belgium is active in the implementing agreement 'Advanced Fuel Cells', but it is recommended that Belgium should become a member of the implementing agreement on 'Hydrogen'. Last year the Belgian participation in the 'IEA Hydrogen Coordination Group' resulted in necessary additional information for Belgian policy makers on hydrogen.

Define relevant Belgian vision and targets within policies on environment, energy and innovation… and compatible with the European vision

Belgium should not just copy all international actions into the Belgian policy framework. It is much better to define a real Belgian vision and targets on hydrogen and implement these in policies on environment (e.g. NOx, post-Kyoto-targets, transport ,…) energy (nuclear energy, renewable energy,…), innovation (technological developments on hydrogen and fuel cells in Belgian industry and R&D,….).
Of course this Belgian Vision and Research agenda should be compatible with the European initiatives.

Define a Belgian action plan (R&D, demonstration,…)

Based upon a Belgian vision on hydrogen and fuel cells, the Belgian government should define a concrete action plan in close consultation with the regional authorities.
Within this action plan concrete targets on Belgian R&D activities (industrial R&D in close cooperation with the Belgian scientific world (universities, research centres,…) should be defined. Based on promising introduction markets for hydrogen in Belgium, the Belgian policy makers should suggest the contents and structure of large, visible demonstration projects.

6.6 References

1 Energy Statistics of Non-OECD Countries 2001-2002; IEA Statistics, 2004 Edition; OECD/IEA, 2004

2 Energy Balances of OECD Countries 2001-2002; IEA Statistics, 2004 Edition; OECD/IEA, 2004

3 COMMUNICATION FROM THE COMMISSION TO THE COUNCIL AND THE EUROPEAN PARLIAMENT: The share of renewable energy in the EU; Commission Report in accordance with Article 3 of Directive 2001/77/EC, evaluation of the effect of legislative instruments and other Community policies on the development of the contribution of renewable energy sources in the EU and proposals for concrete actions; Brussels, 26.5.2004 COM(2004) 366 final - http://europa.eu.int/comm/energy/res/legislation/country_profiles/com_2004_366_en.pdf

4 European Commission Directorate-General for Energy and Transport: Renewable energy to take off in Europe? Memo 2004 http://europa.eu.int/comm/energy/res/legislation/country_profiles/2004_05_memo_res_en.pdf

5 BMU-Pressedienst Nr. 043/04: EU genehmigt Steuerbefreiung für Biokraftstoffe, Berlin, 18 February 2004, http://www.bmu.de/pressearchiv/15_legislaturperiode/pm/pdf/5530.pdf

7 CONCLUSION

To assist Belgian politics, this project has as aim to make the first steps for Belgium into hydrogen. It made available the international knowledge on hydrogen and it developed tools in order to be able to assess the role of hydrogen in Belgium in the future. These tools have been tested by a preliminary scenario formulated by an expert panel of mostly industrial representatives.

The following items have been worked out in this project:

* databases with international knowledge and experiences on hydrogen
* hydrogen module within MARKAL-TIMES, illustrated by a scenario calculation
* initial technology assessment on hydrogen, focussed on the scenario
* translation of the progress in foreign legislation and licence procedures on hydrogen
* definition of relevant policy issues concerning hydrogen

Each item has been elaborated in a separate chapter in this report. The conclusions of each chapter are given below.

- **Databases on hydrogen knowledge and experiences**

Hydrogen is traditionally used by the chemical industry in Belgium. Using hydrogen as an energy vector is however new. The advantage of hydrogen as an energy vector is that it is clean (no greenhouse gases are formed at oxidation) and that it can be stored (this is an advantage over electricity).

Hydrogen in its free form does not just exist on earth. It has to be generated. However, it can be made from every primary energy source (section 2.3.1, annex 1). The main pathways for carbonaceous fuels are reforming (especially for natural gas) and gasification (in particular for coal) into hydrogen and carbon dioxide. Other energy sources like the sun and wind can be transformed into hydrogen by means of electrolysis. For electrolysis electricity is needed.
The property that hydrogen can be made from all sources makes it a versatile energy carrier able to help the security of energy supply. Hydrogen obtained from the pathway wind/sun – electricity – electrolysis – end use is free from GHG emission. The pathway natural gas – hydrogen – fuel cell car is more efficient than natural gas – internal combustion engine car (annex 3). If hydrogen production from fossil fuels is combined with carbon capture and sequestration the emission of greenhouse gases could be drastically reduced.

Based on the availability of hydrogen, the use of hydrogen in fuel cells is interesting because of the potentially high efficiency compared to classical energy transformers. There exists five types of fuel cells. High temperature fuel cells can also use natural gas or biogas directly as fuel.

An actual problem is the cost level of hydrogen production and fuel cells. An important explication is the small amount of fuel cells and hydrogen production units that are assembled per year. At the turning of the millennium governments started with demonstration projects, like the CUTE buses in 9 European cities (section 2.3.2, annex 2). This stimulates learning by doing. The scale will increase towards complete hydrogen regions. This is the way that automated assembly can start leading to lower costs.

For Europe the desired progress in hydrogen and fuel cells from demonstration programmes towards market introduction is described in the Deployment Strategy, made by the European Hydrogen and Fuel Cells Platform (section 2.3.4, annex 2). This strategy is assisted by a Strategic Research Agenda, filling in future performance and costs.

The demonstrations programmes lead to a demand for regulations. The three worldwide standardisation organisations – IEC, ISO and UN/ECE – have specific working groups for fuel cells and hydrogen (see section 2.3.2). They work in close connection. The countries make their own standards too and rules for permitting. An overview of all regulation and standards has been published in this project as a website with direct links to the organisations behind it: www.podopadd.be.tf.

- **Techno-economic evaluation**

The purpose of this chapter is to illustrate the use of the MARKAL-TIMES model for the evaluation of hydrogen use in the energy system. In a fist step, the MARKAL-TIMES technology database was updated to take account of the recent state of knowledge about hydrogen technologies on the production as well as on the consumption side.

In a second step, we then made some scenario runs with the model. These were compared with a reference run that includes the current Kyoto target and the nuclear phase-out decision. Two scenarios were considered. In a first scenario, we assume that the transport sector is forced to reduce its CO_2-emissions below the emissions of the sector in the reference scenario. The second scenario then assumes a harsher post-Kyoto constraint compared to the post-Kyoto target that was assumed in the reference scenario.

The simulation results suggest that hydrogen fuelled cars will enter the market in any of these two alternative scenarios, but not in the reference scenario. These results seem to be fairly robust, even when considering a sensitivity analysis with reduced investment costs for hydrogen technologies. In that case hydrogen technologies would from 2040 onwards enter the market in the reference scenario.

However, the scenario runs provide no consensus on the *type* of hydrogen vehicles that will enter. Depending on the scenario and on the market segment that is considered, it will either be hydrogen combustion or fuel cell cars. The results are also rather sensitive for the assumed investment costs. It is therefore best not to draw firm conclusions for as far as the car type is concerned.

Finally, we also found the robust result that hydrogen buses are not to be expected in the time horizon considered by the MARKAL-TIMES model. This result stands opposite to the conjecture by hydrogen experts that one of the first and most important applications of hydrogen would be found in the bus segment.

- **Technology assessment**

Methodology: evaluation of the technology assessment

1. The workshop approach proved to be an efficient tool to collect information from the experts.
   On a structured and interactive manner the different experts could explore each others perceptions and assumptions. It was not the intention to reach a consensus on the four statements. It resulted in an overview of, sometimes differing, visions on how to realize a feasible and probable introduction of hydrogen in Belgium.
   The outcomes of the workshop were very valuable and turned out to be decisive for the further development of the project.

2. The well-balanced selection of experts resulted in a very productive discussion in which a variety of perspectives was covered. Sixteen participants was an ideal number: it gave the possibility to work in small groups of four people, but it also allowed to have a good and interactive discussion with a broad scope in the plenary session.

3. The face to face interviews were very crucial to the success of the workshop. They allowed each participant to make more explicit his own position on the 4 statements in a very fast and efficient way.
   The reactions of the participants after the workshop confirmed this positive conclusion.

4. The choice of a professional facilitator seemed to be a good decision. Being not an hydrogen expert, the facilitator was not involved in any technical discussion, and so, he was able to moderate the discussion in a impartial and unbiased way, paying attention to the right methodological approach.

Results

1. The major strong points of hydrogen in Belgium

* A lot of competence and experience on industrial hydrogen is available in Belgium.
* An extensive hydrogen and natural gas distribution network in Belgium for large industrial consumers already exists.
* The size of the country, the dense population and road network and consequently the high concentration of potential consumers result in lower costs for distribution of hydrogen to end-users.
* The existing natural gas network can be used for new projects for a mixture of natural gas/hydrogen.
* There is a real opportunity for meeting CO_2 and other greenhouse gas reduction requirements by production of hydrogen.
* Hydrogen is able to produce/generate useful energy for a variety of applications, this means less dependence on fossil fuels.
* Efficient energy use by fuel cells: a fuel cell has a potentially high efficiency compared to conventional energy converters.
* Hydrogen as storage capacity can result in a more efficient use of renewable energy and nuclear energy.

2. The most likely chances of application of hydrogen in Belgium within 20 years

The most likely chance of application of hydrogen in Belgium within 20 years is in public transport, because central refuelling point and in UPS (Uninterruptible Power Supply), because its good reliability and its cost is less important.
The production of hydrogen has to be based on rational energy use and greenhouse gas reduction

3. The major impediments to the introduction of hydrogen in Belgium

* High costs
* Lack of Belgian roadmap
* Lack of coordination of R&D
* Lack of acceptance by public and industry

4. Suggestions for the government to introduce hydrogen in Belgium

* Apply favourable taxation on hydrogen as energy carrier, based on positive contribution to energy/environment/CO2 requirements.
* Active participation in international (EU and UN) organizations:
  – push for EU wide, or better worldwide, certification standards for products (e.g.) vehicles using hydrogen,
  – promote the development and implementation of consistent standards and regulations in accordance with EU standardization and legislation.
    The introduction of a new energy vector in the Belgian economy can only succeed and have impact if it is in line with a broad EU and even worldwide public and industrial consensus (type of applications, technological choices).
* Play an active role in the definition of a European R&D agenda (7th Framework programme).
* Harmonize regional and federal efforts on legislation and licenses before implementation.
* Initiate large-scale demonstration projects.
* Support public acceptance of hydrogen.

- **Translation of foreign progress in legislation**

Concerning the database on regulation we opted for an internet-site, being currently http://www.podopadd.be.tf/. A combination of Belgian and international information has been compiled and integrated in this web-site. The regulation database was checked with good success : however some legislation texts and links were added in the web site.

An important way to make hydrogen penetration easier should be to establish dialogue between Belgian Regional permitting bodies in order to avoid that the requiring company or public agency have to collect and organise different information to obtain permit. It should be stranger enough that, for example, the filling station requirements should be different in the three different Regions of Belgium.

We hold on to items (from experts) to be managed : it is important to carry out an active involvement in international (EU and international) organizations on product certification and standardization and to harmonize regional and federal legislation and licenses.

In order to apply the development of regulations, codes and standards for hydrogen applications in the transport sector, large attention has been paid to CUTE-ECTOS project (30 busses in 10 European cities). One major challenge, from the project, related to obtaining licences or approval from the authorities was :

- the lack of experience in handling hydrogen for non-industrial or public applications, and
- the absence of regulations explicitly expressing the safety requirements for such applications.

Regarding these foreign experiences, it is important to gain experience and to build competence within Federal and Regional administrations to achieve an effective approval process and in order to avoid Nimby reaction, we recommend to join legal procedure and population information in a complete and coherent mode.

- **Policy issues**

At the moment a lot of countries (Europe, United States of America, Japan, Canada,…) are developing an energy policy for introduction of hydrogen in the energy system. In Belgium for the moment no energy policy on hydrogen and fuel cells exists. Therefore the suggestions for developing a Belgian policy on hydrogen and fuel cells is based on the current European policy.

The main conclusions for Belgian policy makers can be summarized in following statements:

* start thinking/acting on hydrogen
* participate actively in the development of an European Vision
* dialogue with Belgian experts (industry, research,….)
* network with high level international organisations
* define relevant Belgian vision and targets within policies on environment, energy and innovation… and compatible with the European vision
* define a Belgian action plan (demonstration, R&D,…)

Start thinking/acting on hydrogen

Before Belgium can decide to implement the introduction of hydrogen in the energy policy, it is necessary to think about the impact (ecological, economic, innovation, technology development,…) of this on the Belgian society.
Therefore a program has to be defined to calculate/map this impact in an objective way. (calculating specific scenario studies, discussions with international policy makers, discussion with Belgian industry and research,…).

Participate actively in the development of an European Vision

Last years Europe has been very active in defining a hydrogen road map for Europe and recently an European discussion platform has been installed to discuss hydrogen and fuel cells

in Europe. Since august 2005 two important European reports on hydrogen and fuel cells are available: 'Strategic Research Agenda' and 'Deployment Strategy'.
Both reports are essential to define a Belgian policy on hydrogen and fuel cells being compatible with the European Vision.
Therefore is it strongly suggested that the Belgian policy makers participate actively in the European platform.

Dialogue with Belgian experts (industry, research,...)

As every country has its own background and ambitions on hydrogen, it is not possible to copy the complete European vision to each country. Therefore Belgian policy makers need to have a clear view on the possibilities/ambitions of industry and R&D in Belgium, in order to synchronise the Belgian efforts to the European targets as efficient as possible.
Presenting specific Belgian possibilities and targets of Belgian industry and R&D to Europe will give a high visibility of Belgium with respect to the development of an European hydrogen and fuel cell policy.

Network with high level international organisations

The European platform is the most important international organisation with respect to the development of a Belgian hydrogen policy.
But an active participating in the International Energy Agency is also a necessity to be able to assess the international context (technological, economics, ecological, policies,…) of hydrogen and fuel cells. Within IEA the implementing agreements 'Advanced Fuel cells' and 'Hydrogen' are most important for this issue. Since several years Belgium is active in the implementing agreement 'Advanced Fuel Cells', but it is recommended that Belgium should become a member of the implementing agreement on 'Hydrogen'. Last year the Belgian participation in the 'IEA Hydrogen Coordination Group' resulted in necessary additional information for Belgian policy makers on hydrogen.

Define relevant Belgian vision and targets within policies on environment, energy and innovation… and compatible with the European vision

Belgium should not just copy all international actions into the Belgian policy framework. It is much better to define a real Belgian vision and targets on hydrogen and implement these in policies on environment (e.g. NOx, post-Kyoto-targets, transport ,…) energy (nuclear energy, renewable energy,…), innovation (technological developments on hydrogen and fuel cells in Belgian industry and R&D,…).
Of course this Belgian Vision and Research agenda should be compatible with the European initiatives.

Define a Belgian action plan (R&D, demonstration,...)

Based upon a Belgian vision on hydrogen and fuel cells, the Belgian government should define a concrete action plan in close consultation with the regional authorities.
Within this action plan concrete targets on Belgian R&D activities (industrial R&D in close cooperation with the Belgian scientific world (universities, research centres,…) should be defined. Based on promising introduction markets for hydrogen in Belgium, the Belgian policy makers should suggest the contents and structure of large, visible demonstration projects.

ANNEXES

1 ANNEX 1: DATABASE ON TECHNOLOGIES

The aim of this annex is building up databases to collect information on technology, legislation and international experience on hydrogen. These databases serve as input for the tools and opinions to be developed. In this annex the state on hydrogen knowledge will be reviewed and summarized.

The information is based mainly on the following sources:
- The European Hydrogen and Fuel Cell Technology Platform: www.HFPeurope.org
- IEA Hydrogen Coordination Group, an incentive to bundle worldwide research providing a state-of-the-art overview on hydrogen research:
  "Hydrogen & Fuel Cells, Review of national R&D programs", IEA, Paris, 2004
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- R. Edwards, J.-C. Griesemann, J.-F. Larivé and V. Mahieu, 'Well to wheels analysis of future automotive fuels and power trains in the EU context', January 2004, often called: "CONCAWE-study"
- A.D. Little, 'Energy Efficiency and Emissions of Transportation Fuel Chains', Phase I Technical Report to Ford Motor Company, February 1996.

this annex includes detailed information on hydrogen production technologies, on hydrogen storage and distribution as well as on hydrogen conversion and end use. The section on end-use describes the types of fuel cells, the hydrogen application in vehicles and in stationary systems.

1.1 Production

Hydrogen is not a primary energy source like coal and gas. It is an energy carrier. Hydrogen can be produced in different ways: using reformer technology from fossil fuels or electrochemical from water and electricity. The impact of the use of hydrogen is defined by the production method used.

1.1.1 Electrolysis [1,2,3]

General principle

In electrolysis electricity is used to decompose water in hydrogen and oxygen. The decomposition of water by electrolysis consists of two partial reactions that take place at the two electrodes. The electrodes are separated by an ion conducting electrolyte and an ion-conducting separator (diaphragm). Hydrogen is produced at the negative electrode (cathode: H_2 + 4 OH^-) and oxygen at the positive electrode (anode: O_2 + 4 H^+ + 4 e^-). Conventional alkaline electrolysis works with an aqueous alkaline electrolyte. Also PEM (Proton Exchange Membrane) can be used to produce hydrogen. At this moment Alkaline FC is the preferred technology, especially for large scale production.[4] The technology is easily scaled up and easier to thermally manage.
The process is simple and well established technology both at large and small scale but energy-consuming. Interest in large scale production may result in improvements in terms of efficiencies and costs.
At this moment, less than 1% of hydrogen worldwide is produced by this process. Also in Belgium, the most hydrogen is produced by reforming (see further).
The environmental impact of hydrogen production by electrolysis and also its economics depend on the production method of the electricity used. Electrolysis is the only well established production process for hydrogen that need not rely on fossil fuels. The hydrogen produced has a high purity and can be produced on large and small scale

In the GM WTW study[3] different pathways are considered for hydrogen production by electrolysis. The energy supply efficiency and related greenhouse gas emissions depend heavily on the origin of electricity. The pathways considered are: the average European electricity mix, dedicated combined cycle gas turbine plant (CCGT) fuelled from EU NG mix and electricity generated from wind power (on- and off-shore). Regional electrolysis means that the hydrogen produced is transported by pipelines over a distance of maximum 50 km to filling stations. On-site production means that electricity is transmitted to the filling station where the hydrogen is produced. In central electrolysis hydrogen is transported in liquid form with a truck over 300 km. The table below summarises the results of the electrolysis pathways. Both energy use (MJ used per MJ H_2 produced) and GHG emissions (g CO_2 equivalent per MJ H_2) are given in the table. For gaseous hydrogen, figures are given for 350 bar (lowest value) and 700 bar vehicle tanks. Taking into account the Belgian electricity mix results in about 40% reduction of CO_2 emissions compared to the European mix due to the large share of nuclear energy[5].

It was concluded in this study that electrolysis-based hydrogen generates high GHG emissions when the electricity comes from the traditional electric grid mix, and near-zero GHG emissions when the electricity is produced renewably.
It was concluded that – from the pathways considered – electrolysis with electricity based on wind is the best option. It must be remarked that in this study an efficiency of 100% was assumed. Other sources suggest efficiencies of 30%.
Another conclusion is that regional and on-site production give the best results in terms of efficiency and GHG emissions.
It is also clear from this study that electrolysis is an energy-consuming process. Therefore it is only interesting if electricity used can be made from renewable energy sources. The same conclusions were stated in the VTT study.[6]

Hydrogen/electricity produced/scale	Energy input (MJ/MJ H_2)	GHG emissions (g CO2 eq /MJ H_2)
LH2/EUmix/central	5.38	242
LH2/Bmix/central		*145*
LH2/CCGT/central	3.81	220
LH2/Wind/central	1.95	2
CGH2/Eumix/on-site	4.60 - 4.64	207 – 208
CGH2/Eumix/on-site		*125*
CGH2/CCGT/on-site	3.26 - 3.26	188 - 188
CGH2/wind/on-site	1.65 - 1.66	0
CGH2/EUmix/regional	4.59 - 4.64	206 – 208
CGH2/EUmix/regional		*125*
CGH2/CCGT/regional	3.25 - 3.30	187 - 190
CGH2/wind/regional	1.65 - 1.66	0

Table 1-1: Energy input and GHG emissions as calculated in GM WTW study

Efficiency

Different figures on efficiency are given in literature. In the table below efficiency figures from different studies are summarised. The contribution of electricity production is not taken into account and depends on the production method. The efficiency is function of the scale of the plant. Smaller plants have a smaller efficiency compared to larger ones.

Efficiency	Remarks	Reference
70 - 75%	Large scale plants	5
88 - 95%	By increasing temperature	5
50 - 70%	Dependent on scale	1
65 - 85%		2
88%	HHV of hydrogen produced	8

Table 1-2: Efficiencies of electrolysis estimated in different studies

Production capacities of 1 kW_{el} – 125 MW_{el} are available. The price of commercial electrolysers is in the order of 250 – 500 €/kW. Smaller electrolysers are more expensive (up to 5000 €/kW).[1] New are the electrolyser that operate at higher pressure (up to 5 bar). The price of these units is also higher.

A Canadian study[7] also looked at different production routes for hydrogen. Among them decentralise electrolysis based on wind energy, hydro energy, nuclear energy, natural gas and coal. According to the study wind power-based electrolysis has the lowest environmental impact. Some challenges do exist regarding the availability, cost and site selection of wind turbines. The hydroelectricity based electrolysis also have very low operating emissions. However significant social and environmental challenges exist when locating large hydroelectric reservoirs. Also nuclear power based electrolysis has extremely low life-cycle air emissions. However the issue of nuclear waste has to be considered. Electrolysis based on natural gas results in elimination of tailpipe emissions but has higher upstream emissions compared to conventional systems. Electrolysis based on coal has very high emissions.

A. D. Little[8] considered in his study three cases for hydrogen production via electrolysis: the use of average electricity mix, the use of nuclear power and the use of renewable energy sources. It is assumed in this study that hydrogen is transported an average of 1,600 km in high pressure pipelines to the refuelling station where it is compressed to 400 bar during vehicle refuelling. Comparison of the different production routes shows that in terms of emissions hydrogen production via electrolysis is the best choice if electricity is generated by nuclear power (nuclear waste is not considered in the study) or renewable energy. It must be remarked that the American electricity mix is generated for 48% from coal, 18% from nuclear energy, 17% natural gas and 11% hydro and other. However the Belgian electricity mix is quite different: almost 60% is produced by nuclear power, 13% in combined cycle (steam and gas turbines), 17 % in conventional thermal power plants (25% on natural gas, the others on coal), 6.5% by cogeneration and 1.8% by wind and hydro power. If a large amount of hydrogen is produced via electrolysis it is possible that new power plants are needed to meet the electricity demand. In that case the average electricity mix is not a good reference. Other hydrogen production routes considered in this study are mentioned below.

Pollutant (g/GJ)	Electrolysis Av. U.S. mix	Electrolysis Nuclear Power	Electrolysis Renewable en.	Natural Gas SMR	Coal gasification
CO_2	229,142	13,063	4,183	73,234	151,647
SO_2	896.99	51.69	16.70	22.16	90.98
NO_x	682.05	51.02	25.32	83.29	95.10
CO	93.37	5.09	1.50	20.11	14.06
NMHC	22.11	0.43	0.10	21.26	5.00
CH_4	601.16	0.54	0.09	95.86	508.29
PM	144.16	8.63	2.64	5.32	15.75

Table 1-3: Pollutant emissions for hydrogen production routes by A. D. Little

Electrolysis can also be used for small scale hydrogen production to provide hydrogen to 1 or 2 vehicles. Several small scale hydrogen production units are used in demonstration projects (Stuart). Vandenborre Hydrogen Systems[9] is a Belgian company and market leader in on-site and on-demand hydrogen production units based on electrolysis. Hydrogen Systems was acquired by Stuart in 2003 and Stuart by Hydrogenics in 2005. Their hydrogen production units (IMET electrolyser: Inorganic Membrane Electrolysis Technology) are used in the European Cute project (see also WP 1.3) in Barcelona, Amsterdam and Porto. According to the manufacturer the efficiency is 3.9 kWh/Nm^3. Stuart provided a complete hydrogen filling station (including production, storage and dispensing unit) that is capable of producing 120 kg pure hydrogen (The average consumption per bus is 40 kg/day).

An American study[10] on hydrogen production by electrolysis was reported in March 2004. In this study a technical and economical analysis of commercially available electrolytic hydrogen production systems was made. Five manufacturers' electrolysis units were considered: Stuart IMET, Teledyne HM and EC, Proton HOGEN, Norsk Hydro HPE and Atmospheric and Avalence Hydrofiller. Most are alkaline technologies except for the PEM Proton HOGEN. The largest electrolyser units available today produce 380,000 kg hydrogen per day. The cost analysis shows that electricity cost will be the major price contributor. For the larger units (1000kg/day) electricity costs represent 80% of total hydrogen cost. For small units (20 kg/day) electricity represents only 35% of hydrogen costs. The efficiencies range from 56-73% (lower value is for PEM electrolyser). An efficiency goal for electrolysers in the future is reported to be 50 kWh/kg or a system efficiency of 78% (including compression to 420 bar). The systems considered comprise an electrolyser and gas purification system resulting in hydrogen purities of 99.9 – 99.9998%.

In Hysociety[11] an investment cost of 400 euro/kW was estimated for large (50,000 kW/h) and smaller electrolysers. The operating and maintenance cost was estimated at 1.5% of the investment cost: 300,000 euro/year.

1.1.2 Thermochemical reforming

General principle

Most of the world hydrogen today is produced from fossil feedstock using different thermochemical reforming processes. Reforming is a chemical process that reacts hydrogen-containing fuels in the presence of steam, oxygen or both into a hydrogen-rich gas stream (reformate). When applied to solid fuels the reforming process is called gasification.
The most important is steam reforming of natural gas. Different reforming processes are discussed below.

<u>Steam reforming</u>

Steam reforming is the endothermic catalytic conversion of light hydrocarbons (methane to gasoline) with water vapour. Industry scale processes of this kind are normally carried out at temperatures of 850 °C and pressures in the order of 2.5 MPa.[1]
Air Products and Chemicals, the largest manufacturer of hydrogen, uses STM of natural gas as primary production method for hydrogen.

$$C_nH_m + H_2O \rightarrow n\,CO + (n+m/2)\,H_2$$

Steam reforming is usually followed by water gas shift reaction, which increases the hydrogen yield by combining carbon monoxide and hydrogen into hydrogen and carbon dioxide:

$$CO + H_2O \rightarrow CO_2 + H_2$$

The temperature of the shift reaction is 350-450°C.
CO_2 is removed from the gas mixture using absorption or membrane separation. Other unwanted components are removed by further purification.

The industrial scale production of hydrogen is carried out in hydrogen production plants with usual capacities in the order of 100,000 Nm^3 H_2/h. The process is technically well-proven. The estimated price is 40 eurocent /Nm^3.[1] This corresponds to 1.16 euro / L gasoline equivalent. Air Liquide gives a price estimation of 40 – 50 eurocent/Nm3 if compressed hydrogen is delivered by truck.[1]
According to the Hysociety[11] study the cost is 1.03 eurocent/kWh H_2 without the cost for natural gas (1.5 eurocent/kWh). Taking into account natural gas costs, compression, transport, and refuelling the study comes to a total cost of 21 eurocent/Nm^3 H_2, still much lower than the other estimates.

It is estimated that carbon sequestration will increase cost by 20-30%.[4]

Partial oxidation

In partial oxidation (POX) the fuel is partly combusted to produce a synthesis gas that consists of H_2, CO and CO_2. The process is exothermic. The synthesis gas can be converted into pure hydrogen by the water gas shift reaction and by subsequently separating the carbon dioxide.
An idealised equation for the combustion of any hydrocarbon fuel can be written as[6]

$$C_nH_m + x\,O_2 + (2n - 2x - p)\,H_2O \rightarrow (n\text{-}p)\,CO_2 + p\,CO + (2n - 2x - p + m/2)\,H_2$$

The produced gas mixture is further purified by the reactions described above. Mostly heavy hydrocarbons (e.g. residual oil from the treatment of crude oil) are used. Also coal can be used; in this case the process is called 'gasification'.

A POX reactor operates at a temperature level of around 1000°C or in a catalytic version at 700°C. The hydrogen yield for POX is lower compared to SMR. According to the VTT study[6] the hydrogen yield for STM is 0.503 compared to 0.377 for POX, expressed as kg hydrogen per kg methane. The extra energy needed for the endothermic SMR process is not taken into account.

The oxygen/fuel ratio is very critical in the POX process. Sufficient oxygen is needed to have a exothermic reaction but not to much hydrogen may be lost in burning with oxygen.

The estimated price is 50 eurocent /Nm^3 (and 60 eurocent in the case of gasification of coal).[1] According to the Hysociety study[11], the partial oxidation reactor is less expensive than the steam reforming but the downstream processing stages are more expensive if air is used for the reaction (instead of pure oxygen) because of the presence of nitrogen.

Autothermal reforming

Autothermal reforming (ATR) is a process which combines STM and POX, utilising process heat for neutral energy balance. In this process natural gas is reacted with both steam and oxygen to produce carbon monoxide and hydrogen. The mixture of natural gas, steam and oxygen is adjusted so that the heat released by the reaction of POX is sufficient to lead the endothermic reaction of steam reforming. Additional heat is needed for start-up: the reactor starts in partial oxidation mode and when temperature is reached changes to autothermal mode. Operating conditions are 850-1000 °C and 20-40 bars.

Comparison of different thermochemical reform processes

In the GM WTW study[3] different pathways are considered for hydrogen production by thermochemical reforming of natural gas. Different scale of production (central, on-site in fuelling station) and resources of natural gas are considered in the study.

Central hydrogen production makes use of European gas mix or Russian gas. For the production of compressed hydrogen a steam reformer with loss of steam is assumed. For central production it was assumed that the hydrogen is transported over a distance of 50 km

by pipeline to the refuelling station. In the case of liquid hydrogen production a steam reformer that uses excess heat for electricity generation that is used for liquefaction. The additional energy needed for liquefaction is generated from CCGT on natural gas.
In the case of liquid hydrogen production from remote gas, hydrogen is transported over a distance of 10,200 km by ship followed by cryogenic transport by truck over a distance of 500 km. For the hydrogen production from European or Russian gas, the hydrogen is transported over a distance of 300 km by truck. The table below summarises the results of the GM study (fuel consumption and GHG emissions). The range given represent the application for a 350 bar and 700 bar vehicle tank. The source of the natural gas feedstock has a large impact on GHG emissions; GHG emissions are lower for the hydrogen production from European mix, compared to Russian or 'remote gas'. Central production of gaseous hydrogen performs better than on-site production and production of liquid hydrogen. This is due to the higher efficiency of larger plants and the high energy losses for liquefaction. Both energy use and GHG emissions are lower compared to electrolysis (based on the Belgian electricity mix).

Hydrogen/electricity produced/scale	Energy input ($MJ/MJ\ H_2$)	GHG emissions ($g\ CO_2\ eq\ /MJ\ H_2$)
CGH2/EUmix/central	1.57 – 1.61	88-90
CGH2/RussianGas/central	1.86 – 1.90	107 – 109
CGH2/EUmix/on-site	1.83 - 1.87	101 – 103
LH2/EUmix/central	2.14	124
LH2/RussianGas/central	2.61	154
LH2/remote gas	2.55	147

Table 1-4: Energy input and GHG emissions for electrolysis based hydrogen production routes, as calculated in GM WTW study

In an American study[13] different transportation fuels and technologies are compared. Also hydrogen is considered as transportation fuel in FC vehicles. Multiple pathways for hydrogen production are considered in this study. Hydrogen can be produced in either gaseous or liquid form.GH2 can be produced in larger centralised plants (near NG fields) or in refuelling stations (decentralised production). LNG can be produced from NG or flared gas (FG). Worldwide about 5% of the NG produced is flared.
In this study it was estimated that the boiling-off during transport via ocean tankers was used to fuel the tankers. It was assumed that 3% was boiled off during transport and another 3% during storage and distribution.
The results of the study are given as g/km. Hydrogen is used in FC vehicles for 4 different hydrogen production routes. In the figure below, the emissions of hydrogen as fuel for FC vehicles are given for different production routes (the emissions during use are not included). A relative comparison of the different production routes is possible with these figures. Central hydrogen productions has lower fuel consumption and lower emissions compared to on-site production. This is in line with the results of the GM study. The production of LH2 from NG has higher energy is and GHG emissions. Most other emissions (except for PM) are lower compared to CGH2 for on-site production.

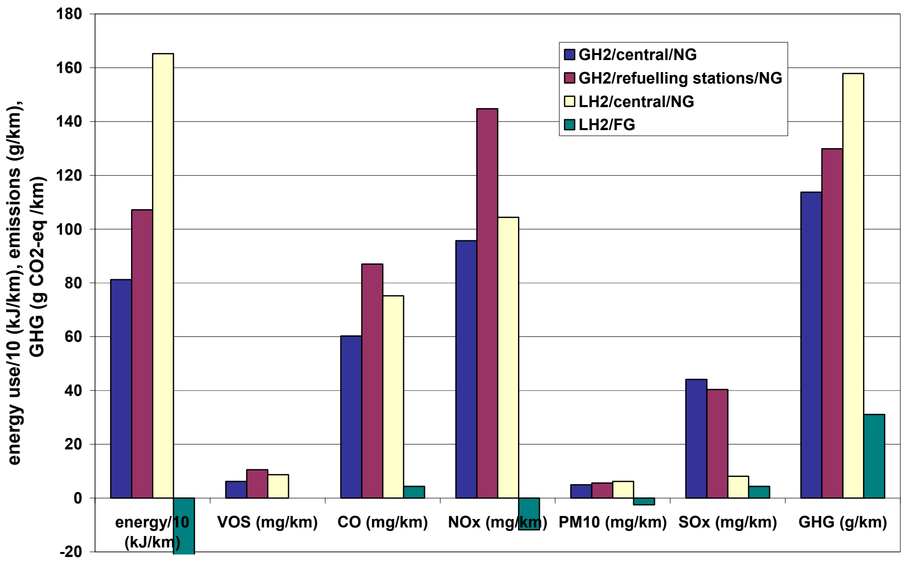

Figure 1-1: Energy use and emissions of different hydrogen production routes

It must be noted that the study is carried out for the American situations and impacts of e.g. transportation to refuelling stations and production plants can be different.

In another American study[14] a life cycle assessment (LCA) of hydrogen production via natural gas steam reforming was performed to examine the net emissions of GHG and other major environmental consequences. Conventional steam reforming is the selected technology. The energy use per MJ hydrogen produced calculated in this study is 1.52 (=1/0.66 MJ H2 produced per MJ energy consumption for production). GHG emissions are 11,888 g CO_2 equivalent per kg hydrogen produced. Estimating an LHV of 119.972 this results in 99 g CO_2 /MJ H_2). Both values are in good agreement with the GM study. Other emissions are given in the table below.

Pollutant	g/kg H_2
CO	5.9
CH_4	146.3
NO_x	12.6
NMHC	26.3
PM	2.0
SO_x	9.7

Table 1-5: Emissions calculated in the LCA study[14]

Most of the CO, CH_4, NMHC and NOx emissions are a result of natural gas production and transportation. The majority of PM is produced at construction and destruction and also the production and distribution of NG. The main conclusion of this study is that however hydrogen is considered as a clean fuel, it is important to know that the production from methane via steam reforming results in a considerable environmental impact. Comparison to other production routes needs to be investigated.

A. D. Little investigated the energy efficiency and emissions of numerous transportation fuel production cycles. Hydrogen production routes via NG steam reforming, gasification of coal and electrolysis are considered. The three electrolysis production routes are already discussed in paragraph 'electrolysis'. The emissions for NG steam reforming and gasification are given in the table below.

Pollutant	g/GJ H_2	
	NG/STM	Coal/gasification
CO	20.11	10.8
CH_4	95.86	458.21
NO_x	83.29	43.77
NMHC	21.26	13.61
PM	5.32	5.5
SO_x	22.16	23.65

***Table 1-6: Emissions estimated by A.D.Little*[8]**

In a Canadian LCVA (Life Cycle Value Assessment) study central and local hydrogen production routes are compared. One of the main conclusions is that FC vehicles fuelled with hydrogen from renewable energy-based electrolysis show the greatest opportunity for minimizing negative environmental and social impacts of vehicle/fuel supply systems. However, at the current level of technology maturity fuel cost are estimated to be higher compared to conventional technologies. Steam reforming is the next most environmental source of hydrogen according to this study. The most important barriers are distribution logistics (Canadian situation) for centralised plants and operational issues for decentralized plants. It is expected that the efficiency of decentralized production units will improve resulting in reduction of life cycle emissions. The decentralized plant –prototype- consumes less NG (-8%) but more electricity (+48%) compared to commercial centralized production units. The resulting life cycle emissions for decentralized hydrogen production can be a few percent less (electricity generated from renewables) to 20 % higher (electricity generated from coal) compared to centralized production; depending on the electricity generation in the region that is considered.
Liquid hydrogen requires a considerable increase in electricity (a factor of 5.4 according to the study) compared with gaseous hydrogen (700 bar). The effect on emissions is different for different regions since it is influenced by the electricity production. This study illustrates the importance of electricity generation in the comparison of different hydrogen production routes.

Efficiency

Efficiency	Remarks	Reference
70-80%	SMR	5
73%	SMR (centralised without steam production)	13
70%	SMR (decentralised)	
85%	SMR	2
90%	SMR methanol	
(5-10% lower compared to SMR)	POX	
66%	Conventional SMR	14

Table 1-7: Efficiencies for hydrogen production by reforming according to different studies

On-board reforming

For vehicle applications on-board reforming of natural gas, methanol, gasoline or other fuels was long considered as intermediate solution. At this moment however, direct use of hydrogen in fuel cells is considered as only option. On-reforming avoids hydrogen storage problems and the installation of a distribution network. However complexity is increased and efficiency is decreased.

1.1.3 Hydrogen from biomass

In an IEA study possible hydrogen production paths of biomass are evaluated.[15]
The GM study[3] also investigated biomass based pathways for hydrogen production. The production routes considered are: production of gaseous hydrogen via gasification of woody biomass (residual wood or cultivated) and steam reforming of biogas. It was assumed that the wood is transported over a distance of 50 km to the allothermal gasification plant. The hydrogen is transported through a H_2 pipeline of 10 km to the refuelling station. Gaseous hydrogen is compressed from 50 to 350 or 700 bar in vehicle tanks. In the case of steam reforming of biogas organic waste from households, catering and food industry is converted to biogas by fermentation. It is assumed that there is no additional transport of the waste in comparison to current waste disposal; The methane is transported to the refuelling station by pipeline (e.g. via the natural gas grid) where it reformed on-site to hydrogen.
The results are given in the table below. Although energy losses are relatively high, most of the energy is renewable. Energy losses and GHG emissions are generally lower for those pathways involving residual biomass or waste products. Some of the pathways have negative GHG emissions because the CO_2 is removed from the atmosphere during the growth of the plants. GH2 is compressed from 150 to 350 or 700 bar.

Hydrogen/production	Energy input (MJ/MJ H_2)	GHG emissions (g CO_2 eq /MJ H_2)
CGH2/gasification/res.wood.biomass/10MW	1.84 - 1.88	6.9 - 7.0
CGH2/gasification/res.wood.biomass/2.5MW	2.08 - 2.12	8.3 - 8.5
CGH2/gasification/cult.wood.biomass/10MW	1.89 - 1.91	21.3 - 21.7
CGH2/gasification/cult.wood.biomass/2.5MW	2.13 - 2.16	24.6 - 25.2
CGH2/SMR/biogas	2.24 - 2.26	0.4

Table 1-8: Energy input and GHG emissions for biomass based hydrogen production routes, as calculated in the GM WTW study

Hydrogen cost projections for 2010 for fuel production and delivery reported in the EU study range from 14-18 €/GJ for GH2 by steam reforming from natural gas up to 49-55 €/GJ for LH2 from off-shore wind.[16]

1.2 Distribution and transport

1.2.1 Hydrogen distribution by pipelines

- **Existing hydrogen distribution network in Belgium**

A wide hydrogen distribution network for hydrogen is already available in Belgium (see figure below). The network is used to provide hydrogen to industry. Air Liquide is the owner of the hydrogen distribution network by pipelines. Hydrogen is transported at 60-100 bar. Note that locally produced hydrogen can be transported by medium or low pressure pipelines. According to the EU study[11] for hydrogen pipeline transport the energy need is a factor of 1.5 higher compared to natural gas. The main reason is that for hydrogen a higher compression energy is required for transporting the same energy equivalent.

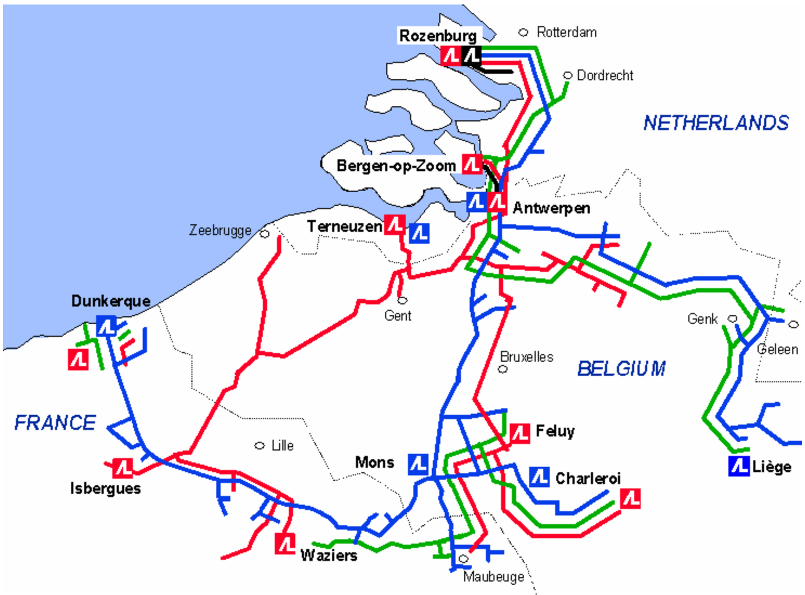

Figure 1-2: Existing industrial gas distribution network in Belgium (red: hydrogen, blue: nitrogen , green: oxygen).

- **New hydrogen distribution networks**

Hydrogen transport by pipelines is the most economical way of transporting hydrogen but investment cost of installing new pipelines are high (estimated at 200 – 500 €/m).[17] Due to physical properties of hydrogen, natural gas pipelines can not be used for transportation of hydrogen. Hydrogen can result in fracturing of pipelines as it causes the embrittlement of steel and since it is a small molecule is easily diffusible so could escape through the existing pipes. The natural gas pipeline network would need to be upgraded in order to accommodate hydrogen. The carbon content of the steel is important for the compatibility with hydrogen.
Mixing up to about 30% hydrogen with natural gas without modifications to the pipeline would be possible. However, this method would be cost effective only if there is cheap technology to separate hydrogen and natural gas at the point of use.

The table below shows the energy consumption of a compressor for different compression ratios.

Inlet – outlet pressure	Adiabatic efficiency	Energy use (kWh/kWh H_2)
20 – 69 bar	70 – 80%	0.018 – 0.021
7 – 480 bar	50 – 70%	0.078 – 0.108

Source: Hysociety [11]

Table 1-9: Energy consumption for compression of hydrogen

According to a European study[18] on hydrogen as fuel for transport, the energy consumption for hydrogen compression is estimated at 0.11-0.13 $kWh_{el}/kWhH_2$ for compression from 2 bar to 450-880 bar and 0.05 – 0.07 $kWh_{el}/kWh\ H_2$ for compression from 30 bar to 450 - 880 bar. It must be noted here that the energy consumed for compression does not increase proportional to the output pressure.
In Hysociety[11] a transportation for hydrogen by pipeline cost of 0.36 eurocent/kWh is estimated using an investment cost of 620 €/km pipeline.

1.3 Compressed hydrogen transport by truck

The storage tanks to be used for transport can be classified into three types: cylinders (0.5 – 150L), cylinder bundles and tubes (150 – 3000L) (directive 97/23/EC)[19]. The choice of transport is dependent of the size of supply, the distance and costs. The weight of heavy tanks strongly limits the way of transporting gaseous hydrogen. Typically gaseous hydrogen transported by truck is stored at 200 – 250 bar. For large supply volumes tube trailers are preferred. For example Air Products has realised a tube trailer that can store hydrogen at 420 bar to achieve fast-fill at 350 bar.
The vessels are to be realised using special steel or other material in accordance of the EN-11114-1. At international level there is the working group of ISO technical Committee TC 197 and the working group TC 58 'Gas cylinders'. The tanks are also required to satisfy the ADR (Autotransport Route Dangereuse) standards and national standards on freight transport. Issues on regulation and standards will be further discussed in WP1.2.

Presently the storage technology for gaseous hydrogen transport is fully developed however improvements can be made through the adoption of new materials that allow higher storage pressures and improve the ratio (hydrogen transported / total weight). Since decades cylinders are made of steel and recently also composite materials (at pressures of 300 bar) are used.
The use of gaseous hydrogen storage tanks is adequate to transport hydrogen for shorter distances (no more than 100 km). It must be remarked that only a portion of the transported hydrogen can be delivered at the destination site dependent on the pressure at which hydrogen is stored and transported. According to the EU study[18] trailer transport of CGH2 can be realised only up to about 6,000 Nm^3 and at low energy efficiencies which limit the distances of below 200 km and to small quantities.
The transport cost by truck transporting hydrogen pressure vessels is estimated at 1.61 eurocent/kWh hydrogen. It was estimated here that the hydrogen was transported over a distance of 100 km. The cost will increased if the transported distance is higher. Transportation over 300 km would increase the price with more than 0.3 eurocent (one way, only taking into account fuel cost). The cost is significant higher than the cost calculated for liquid hydrogen distribution.
The storage cost estimated for compressed hydrogen storage in pressure vessels (transportable by truck) is 0.95 eurocent/kWh H_2 for 2000 and 0.72 for 2020. (Hysociety[11])

1.3.1 Cryogenic hydrogen transport by truck

Liquid hydrogen is transported in cryo-containers or trailers of typically 30 – 60 m^3 at cryogenic temperatures of about 253 °C. Larger containers are used for space projects.
Liquid hydrogen can be transported to refuelling stations and stationary applications by trailer transport comparable to today's delivery of liquid hydrocarbon vehicle fuels.

Hydrogen liquefaction is done in large liquefaction plants. Energy losses due to liquefaction are about 30% (VTT study) of the stored volume of hydrogen, up to 40% (Hydrogen course Part 2)[2] according to other references.
Because hydrogen is stored just below the boiling point, any heat transfer results in evaporation of hydrogen. On long hauls the hydrogen boil-off is estimated at 0.3% per day.
Hydrogen transport in liquid form is more economically due to its higher gravimetric density.
Liquid hydrogen vessels are typically spherical to reduce the surface area.

In Hysociety[11] a cost of 0.76 eurocent/kWh is estimated for liquid hydrogen transport. The cost for liquefaction is not included. The assumptions made in that study are: tank size of 56 m^3, (corresponding to 4015 kg hydrogen), the estimated tank cost is 345,000euro (which is 50% more than the cost of a similar tank for LNG) and an additional cost for the truck of 115,000 euro is assumed. The maintenance cost is assumed at 8% of the investment cost. This results in an annual operating and maintenance cost of 96,400 euro (including also fuel cost, tax insurance, etc.). The operating cost was calculated based on a trip distance of 300 km. The annual distance driven by one truck is assumed at 200,000 km resulting in a capacity of 54,480,000 kWh LH2 per year.
An American study investigated the cost of storing and transporting hydrogen[20]. Cost per energy unit hydrogen were calculated for different trip distances and production rates. The truck capacity was 4082 kg hydrogen. For a production rate of about 126,000,000 kWh LH2 per year the calculated cost is 0.07 \$/kg H_2 (or 1.8 eurocent/kWh H_2) for a distance of 162 km. In this study, the total annual cost is up to 40 % of the capital investment cost, which is higher than assumed in the Hysociety study[11].

The cost for hydrogen liquefaction is estimated at 0.064 eurocent/kWh (year 2020) in the Hysociety study.

Further research related to liquid hydrogen include the development of lightweight, low-volume and low-cost materials that have very low heat transfer. Also methods to safely handle boil-off are required. Further improvement of the liquefaction process to improve the energy efficiency can result in cost reductions.

1.4 Storage

Hydrogen has a high energy content per weight (120 MJ/kg Lower Heating Value) but the volumetric energy density is low (10.8 MJ/Nm^3 Lower Heating Value). This makes it very challenging to store hydrogen, especially for mobile applications. Also transportation by road transport is not efficient.

Hydrogen can be stored in a variety of ways; the most important are: compressed gaseous, cryogenic liquid and chemically bound (e.g. metal hydrides).

1.4.1 Gaseous hydrogen

Gaseous hydrogen is stored at higher pressures to improve the energy density. Initially hydrogen was stored at 200 bar. At this pressure, only 5 weight% of the total weight is hydrogen. The pressure used at this moment for mobile applications is 250-350 bar. Current hydrogen research activities are focussed on pressures of 700 bar[21]. Compressed hydrogen tanks of 350 – 700 bar have been certified worldwide according to ISO 11439. Composite storage tanks are being developed, mostly in order to meet the demand of increased storage density for on-board storage. Advanced lightweight pressure vessels have been demonstrated 12 weight% hydrogen storage at 700 bar.
Compression of hydrogen includes energy losses. Compression of ambient pressure to 300 bar requires 7.2 % of the HHV of hydrogen.(Hysociety[11], storage) The cost is estimated at 0.95 eurocent/kWh hydrogen (2000) to 0.72 eurocent/kWh (by 2020).

The cost of storing hydrogen depends on the capacity and storage time. In Hysociety a cost of 0.75 eurocent/kWh H_2 is used for stationary applications (Amos 1998)[20]. This calculation was based on a rental cost of 1000 – 2000 €/month for a 50 bar steel storage vessel of 1305 Nm^3 max. capacity. The cost of compressed hydrogen storage is highly dependent on the turn-over rate. According to the American review[20] the total storage cost is 0.5 – 1.3 eurocent/kWh H_2 for tube storage of one day. This cost is increased to 2.3 – 11.3 eurocent/kWh for 30-day storage.
Storage of small quantities of hydrogen for stationary applications is universally done by above ground compressed gas vessels. The most common storage is high pressure gas cylinders which are operated at a pressure of 200 bar. For very small quantities, bottle type storage is also used (2 – 50L) with operating pressures of 200 bar.

On-board storage of hydrogen

The figure below shows the on board storage of compressed hydrogen as used for buses in CUTE project. The fuel storage system consists of 9 high-pressure cylinders of the DyneCell® type with a volume of 205 L each. The DyneCell cylinder is a lightweight composite cylinder. The total storage capacity (at 15 °C and 350 bar) is 40 kg H_2. The weight of this cylinder type is a factor of 2 – 4 times lower compared to conventional cylinders.

Figure 1-3: Compressed gaseous hydrogen on-board storage (as used in CUTE buses)

The cost of a fibre-reinforced composite tank (aluminium-carbon) with a design pressure of 550 bar is estimated at 5100$/GJ (1998) (approximately 520 €/kg), according to the American study.[22]

Within the EIHP2 project a study was performed to know the optimum storage pressure for on board storage of compressed hydrogen in city buses.[23] It was concluded that there is no technical barriers to use CGH2 storage systems in the range of 350 – 700 bar. In city buses, where volume is not as critical a constraint as in cars, optimum pressures based on system weight is 350 bar for Type 4 storage systems (non-metallic liner with full fibre overwrap) and 500 bar for Type 3 storage systems (metallic liner with full fibre overwrap). The optimum values were derived on a the basis of a 40 kg storage capacity to provide a vehicle range of 400 km. In the study it was concluded that -taking into account safety, technical and economical issues and the probable direction of storage technology- for city buses an on-board storage pressure not exceeding 350 bar. It was also stated that overnight slow fill may be the most attractive refilling option. For passenger cars there are clear demands for a vehicle range comparable to with conventional vehicles. In the study it was concluded that given the sparse data on hydrogen systems at very high pressures, no definite recommendation on an optimum pressure for cars can be made, except to support continued research at 700 bar (and above).

According to the draft regulation of containers for storage of compressed hydrogen are classified into 4 types[24]:

Type 1: seamless metallic container
Type 2: hoop wrapped container with a seamless metallic liner
Type 3: fully wrapped container with seamless or welded metallic liner
Type 4: fully wrapped container with a non-metallic liner

Hydrogen components are classified with respect to their nominal pressure as follows:

Class 0: High pressure components/systems containing hydrogen at nominal working pressure of more than 30 bar
Class 1: Medium pressure components/systems containing hydrogen at nominal working pressure of more than 4.5 and up to and including 30 bar
Class 2: Low pressure components/systems containing hydrogen at nominal working pressure up to and including 4.5 bar.

1.4.2 Liquid hydrogen

Hydrogen can be stored just below its normal boiling point (-253 °C) at or close to ambient pressure in a double-walled superisolating tank (or Dewar). However, no matter how good the insulation, all tanks allow some heat transfer of the surroundings and this results in evaporation of hydrogen. If hydrogen is not consumed, the evaporated hydrogen is vented through a pressure relief valve. The loss of hydrogen through evaporation is called boil-off. Current automotive tanks have a boil-off rate of 1-2% per day. Tanks have a maximum overpressure capacity of about 5 bar. Liquid hydrogen tanks do not need to be as strong as high-pressure gas cylinders although they need to be adequately robust for automotive use.
Liquid hydrogen storage is adequate for large quantities of hydrogen because of the high investment cost of the liquefaction plant and the relative high boil-off rate for smaller storage quantities.

On-board storage

When on-board liquid hydrogen storage is used, hydrogen can be drawn from the tank as liquid or as gas. When used in internal combustion engines, hydrogen can be injected directly into the cylinder in order to increase the amount of fuel combusted. When used in a fuel cell, hydrogen can be drawn at sufficient pressure to feed the fuel cell. The BMW vehicle with ICE on hydrogen has a liquid hydrogen fuel tank. An example of a liquid hydrogen storage tank is given in the figure below.

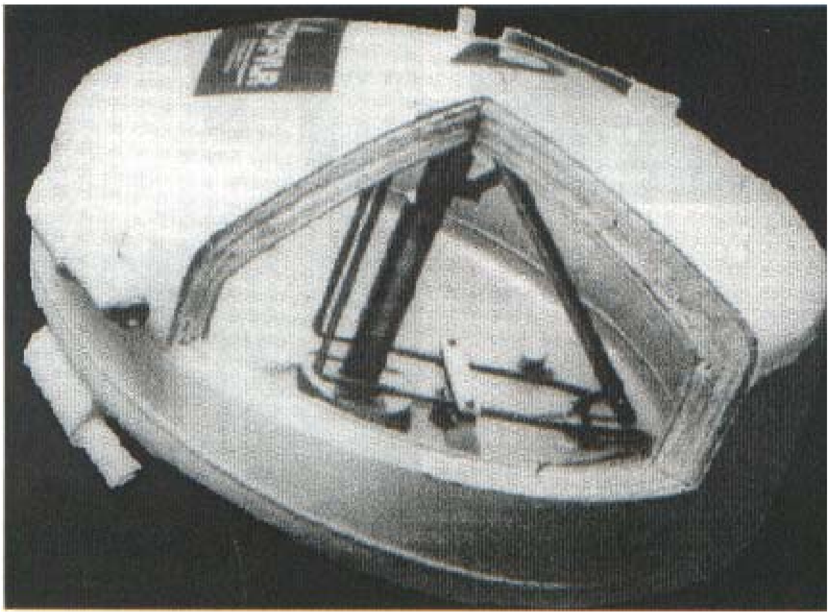

Figure 1-4: On-board liquid hydrogen storage tank

1.4.3 Metal hydrides

Metal hydrides are an alternative to storage in cylinders or cryogenic vessels. The hydride allows the hydrogen to be stored in a solid form at high energy densities (kWh/L). In metal hydrides hydrogen is stored by chemical bonding with the metal. Different types of metal hydrides are available – most common are based on alloys of Mg, Ni, Fe and Ti - classified in high and low temperature technologies. High temperature technologies are less expensive and able to store more hydrogen but require extra heat to release hydrogen.
A disadvantage of low-temperature hydrides is that the hydrogen is released at room temperature. So, higher pressures are required increasing the complexity.

1.4.4 Other storage techniques

Underground storage
Underground storage is most suitable for large quantities and/or longer storage time. For underground storage of hydrogen a large cavern of area of porous rock with an impermeable rock layer above it is needed to contain the gas. Operating cost for underground storage are primarily for compression power. Amos[20] estimated the investment cost at 73$/GJ.
This storage technology has been demonstrated in Germany, France and the US. For Belgium the availability of an appropriate cavern should be investigated but this is not in the scope of this study.

Carbon micro fibres or nanotubes
A new storage technique is the use of carbon micro fibres. This technique is characterised by a high energy density (higher than liquid hydrogen). However, high temperatures are needed to release the hydrogen.

Glass microspheres

Glass microspheres are small pellets with a diameter of less than 100 µm. In theory glass micro spheres have the potential for more than 10 weight% storage under very high pressure (690 bar). It is currently an expensive solution on laboratory scale..

1.4.5 Refuelling infrastructure

A certain number of hydrogen refuelling stations are already available in Europe. These have been mainly build to supply demonstration fleets. In 2003 13 refuelling stations were operational in Europe (Hysociety database[11]). An overview of refuelling stations worldwide is given on http://www.fuelcells.org/info/charts/hydrogenfuellingstations.pdf Note that the plans to build a hydrogen fuelling station in Leuven –also mentioned in this list- were never executed. In the EU report[18] 16 compressed hydrogen, 5 liquid hydrogen and 6 LCGH2 filling stations are operational in demonstration projects in Europe.

A typical scheme for a *gaseous hydrogen filling station* is shown in Figure 1-4. Hydrogen is delivered to the fuelling station by pipeline or truck. An alternative is on-site generation through natural gas reforming or electrolysis of water. Truck trailers are the most convenient transport means for short distance and small amounts. A compressor (with a compression range of 30 – 400 bar) feeds a pressurised storage tank of about 5.2 m^3 hydrogen with a maximum capacity of 126 kg H_2 at 400 bar. The maximum delivery pressure is determined by the storage pressure of hydrogen. A pressure difference is needed to fill the tank. For example 350 bar on board storage required 450 bar on-site storage and 700 bar onboard storage requires 880 bar on-board storage. The tanks are connected to two dispensers to feed the vehicles with storage tanks that allow pressures of 200 – 250 bar at a max. output flow of 1.7 kg/min. The station is designed to weekly fill about 550 hydrogen vehicles (or 78 fills-up per day). The station is able to deliver about 330 kg hydrogen every day.

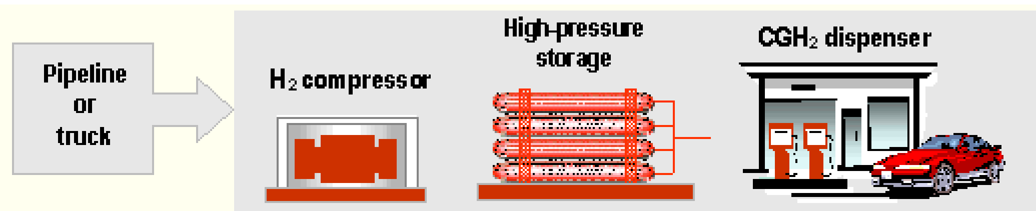

Figure 1-5: Scheme for gaseous hydrogen filling station (source: Hysociety [11])

In Hysociety[11] the cost for hydrogen compressing, storage and refuelling at the fillings station is calculated at 1.49 eurocent/kWh in 2000 to 1.46 in 2020. These values were obtained assuming a station with specifications described above for reference year 2000. for 2020 it was assumed that the final pressure will increase to 880 bar (instead of 200 for 2020) and the daily capacity will increase with 50%. The capital cost is 296699 euro in 2000 and 460295 euro in 2020. Calculation were based assuming a plant life of 20 years. The CO_2-emissions are 21.4 g/kWh in 2000 and 22.4 g/kWh in 2020. The primary energy demand is 0.12 and 0.17 kWh/kWh hydrogen for 2000 and 2020 respectively.

In EIHP2 a report[25] was prepared dealing with guidelines for designers and operators of gaseous hydrogen vehicle refuelling stations. It is considered to reflect the best practice currently available.

Transport vehicles can also be refuelled with *liquid hydrogen*. Liquid hydrogen is delivered in trailers/containers to the fillings station and stored on-site. Liquid hydrogen is transferred to the vehicle tank with a cryogenic pump in no more than 3 minutes for a typical passenger car tank (100 – 140 L). Transfer of liquid hydrogen requires special transfer lines that need to be adequately insulated. A special cryogenic coupling to connect the refuelling station to the vehicle tank was developed by Linde.
At Munich airport, Linde has build together with MAN, BMW, Aral and other partners the first public fuel station for liquid hydrogen. The refuelling of the vehicle happens fully automatic. In this station also high pressure gaseous hydrogen is supplied to shuttle buses.[26]
In Hysociety [11] the cost for liquid hydrogen refuelling at the fillings station is calculated at 6 eurocent/kWh in 2000 to 1 in 2020. The future cost estimation is lower compared to compressed hydrogen refuelling. These values were obtained assuming a station for respectively 1 bus (38 kg/day) and 10 buses refuelling capacity for 2000 and 2020. The capital cost is 15,000 euro in 2000 and 117,000 euro in 2020. Calculation were based assuming a plant life of 20 years.
The CO_2-emission are 16.7 g/kWh in 2000 and 11.9 g/kWh in 2020. The primary energy demand is 0.09 kWh/kWh hydrogen for 2000 and does not change for 2020.

An other option is $LCGH_2$ station. In this case liquid hydrogen is supplied and compressed , vaporised and dispensed at the required storage pressure of up to 700 bar. This method is used if liquid and compressed hydrogen is requested at the filling station. However liquid hydrogen is not considered as the most economic option for compressed hydrogen use. Moreover high pressure compressed hydrogen processes have been advanced significantly during the last years so that fast refuelling can be obtained using compressed hydrogen.

According to the European study[18] in a future well-established market a typical filling station – having 4 – 8 hydrogen filling nozzles – for passenger cars will sell 3 – 6 million Nm^3 hydrogen per year (with 500 to 1,000 Nm^3/h on-site production capacity) supporting some 2,500 to 5,000 FC cars per day or 180 to 360 fills-up. In this study it is stated that the cost lie in the order of 0.5 to 1.5 million euro, depending on the capacity of the station and the technology. This means that the assumptions in the Hysociety study are a lower limit, also assuming a small capacity.

An American survey on hydrogen economics[22] refers to studies dealing with the cost for a hydrogen station with *on-site hydrogen generation*. One of the studies estimated the capital cost at 26,000 – 40,000 euro. The assumptions were made for a 50- and 100-cars refuelling station resulting in a hydrogen cost of respectively 0.7 and 0.64 euro/kg hydrogen. This is somewhat higher as the Hysociety study[11] (1.5 eurocent/kWh or 0.5 euro/kg H_2) but includes also production of hydrogen.
Another reference mentioned in this study calculated the cost for on-site generated hydrogen at 0.18 euro/Nm^3 using steam reforming and 0.25 euro/Nm3 using alkaline electrolysis. Another study referred to (Ogden) estimated the delivery cost of hydrogen at refuelling stations (800 cars per day) at 0.13-0.43 euro/Nm^3 for on-site reforming, up to 0.28 – 0.38 euro/Nm^3 for on-site advanced electrolysis.

1.5 Conversion and end-use

Hydrogen can be used as a fuel in fuel cells, engines and turbines. All these techniques have different requirements on hydrogen (purification, humidification, storage,...etc). Different technologies will be discussed. First a general characterisation of fuel cell technology will be given. Further different applications will be discussed: stationary and vehicle application.

1.5.1 Fuel cells: general

In fuel cells current is produced by electrochemical reaction: Hydrogen is combined with oxygen without combustion. The chemical energy in the fuel is directly transformed to electrical energy without intermediate thermal or mechanical processes. A fuel cell consists of two electrodes (anode and cathode) separated by an electrolyte that conduct ions. Electrodes are externally connected by an electric circuit. Hydrogen is oxidised at the anode and oxygen is reduced at the cathode producing water, electricity and heat. In combustion engines the reaction occurs by combustion and energy is released in the form of heat that can be partly transformed to mechanical energy.
In electrolysers the reverse reaction is used to produce hydrogen from electricity.
The voltage generated by one cell is low (typically < 1 V), therefore several cells have to be combined to generate sufficient voltage and power density. The combination of different cells is called a stack. It is also important to note that fuel cells require a complex support and control system e.g. compressed air is required for fuel cell operation. The complete system will be discussed below.
Fuel cells can be used in co-generation applications. In addition to electrical power, fuel cells generate pure water and heat. Both can be used in association with domestic or industrial applications.

Fuel cells are characterised by the electrolyte they use. The electrolyte determines the working temperature. According to their temperature fuel cells can be classified in high- and low temperature fuel cells. Operating temperature is a critical parameter for vehicle applications because the requirements of fast start-up and thermal isolation. A schematic overview of the working of different types of fuel cell and main reactions are given in the figure below.

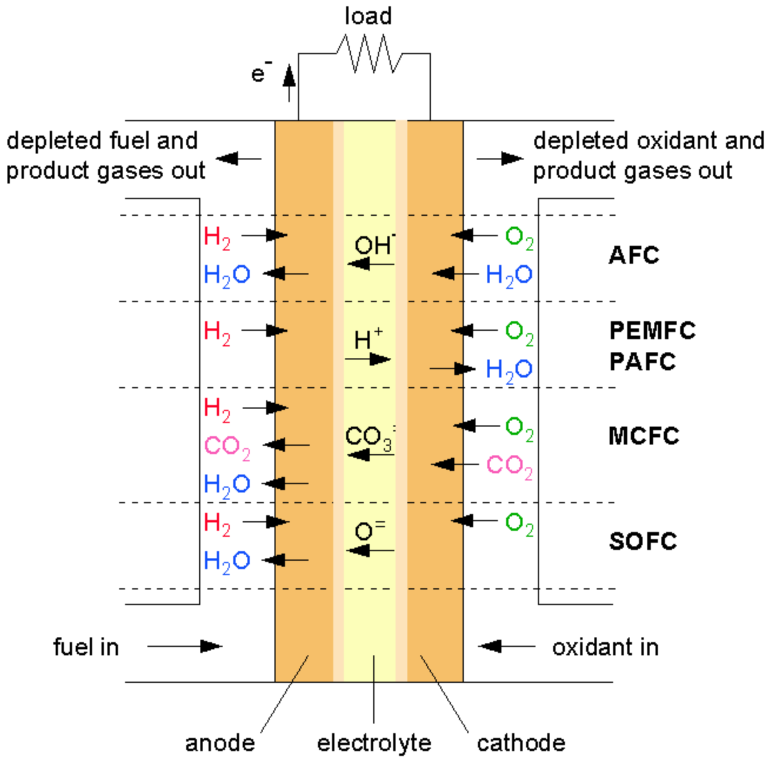

Figure 1-6: Schematic representation of the working principle of different types of fuel cells (AFC: Alkaline Fuel Cell), PEMFC (Proton Exchange Membrane Fuel Cell), PAFC (Phosphoric Acid Fuel Cell), MCFC (Molten Carbonate Fuel Cell), SOFC (Solid Oxide Fuel Cell)

The table below gives an overview of different types of fuel cells with their characteristics and advantages and disadvantages. The low-temperature FC are PEM, PAFC and AFC. The two main types of high temperature FC are SOFC and MCFC.

Fuel Cell Type	PEM	AFC	PAFC	MCFC	SOFC
Operating Temperature (°C)	70-80	80-100	200-220	600-650	800-1000
Current Density	High	High	Moderate	Moderate	High
Stage of Development	Early prototypes	Space applications	Early commercial applications	Field demonstrations	Laboratory demonstrations
Likely Applications	Electric utility, portable power and transportation	Military and space	Electric utility and transportation	Electric utility	Electric utility
Advantages	• Low temperature • Quick start-up • Solid electrolyte reduces corrosion and management problems	• High performance	• High efficiency for cogeneration • Can use impure hydrogen fuel	• High efficiency • Flexibility of fuels	• High efficiency • Flexibility of fuels • Solid electrolyte reduces corrosion and management problems
Disadvantages	• High sensitivity to fuel impurities • Requires expensive catalysts	• Expensive removal of carbon dioxide from fuel and air supplies	• Low current and power • Large size and weight	• High temperature enhances corrosion and breakdown of cell components	• High temperature enhances corrosion and breakdown of cell components
Prospect for High Efficiency	Good	Good	Good	Good	Good
Prospect for Low Cost	Good	Good	Fair	Fair	Fair-Good

Sources: Karlhammer et al., 1998; Thomas and Zalbowitz, 1999.

Table 1-10: Overview of main characteristics of fuel cells[27]

- **PEM**

PEM (Proton Exchange Membrane or "solid polymer") fuel cells use an electrolyte that conduct hydrogen ions from the anode to the cathode The electrolyte that ensures the proton (H^+) transfer is composed of a solid polymer film. PEMFC typically operate at 60 to 90 °C and pressures of 1-2 bar(a).
The half cell reactions are:

Anode: $H_2 \rightarrow 2\ H+ + 2\ e-$

Cathode: $O_2 + 4\ H^+ + 4\ e^- \rightarrow 2\ H_2O$

PEM fuel cells have a low operating temperature (<100°C) and is therefore most suited for automotive applications. They have a high power density. Another advantage is their large tolerance to CO_2 so unscrubbed air can be used as oxidant. A disadvantage is their high sensitivity to CO impurities (50 ppm tolerance) and sulphur (a few ppm) so that hydrogen of high purity is needed. PEMFC needs humidification of reactant gases which increases the complexity of the system. They have a high efficiency (60%).
Most of the research effort is focussed on PEMFC for automotive applications and most prototype FC vehicles use PEMFC.

According to the EU study[18], present cost goals for entire PEMFC propulsion systems for passenger cars are slightly higher than for ICEs. The goal is to offer PEMFC cars for prices comparable to diesel cars. To achieve the cost goals platinum load has to be reduced significantly compared to today's levels. Platinum quantities of some grams per car – comparable to catalytic converters- have to be achieved.

- **DMFC (Direct methanol-Air Fuel Cell)**

DMFC is a special type of PEMFC and uses a methanol/water mixture as fuel and air as oxidant source. In the presence of a precious metal catalyst, methanol is directly decomposed at the anode according to the overall reaction:

Anode: $CH_3OH + H_2O \rightarrow 6\ H^+ + CO_2 + 6\ e^-$

This type of FC does not require on-board reforming or storage of hydrogen.
A disadvantage is their CO_2-emissions. DMFC are still in an early development stage. They have inferior performance compared to PEM using hydrogen and their efficiency is lower (up to 30%). However when comparing to hydrogen fuelled FC hydrogen production or reforming on-board needs to be taken into account.

- **PAFC (Phosphoric Acid Fuel Cell)**

PAFCs use liquid phosphoric acid within a silicon carbide matrix material as electrolyte. These type of fuel cells operate at a temperature of 150 – 220 °C and pressure of 1 bar(a).

An advantage is their large tolerance to CO_2 (30%) so unscrubbed air can be used as oxidant. They have a somewhat higher tolerance to CO compared to other types (1-2%) but a limited tolerance to sulphur compounds (50 ppm). PAFC is the most commercially developed fuel cell and are already used for stationary applications.
A disadvantage is their long warm-up time making them less suited for automotive applications. Also the corrosive liquid electrolyte is a disadvantage resulting in material corrosion problems and liquid handling problems. PAFC are large and heavy limiting their use to stationary applications.

- **AFC (Alkaline Fuel Cell)**

Alkaline fuel cells use an electrolyte that conducts hydroxyl ions (OH^-) from the cathode to the anode. The electrolyte is typically composed of an alkaline mixture such as potassium hydroxide (KOH). The electrolyte can be mobile or immobile. Mobile alkaline electrolyte fuel cells use a fluid electrolyte that continuously circulates between the electrodes. The liquid electrolyte is corrosive and introduces handling problems. Immobile alkaline electrolyte fuel cells use an electrolyte that consists of a thick pasta within a porous support matrix. Alkaline fuel cells operate at a temperature of about 65 – 220 °C and a pressure of 1 bar(a). The advantage is their low operating temperature.
Alkaline fuel cells have fast start-up time and high efficiency (70%). They have low weight and volume.
A disadvantage is their sensitivity to carbon dioxide (300 ppm) and CO. This means that pure oxygen is needed or a CO_2 scrubber when used with air.

Alkaline fuel cells are one of the most developed ones because they have been used in space programs (Apollo flights and NASA space shuttles). They have also been demonstrated in London taxis.
Compared to PEM, AFC are relatively cheap because they do not require noble catalyst.[18] On the other hand, they have lower power densities and are relatively sensitive to CO_2 and CO poisoning of the electrolyte. Therefore CO_2 must be removed increasing the complexity of the system.

- **SOFC (Solid Oxide Fuel Cell)**

SOFCs use a ceramic as electrolyte. The electrolyte conducts oxygen ions (O^{2-}) from cathode to anode. SOFCs are built through sequential deposition of various layers of materials in tubular or flat designs. Metals such as nickel and cobalt are used as electrode materials. This type of fuel cell has high operating temperature of 800 - 1000°C. High operating temperatures results in special materials requirements. On the other hand internal reforming of hydrocarbons is possible in this type of fuel cell. This FC can operate on pure hydrogen and reformate gas. Other advantages are their very high efficiency (60%), and fast reaction kinetics. A disadvantage is their moderate tolerance to sulphur compounds (50 ppm).
SOFC are still in development stage. Developments focus on stationary applications and on APUs for cars and trucks. Because of their long start-up times and slow response in load change, they are not suitable for vehicle application other than APU.
At present SOFC are being developed for operation with fossil fuels, especially natural gas.
SOFC fuelled with pure hydrogen has zero emissions. When fuelled with hydrocarbons, e.g. natural gas, SOFCs emit very small amounts of CO, NOx and hydrocarbons.

- **MCFC (Molten Carbonate Fuel cell)**

The electrolyte of MCFC is composed of a molten mixture of lithium and potassium carbonates within a ceramic support matrix of lithium aluminates. The electrolyte conducts carbonate ions (CO_3^{2-}) from the cathode to the anode. This type op FC operate at a temperature of 600 - 650°C and a pressure of 1 – 10 bar. Because of their high operating temperature internal reforming of light hydrocarbon fuels is possible. High temperature also results in the need for suited materials. MCFCs have a high efficiency and fast reaction kinetics. A disadvantage is their low tolerance(1-5 ppm) to sulphur compounds, primarily H_2S and COS. Also long warm-up period is a disadvantage for some applications. MCFC do not require precious metal catalysts.
MCFC can be used for power generation.

- **Fuel cell systems**

Individual fuel cells have a maximum output voltage of about 1Vdc. Substantial voltages and power outputs are obtained by connecting many cells in series to form a fuel cell stack.
As already stated fuel cells need support and control system for operation. A fuel cell needs fuel, oxidant (oxygen) and cooling for their operation. The composition, pressure and flow rate of these flows must be regulated. Moreover gases need to be humidified (for some fuel cell types) and cooling temperature has to be checked. To obtain this, a lot of side equipment is needed.

For vehicles the power generated by the fuel cell must be transferred to the wheels resulting in transmission losses.
An example of a fuel cell stack integrated into a fuel cell system is given in the figure below. The figure represents the fuel cell system used in the CUTE buses. The main components are the hydrogen storage tanks, fuel cell stack and electrical traction engine.

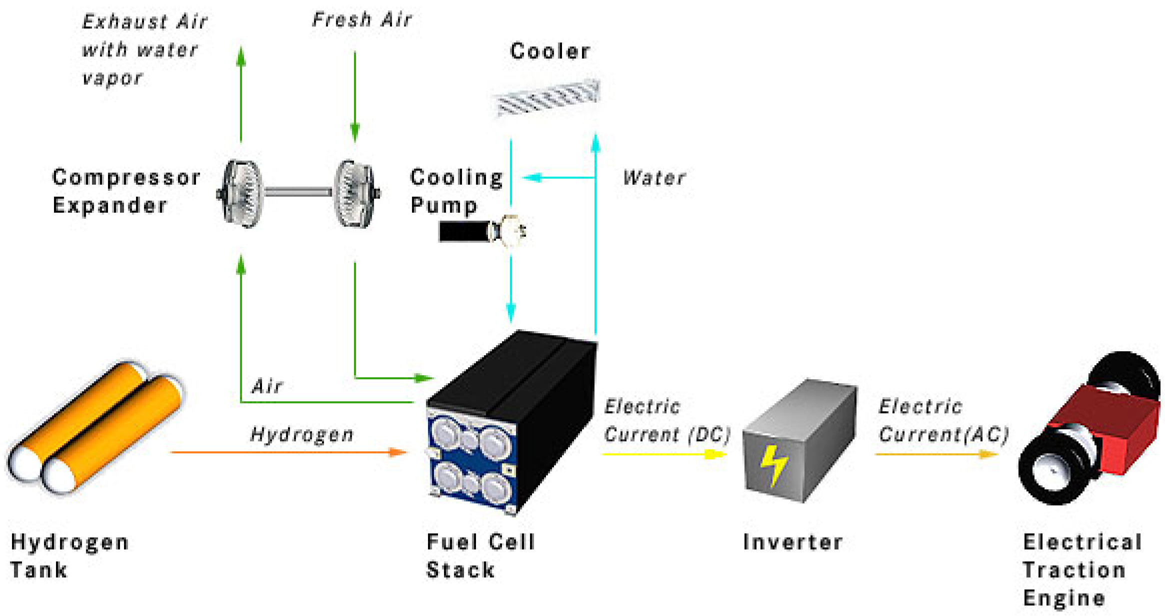

Figure 1-7: Simplified schematic of fuel cell engine directly operating on hydrogen.

When comparing efficiency between fuel cells and other power generating systems, both must be defined in a similar way taking necessary additional equipment into account.

In the next paragraphs vehicle and stationary applications are discussed. Fuel cells are applied in portable applications like mobile phones and camcorders as well. However, their energy use is so low that is not influencing the role of hydrogen. This kind of application is therefore not treated here.

1.5.2 Vehicle applications

- **Fuel cell**

The main requirements for automotive applications are high power density for acceptable weight and space requirements, good dynamics (fast response and short warm-up), estimated low production costs and possibilities for future mass production. For light-duty application a low operating temperature is a condition due to space constraints. Some heavy-duty applications with more space available could allow also systems working at higher temperatures.[28]
The PEM fuel cell is considered as most promising option for vehicle applications. In the EU study on potential for hydrogen as fuel in transport (2020-2030)[18] it was stated that "PEMFC have separately achieved all major technical goals required for commercially competitive mass manufacturing for passenger cars: long lifetime, high power density and low platinum

load. The major development task is to achieve these combined goals in one single stack technology."
SOFC are being developed for use as APU in passenger cars. Market entry of SOFC Apes for passenger cars is scheduled within 2 years (2006).

Fuel cells work particularly in the part-load range at high efficiencies (up to 50%). In the EDC (European Driving Cycle) for passenger cars, fuel cell powered cars achieve an efficiency of 37%, twice that of a normal gasoline vehicle.[11] Automotive manufacturers have stated that they expect these vehicles to be available in the 2010-2012 time frame. Recent developments in fuel cell vehicles is given in the table below. A full overview is available at http://www.h2cars.de ([29]).

Manufacturer	Name	Type	Energy Storage	Power (kW)	Range (km)	Max. speed (km/h)
Opel (Zafira)	Hydrogen 3	PC	LH2: 4.8 kg 68L tank	75	650	180
Daimler Chrysler	Necar 4	PC	CGH2: 2.5 kg (350bar)	75	200	145
Toyota	FCHV5	PC	CGH2: 35 l (500bar)	90	500	
Ford	Think FC5	PC	CGH2: 350bar	75		
Honda	FCX V4	PC	CGH2:130L 350 bar	60	300	140
Audi	A2	PC	CGH2: 1.8 kg 350 bar	66	220	175
Fiat / Nuvera	Seicento	PC	CGH2:68 L tank 350 bar	40	220	130
Daimler Chrysler	Sprinter	LD	CGH2: 350bar	55	150	120
Toyota	Hino bus	bus	CGH2: 250bar	180	300	80
Daimler Chrysler	Citaro bus	bus	CGH2 350 bar	250	300	80
MAN/linde	SL 202	bus	LH2: 600L	140	300	75

Table 1-11: Recent developments in fuel cell cars and buses[11,29]

Fuel cell efficiencies and costs

As already mentioned, when comparing efficiencies of fuel cells and internal combustion engines FC system efficiency must be estimated; when a reformer is used, also his efficiency must be taken into account.

Vehicle costs are an important issue for large-scale introduction of fuel cell technology. However reliable data are scarce.
In the EU study an overview of the latest cost estimates was given.[18] Early estimates on fuel cell costs (studies in mid 1990ies) estimate fuel cell system costs of 50 to 250 €/kW for passenger cars up to 425 €/kW for heavy duty applications. Recent analyses for the US Department of Energy (DOE) come to the conclusion that current PEMFC technology would allow manufacturing cost of 280 €/kW for automotive fuel cell systems at a volume of 500,000 cars per year. Projected technology advances would allow a cost reduction to 85 €/kW. The FreedomCAR Partnership between the US DOE and the North American automotive industry has set a manufacturing cost goal of 30$/kW for automotive fuel systems for 2015, which would represent full competitiveness to ICEs. Recently high level representatives of different car manufacturers (Daimler Chrysler, Honda, GM/Opel) have agreed on a conference that a manufacturing cost goal of 45 €/kW for the entire fuel cell power train can be achieved at a production volume of several 100,000 to one million units.

In the three phase program (of the US DOE) cost goals leading to the commercialization of hydrogen fuel cell vehicles are defined for three different phases (assuming manufacturing volumes of 500,000): 200$/kW for 2004, 125$/kW for 2009 and 30$/kW for 2015.

The fuel consumption and efficiency predictions for fuel cells and ICE as given in the GM study[3] are summarised in the table below.

Vehicle type	Fuel consumption*		Engine efficiency	Vehicle efficiency
	L/100 km	kg/100km	(%)	(%)
CGH2 FC	3.59	0.95	56.6	44.3
CGH2 FC hybrid	3.31	0.87	55.6	48.9
LH2 FC	3.51	0.92	56.6	44.3
LH2 FC hybrid	3.24	0.85	55.6	48.9
ICE	6.37	1.68	27.7	24.2
ICE Hybrid	4.70	1.24	37.7	34.9

* Fuel consumption (L/100 km given as gasoline equivalent and kg hydrogen)

Table 1-12: Fuel consumption and efficiencies as predicted in the GM study[3]

In the Hysociety[11] study a power train efficiency of 44.3% is estimated for passenger cars. A cost of 59 eurocent/kWh or 8.2 eurocent/km is calculated for reference year 2020. The calculations assumed a power train cost of 80 euro/kWh or 6400 euro per vehicle (80 kW). An operating and maintenance cost of 1.5 eurocent/km was estimated. The annual driving distance was estimated at 13,000 km.

According to the US study[22] the cost of a fuel cell vehicle is estimated at 20,200 $ (compared to 18,000 $ for a gasoline car). These estimates are lower than other references who estimated 26,900 $ for fuel cell vehicle (compared to 19,300 $ for gasoline car). In the same study cost estimates are reported for heavy duty applications. A prototype bus costs 1.4 million dollar. The goal for small fleets is 600,000 dollar, a price that is double that of a natural gas bus.

The recent "Well to wheels analysis of future automotive fuels and power trains in the EU context"[30] (often called "CONCAWE-study") gives price estimates for passenger cars for both fuel cell and internal combustion engines. An overview of the estimated cost for 2010 configurations is given in the table below. The fuel cell car has 80 kW and the ICE 77 kW. The hydrogen ICE considered for 2010 is a new born advanced technology (1.3 L downsized turbocharged engine). The estimated fuel consumption (over the NEDC) given in the study is also shown in the table below.

Vehicle configuration	Cost (euro)	Fuel consumption (MJ/100 km)	(kg H_2/100km)
FC_CH2_25	29145	94.0	0.78
FC_CH2_70	28863		
FC_LH2	28863		
FC_Hybrid_CH2_25	30302	83.7	0.70
FC_Hybrid_CH2_70	30050		
FC_Hybrid_LH2	30050		
ICE_CH2_25	24570	167.5	1.40
ICE_CH2_70	24030		
ICE_LH2	24030		
ICE_Hybrid_CH2_25	25271	148.5	1.24
ICE_Hybrid_CH2_70	24821		
ICE_Hybrid_LH2	24821		

Table 1-13: Cost and fuel consumption of different vehicle configurations

The GM estimations for fuel consumption are 20% higher compared to the CONCAWE study, except for ICE hybrid.

Prototypes

Since 1967 more than 100 different FCV (Fuel cell vehicles) have been developed. Most of the vehicles have been presented after 1995. None of these prototypes is economically competitive with conventional ICE vehicles. Both fuel storage and propulsion technology are more expensive compared to conventional technologies. FCV require complete new manufacturing lines and are at this moment only hand-assembles and therefore extremely expensive.
In the large demonstration project CUTE/ECTOS/STEP (see also international initiatives) comprising 33 buses a total distance of 760,000 km was covered in May 2005.

- **ICE (Internal combustion engine)**

Technical characteristics

In general, it can be stated that it is not difficult to run an ICE on hydrogen but the challenge is to run it well.
The properties of hydrogen relevant to its use as a combustible fuel are: wide range of flammability, low ignition energy, small quenching distance, high auto-ignition temperature, high flame speed at stoichiometric ratios, high diffusity and very low density. The impact of these characteristics will be briefly discussed in the next paragraph.

Hydrogen is used as fuel in a spark ignition engine. Using hydrogen in a compression engine is not possible without ignition because the auto-ignition temperature is too high. On the other hand, because of this high auto-ignition temperature higher compression ratios are possible (before auto-ignition occurs) resulting in higher efficiency of the engine.
Because of its wide range of flammability, hydrogen can be combusted in an ICE over a wide range of air/fuel mixtures, so also on lean mixtures. The stoichiometric air/fuel ratio is 34/1.

Hydrogen can be combusted at a lambda equivalence ratio (ratio of real air to fuel ratio and stoichiometric air to fuel ratio) of 1-5. In general, the advantage of lean mixtures is the higher fuel economy, more complete combustion and lower combustion temperature. However a too lean operation can significantly reduce power output. The low ignition energy– in combination with the wide range of flammability - of hydrogen enables hydrogen engines to ignite lean mixture. Unfortunately this means that hot gases and hot spots on the cylinder can serve as sources of ignition resulting in premature ignition and flashback. This is one of the challenges associated with running an engine on hydrogen.
Hydrogen has a high flame speed at stoichiometric ratios. This results in a higher thermodynamic efficiency at stoichiometric ratios. The high diffusity facilitates the formation of a uniform mixture of fuel and air.
The low density of hydrogen firstly results in storage problems on-board as already discussed in paragraph 1.4. Secondly, the energy density of a hydrogen-air mixture and hence the power output is reduced.

Main problems with ICE on hydrogen are pre-ignition due to the low ignition energy of hydrogen. Adapting or redesigning the fuel delivery system can eliminate this problem. Most sophisticated systems use direct injection into the combustion cylinder avoiding 'backfire'. Special care must be taking in the selection of the ignition system.
Internal combustion engines still have NOx-emissions. FC vehicle have zero-emissions in use. NOx emissions -formed from nitrogen and oxygen in air- are related to combustion temperature. NOx emissions of lean-burn hydrogen ICEs for road vehicles are very low. Engine development focus on improving the efficiency and performance of ICE engines while maintaining their emission characteristics of low NOx and almost avoiding other emissions completely.
Conversion of a gasoline engine to hydrogen is more difficult than the conversion to LPG or natural gas.

Efficiency and costs

In Hysociety[11] an efficiency of 22% was estimated for 2000 increasing to 27% for 2020. The fuel consumption is 1.96 kg/km (2000) and 1.56 kg/km (2020) resulting in an energy use of respectively 0.64 and 0.51 kWh/km (taking LHV). It was estimated in this study that the fuel consumption in gasoline equivalent is the same as for an average middle class gasoline engine: 7.4 L/100 km. assuming that the higher vehicle weight is compensated by the higher engine efficiency on hydrogen. It is further estimated that a 20% reduction in fuel consumption will be reached by 2020, assuming mild hybridisation a standard technology. The drive train cost is estimated at 3250 euro (100kW), no figures for 2000 are given. A conventional gasoline engine drive train cost is assumed 30 €/kW in 2020. The annual driving distance is estimated at 13,000 km with an operating and maintenance cost of 195 €/year. The life span is estimated at 150,000 km in 2000 and 200,000 km in 2020. CO_2 emissions are estimated at 3 g/km, originating from lubricating oil.

Prototypes

BMW and Ford are the two leading developers of hydrogen fuelled ICE vehicles. Commercial availability is expected in a few years, depending on the availability of hydrogen refuelling stations. The number of filling stations needed is reduced if engines are bi-fuel. Bi-fuel

engines are not optimised for efficiency and emissions, and have higher production costs. Therefore, it is expected that mass market introduction will occur with dedicated mono-fuel hydrogen vehicles.
The cost goal for ICE is maximum 10 % additional compared to conventional engines.[18] At present only prototypes are available. The fuel storage and supply part will incur higher extra cost compared to the engine. Hydrogen vehicles will achieve fuel consumptions comparable to diesel engines where fuel cell vehicles consume less than advanced diesel ICE.

BMW[31] has a fleet of 15 bi-fuel research cars based on the previous V12 7 series and designated 750hl. The heart of the 750hl is a hybrid, 12-cylinder combustion engine with two independent electronically controlled fuel induction systems. These systems allow the 750hL to run on either gasoline or hydrogen.
These vehicles were demonstrated on a world tour and covered 150,000 km. These vehicles are equipped with a 5 kW PEM fuel cell as APU. The range (on hydrogen) is 300 km. Hydrogen is stored in liquid form in a 140 L tank.

The 745h is the second generation hydrogen-powered vehicle. The 745h is powered by a 4.4-liter V8, featuring bi-VANOS variable valve timing, Valvetronic variable intake runners, and a fully variable intake manifold. The 745h can use either hydrogen or gasoline.
Running on hydrogen, the 745h produces 184 horsepower and can achieve a top speed of 133 mph. The cruising range is 190 miles. Added to the 400-mile range of the normal fuel tank, the 745h can go 600 miles between fill-ups. An Auxiliary Power Unit (APU) runs the 745h's power-consuming features. The APU operates on a PEM fuel cell that is independent of the engine, thanks to a direct hydrogen feed from the boot-mounted tank. This means power accessories like air conditioning can be operated when the engine is shut off, saving a gallon of gas for every 235 miles of city driving.

In 2001 Ford presented a P2000 H2ICE concept vehicle, which uses a modified version of the Zetec 2.0-liter gasoline engine. Gaseous hydrogen is stored on-board at a pressure of 250 bar in 2 composite tanks with a total volume of 87 L. Hydrogen is delivered to the engine at a pressure of 5.2 bar. The vehicle has been tested over the American test cycle (FTP-75). CO and hydrocarbon emissions are very low, NOx emissions on the other hand were not negligible. (CO: 0.6 g/km, HC 0.005 g/km, NOx: 0.46 g/km, CO2: 0.87 g/km) The relative high NOx emissions are the result of the enrichment of the air/fuel mixture to improve 'drivability'. Also other experiments showed that NOx emissions increase when lambda is below 2.

The Ford Model U Concept is propelled by an internal combustion engine (ICE) optimized to run on hydrogen. The engine is supercharged and intercooled for maximum efficiency, power, and range. According to the manufacturer, the emissions are nearly zero, and the engine is up to 25 % more fuel-efficient than a typical gasoline engine.
The engine is based on Ford's global 2.3-liter, I-4 engine used in the Ford Ranger, the European Ford Mondeo, and a number of Mazda vehicles. It is optimized to burn hydrogen through the use of high-compression pistons, fuel injectors designed specifically for hydrogen gas, a coil-on-plug ignition system, an electronic throttle, and new engine management software.
Designing a gasoline engine to burn hydrogen fuel has typically resulted in significantly lower power output—until now. Ford researchers have shown that with supercharging, the hydrogen ICE can deliver the same power as its gasoline counterpart and still provide near-zero-emissions performance and high fuel economy.

Ford has equipped the Ford Focus with a prototype hydrogen ICE. The vehicle was recently (July 2004) unveiled[32].
The base engine is a 2.3 L 4-cilinder gasoline engine of 110 hp (82 kW). The hydrogen vehicle differs from the base vehicle in the packaging of the engine, the location of the batteries and special safety systems and sensors. A supercharger enables the hydrogen vehicle to have similar performance to the corresponding gasoline vehicle.
The vehicle uses gaseous hydrogen stored at 350 bar in three tanks (two are located in the boot and one is located under-floor. The three tanks have a capacity of 119 litres (equal to 2.75 kg) and provides a range of 200 km.

Hydrogen ICE in buses

MAN is developing the use of hydrogen in both ICEs and fuel cells. In the Munich Airport project[33] 3 buses operate on hydrogen ICE. Two MAN articulated buses are demonstrated in this project. The engine works somewhat below stoichiometric and has a catalyst to reduce NOx emissions. The buses are in operation since 1999. Compressed hydrogen is stored at 250 bar in a tank of 2550 L. According to MAN experience with these buses is good. Since their first use some improvements were made regarding fuel injectors and cylinder packing. A NOx catalyst was installed to reduce NOx emissions. NOx emissions measured over the 13 mode test were below 0.4 g/kWh.
A new engine is being developed with direct hydrogen injection.

Hydrogen Systems has demonstrated in 1994 2 buses with hydrogen ICE. A Van Hool (A120) with 12L MAN engine and liquid hydrogen storage (125L). The second one was the ZEM bus: a Scania with DAF engine equipped with a 350L tank for liquid hydrogen (25 kg). Both buses only operated during demonstration and are not in operation now. According to Hydrogen Systems NOx emissions are below 0.25 mg/kWh. Stoichiometry is 5.

1.5.3 Stationary applications

Stationary fuel cells can be used to provide heat and power for small to medium-sized buildings. PEMFC and SOFC are used for small scale residential systems (1-10 $kW_{electric}$), while mostly PAFC, MCFC and SOFC are used for medium-scale industrial systems (100-400 $kW_{electric}$). Excess heat can be used in heating and hot water production. Fuel cell systems can be used as back-up in emergencies.
A general description of the working principle of fuel cell is already given above.

Fuel cells for domestic applications[11]

Fuel cells have a their high electric energy conversion efficiency at full and especially at partial load, both in large-scale as well as small-scale applications. With their zero or near zero emissions they seem to be ideally suited for a variety of applications in urban centres and metropolitan areas. Among these applications are power and combined heat and power production in the domestic sector.

About eighty companies are active in the development of small stationary fuel cell systems world-wide. Most of the systems developed to date are still demonstration units. Companies recognize that residential market cannot support the current fuel cell systems because prices are still too high and also because the lifetime of systems is still too short. This market needs systems that can operate for around 40,000 hours but at this time, few systems could demonstrate a lifespan higher than 10,000 hours. However, most of the surveys conclude that small stationary fuel cell systems will succeed in the mid- to long-term.

In term of technology, most of the systems in the sector of residential applications use proton exchange membrane fuel cells (PEMFC). However, the proportion of systems equipped with solid oxide fuel cells (SOFC) has risen. At the beginning of the year 2002, the proportion on a worldwide scale was 95% for PEMFC and 5% for SOFC and eighteen months later in July 2003, the proportion was respectively 80% and 20%. This may happen because, in commercial buildings, solid oxide fuel cell systems can provide a better match for the thermal-to-electric ratio for buildings than current cogeneration systems and, in industrial cogeneration applications, they produce high temperature waste heat that can be used for hybrid systems with steam turbines. Solid oxide fuel cell technology is looking increasingly promising on the key issues of cost and efficiency. This type of fuel cell is the most demanding from the material viewpoint. On the other hand, it has a high tolerance to impurities so relatively impure fuels can be used, derived from e.g. natural gas. The key problem for small cogenerators is the requirement for on/off cycling which occurs many times per day. An solution applied is that the fuel cell delivers only continuous base load electricity, 1 kW in Japan up to 5 kW in the USA, while electric peak power is drawn from the electricity grid and heat peak demand is made by an extra burner in the cogeneration system (up to 30 kW_{heat}).

The proportion of systems installed in Europe has risen significantly certainly influenced by the 6th framework programme. This increase is mainly due to the efforts of the Swiss manufacturer Sulzer Hexis and the German company Vaillant, which has established a partnership with the American company Plug Power. Sulzer Hexis is one of the few companies that produce SOFC systems while Vaillant produces PEMFC systems. Both work with natural gas.

Sulzer Hexis has been supplying a CE certified pre-series system since the end of 2001. They are designed for use with natural gas and they have been tested in private houses, public buildings, laboratories and apartment blocks. The power of this system reaches a maximum of 1 kW of electrical power and 2.5 kW of thermal power. When a higher thermal power is needed, an auxiliary heating system can be brought into service. The expected electrical efficiency of this system is about 25-30% and the overall efficiency should be about 85%.
The systems supplied by Vaillant provide 4.6 kW of electrical power and 7 kW of thermal power. They can achieve electrical efficiency of 30% (expected) and an overall efficiency of 82%.

In Japan under The Stationary Fuel Cell Demonstration Project many companies started to make 1 kW cogeneration systems. The project operates 31 stationary fuel cells in various sites such as residential areas, heavy traffic areas, and seaside areas.

A study about the use of a 5-kW PEM fuel cell to provide electricity and heat for a family house[34] showed that if the PEM supplied 100% of the electricity home demands, only 40% of the heating demand would be met. Consequently, during the winter, the fuel cell would presumably operate above the electricity demand in order to meet the heating demand and excess electricity would be sold to the grid. The paper's conclusion was that a system driven by the electricity demand (and not the heat) would be economically efficient if the capital cost should be below $1,200/kW.

- **FC for back-up power (uninterrupted power supply)**

There are some industries that cannot experience power black-outs. Banks, hospitals and increasingly the telecommunications industry need secure power supplies and are willing to pay for technologies that can provide this. The Uninterruptible Power Supply (UPS) and backup market is designed to ensure that if a main power supply fails the backup unit provides power until the main supply is back-on-line. This is becoming a niche market for small-scale fuel cells of around 1 kW.

Amongst the technologies in the small stationary market there still appears to be dominated by PEM and SOFC, with AFC being some way behind. Half of them use natural gas as fuel while the other half consumes hydrogen directly. Companies are here PlugPower with its PEMFC 'GenSet', ReliOn with its Independence 1000 and in Europe for example Axane, a daughter of Air Liquide, with its RollerPac.

- **FC for industrial applications**

High-temperature fuel cells have the most positive characteristics for stationary use. MCFC and SOFC are the two technologies in this temperature range and they also permit the generation of process steam for industrial applications. Whereas Fuel Cell Energy in the U.S. and its licensee MTU Friedrichshafen GmbH from Germany together with Ishikawajima-Harima Heavy Industries and Mitsubishi from Japan dominate MCFC development, Siemens Westinghouse is by far the leader in SOFC development.
In December 1997, a consortium of Dutch and Danish utilities began operation of a 100-kW SOFC power system in the Netherlands manufactured by Siemens Westinghouse. This system typically supplies 109 kW electrical power and 63 kW thermal output as hot water in the local district heating network. After 16,000 operation hours the fuel cell was moved to RWE Power in Germany. As of January 2003 the system has operated for 20,000 hours in total achieving 46% electrical efficiency. In cogeneration mode the system yields fuel utilization factors of approximately 80%. The electrical efficiency of an unpressurised 250 kW plant is expected to be 47% to 50%, and with exhaust temperatures up to 600°C. A pressurised SOFC system could be combined with a micro gas turbine and an electrical efficiency up to 70% is expected.
The high temperature (400 – 450°C) of the thermal energy provided by the MCFC power system enables its utilization also in industrial heat and power cogeneration applications. For example at current projects the Hot Module manufactured by MTU has already achieved an electrical efficiency of 46% and a total efficiency of 76%. Alternatively the heat produced by the Hot Module could also be used to run a steam turbine to generate more electricity, reaching an electrical efficiency of about 65%.

The American company UTC Fuel Cells offers the PC25 C as a commercial product, that world-wide is the most applied stationary system. This phosphoric acid fuel cell has so far been utilized in more than 250 applications. The electric power efficiency was 40% maximum. As an example the GEW RheinEnergie AG is operating the only plant in Europe with the renewable energy source of digester gas in a waste water treatment plant in Cologne, Germany. However, it must be pointed out that the potential for reducing costs is inadequate for further market penetration of this cell type, although the company started new developments again recently.

In Liège, at the university campus Sart-Tilman there has been a stationary fuel cell system of the PEM type with an electric power of 220 kW. The heat was used for the university swimming pool. The system was delivered by a consortium of Ballard and Alstom. The fuel cell was fuelled by natural gas. While a PEMfc only works on hydrogen a natural gas reformer had to be included in the system. After two years of operation the project stopped in 2003 and the system was shipped back to Ballard for evaluation.

While high temperature fuel cells (MCFC and SOFT) have the highest efficiency and are the easiest to be fuelled by natural gas, these two types are nowadays the main types to be installed for stationary applications.

- **ICE for stationary applications**

The use of hydrogen in ICE for mobile applications was already discussed above. The general principles for hydrogen use in combustion engines is also applicable here. It results into the classical cogeneration motor fuelled by hydrogen. Although well possible, there seem to be no applications in this area.

1.6 Abbreviations

AFC : Alkaline Fuel Cell
CCGT : Combined Cycle Gas Turbine
CGH2 : Compressed Gaseous Hydrogen
DMFC: Direct Methanol-Air Fuel Cell
FC : Fuel Cell
ICE : Internal Combustion Engine
LH2 : Liquid hydrogen
MCFC: Molten Carbonate Fuel Cell
PAFC : Phosphoric Acid Fuel Cell
PEM : Proton Exchange Membrane
POX : Partial oxidation
SMR : Steam reforming
SOFC : Solid Oxide Fuel Cell
TTS : Tank to Wheel
WATT: Well to Tank
WTW : Well to Wheel

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2 ANNEX 2: FOREIGN HYDROGEN EXPERIENCES

In this chapter, an overview of international experiences and knowledge on hydrogen is given in order to use these experiences for implementation of hydrogen technologies in Belgium. Issues that are covered in this chapter are: demonstration projects, national hydrogen programs and policies.

2.1 Demonstration projects

2.1.1 Demonstration projects in Europe

There are several demonstration projects in Europe, almost in all countries. Some recent larger scale projects are discussed here:

- 30 Busses in 10 Cities: CUTE – ECTOS
- Transport at München Airport: ARGEMUC
- Heat and electricity cogeneration: MTU
- Micro-cogeneration: Virtual Fuel Cell Power Plant.

- **30 Busses in 10 Cities: CUTE - ECTOS**

CUTE (Clean urban Transport for Europe) is a demonstration project set up within the 5th framework programme of the European Commission[1,2]. The aim of the project is to demonstrate the feasibility of an innovative, highly energy efficient clean urban public transport system. In each of 9 European cities 3 FC buses are in operation during 2 years. There are also three of the same buses in Reykjavik. Here the project is called ECTOS (Ecological City Transport System).

The projects have been initiated by Daimler-Chrysler who delivers all buses and carries out their maintenance. The buses are identical. The driveline consists of two 150 kW PEM fuel cells from the company Ballard. The fuel cells give electricity to one electric motor. The bus has a driving range of approximately 200 km with one tank. The tank consists of 9 high pressure cylinders with a volume of 205 l each. The total storage capacity (at 15°C and 350 bar) is 40 kg H_2.

Interesting is that all cities have different hydrogen filling solutions. Hydrogen is made by electrolysis, steam reforming and gasoline partial oxidation. This results into a wider range of energy sources than nowadays is used for buses. Figure 2-3 gives a clear representation of this shift. The consumption is approximately 20 kg hydrogen per kilometre or 67 l diesel equivalent/ 100 km. A corresponding diesel bus consumes 45 l. The actual design has not been optimised towards efficiency. The experiences with the buses are good. The drivers and the passengers are positive. Critical points are the filling stations and the permits. It can be difficult to obtain a permit (In London it took several years to obtain a permit for on-site hydrogen production) and the permits are on a temporary base except Reykjavik. Occurring technical problems are almost all related to the filling stations, in specific with the compressors.

Figure 2-1: Nine cities in the Cute project.

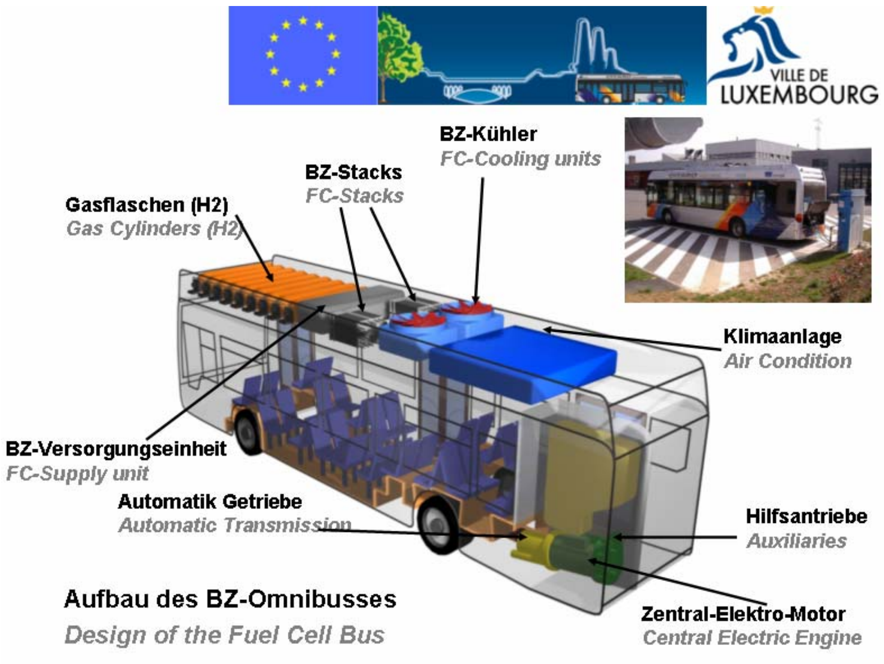

Figure 2-2-: Graphical design of the fuel cell bus.

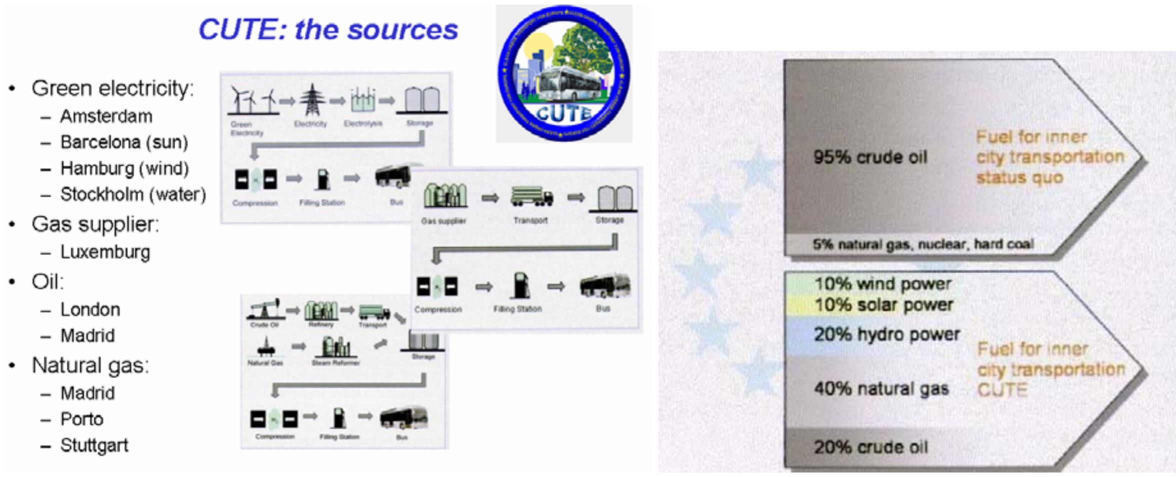

Figure 2-3: The energy sources for the Cute buses

Figure 2-4: Filling station in Luxemburg and in Reykjavik

- **Transport at München Airport: ARGEMUC**

Since 1997 ground transport at München Airport is changing to hydrogen fuel[3]. It started with 3 MAN busses with internal combustion engines and 2 BMW 7 series cars. In the second phase on-site hydrogen was added by means of an alkaline electrolyser at 30 bar from GHW, which is a daughter of Hydro. The hydrogen storage was done in metal hydrides.

In 2004 the third phase started, extending the project considerably. Another hydrogen source has been put in place: steam reforming, and at the transport side a fuel cell bus and fuel cell driven fork-lift trucks are added. Figure 2-6 gives an overview of the infrastructure and the vehicles. The project goals are to:

– Demonstrate the reliability of hydrogen as an energy source
– Present the generation and consumption of hydrogen as a self-contained cycle
– Develop and implement standardized safety technology
– Conduct ongoing analysis of the economic framework
– Demonstrate the use of hydrogen as energy source for mobile applications
– Raise public awareness and acceptance of hydrogen as a fuel
– Secure and create employment.

Figure 2-5: Filling station and fuel cell bus at München Airport

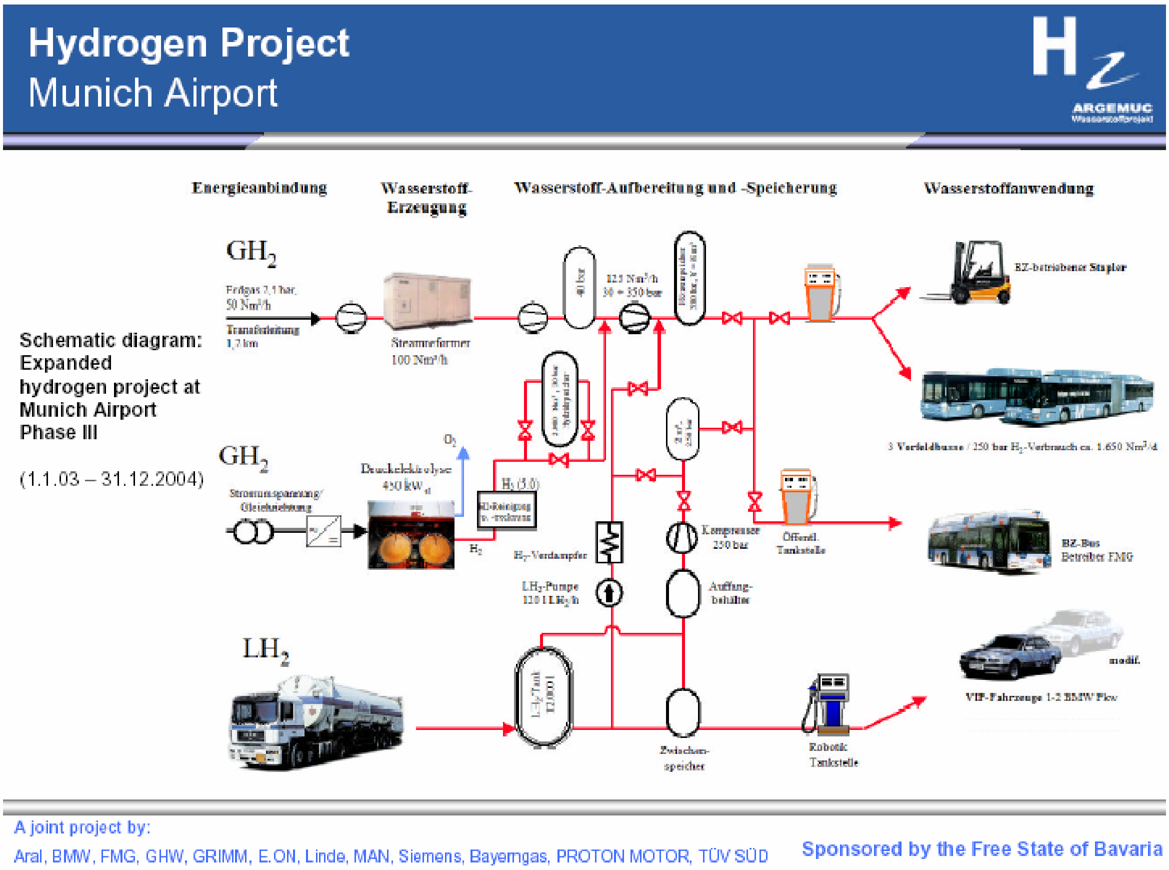

Figure 2-6: The hydrogen project in München with the hydrogen sources and the hydrogen users.

According to project team the results so far are:

– 330,000 km total mileage with the buses
– 170,000 km total mileage with LH_2 cars
– 8,000 successful filling operations
– 60,000 l of liquid hydrogen turned over
– hydrogen technology is ready for implementation
– hydrogen technology meets safety standards
– hydrogen operations are possible as a self-contained cycle
– hydrogen meets with public approval.

- **Heat and electricity cogeneration: MTU**

Actually this is not a project but a European company that placed several fuel cells to be field tested.

For cogeneration of heat and electricity high temperature fuel cells have several advantages. The high temperature makes the heat more worthwhile, these fuel cells can use directly natural gas as a fuel, or more interestingly in view of sustainability, biogas. Their efficiencies are also better than those of low temperature fuel cells.
MTU chose for the molten carbonate fuel cell[4]. The company started in January 2003 as a joint venture of DaimlerChrysler and RWE. It is in its field-trial stage. It has already installed 9 so-called "HotModules" in Europe (see Figure 2-8) and 16 elsewhere. The current modules deliver 250 kW of electricity with 47% efficiency, remarkably more than comparable gas engines with an efficiency of around 35%.

The next goals for MTU are:
– Maturing & Extension of the Product Line
– Value Engineering for Cost Reduction
– Large Scale Production and Assembly
– Market and Customer Development

Figure 2-7: A molten carbonate fuel cell system, 'HotModule' from MTU.

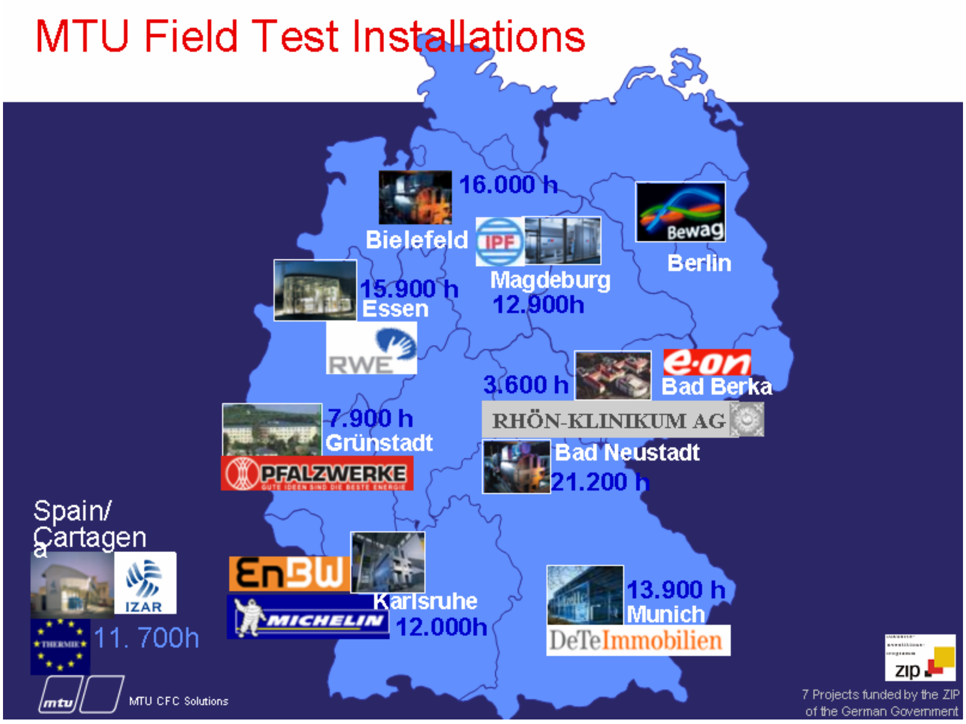

Figure 2-8: Installations of MTU in Europe with their operating hours in spring 2004.

- **Microcogeneration Virtual Fuel Cell Power Plant**

The Virtual Fuel Cell Power Plant is a project in the 5th Framework Programme of the European Union[5,6]. The Virtual Fuel Cell Power Plant is a series of decentralised residential micro-cogeneration units installed in multi-family- houses, small enterprises and public facilities for individual heating, cooling and electricity production. Centrally controlled and grid-connected, these elements of the virtual power plant can contribute to meet peaking energy demand in the public electricity grid and act as a virtual power plant.

The heart is a micro-cogeneration unit made by the combination of Vaillant and Plugpower. It is based on a low temperature fuel cell, PEM-type. To generate hydrogen there is a autothermal reformer in the unit that consumes natural gas. In Figure 2-9 the progress of these units can be seen. The efficiency on the electrical side is 30%. There has been a lot of progress in fuel cell stack lifetime, which is more than a year now. This must be increased a lot more and is the major part of the development.

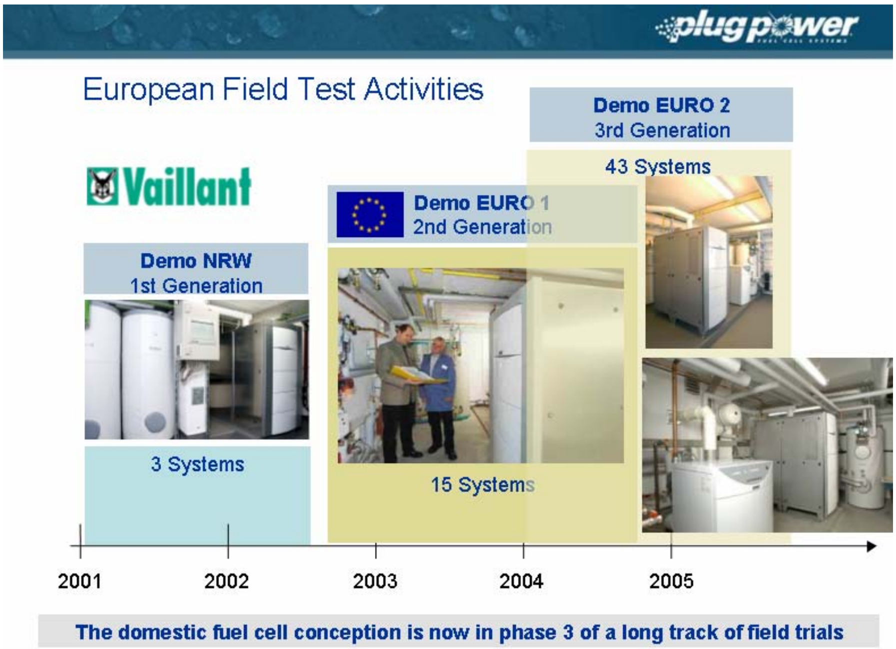

Figure 2-9: Field trial schedule.

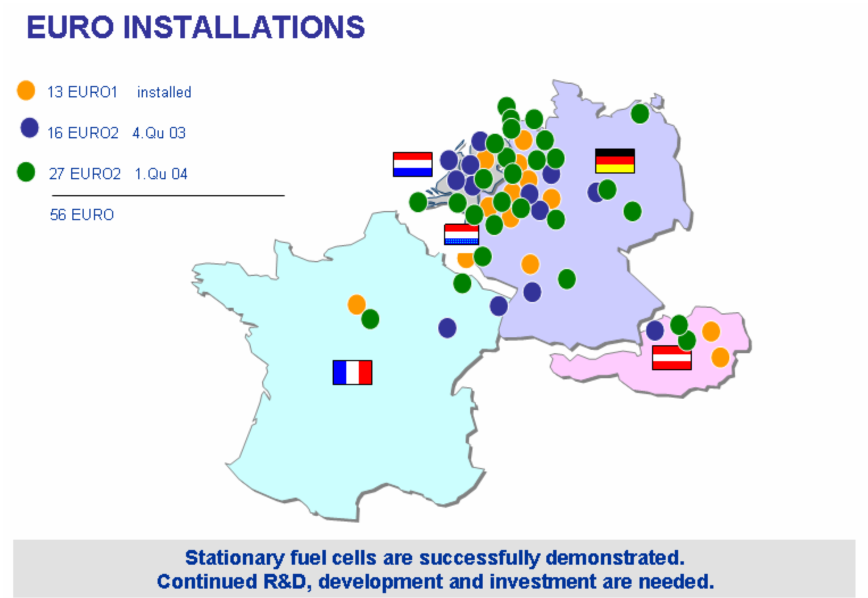

Figure 2-10: The current installations of micro-cogeneration units 'Euro' in Europe.

2.1.2 Related activities in Europe

- **Cleaner Drive**

Cleaner Drive is a EU funded project (2001 – 2003) in the 5th Framework Program. The project addresses different aspects regarding the introduction of cleaner vehicles. One of the work packages addresses some aspects to facilitate the introduction of road vehicles fuelled by hydrogen or methane.

The objectives are:
- Highlight critical gaps and problems in Europe regarding standards, legislation and regulation in the area of refuelling and use of road vehicles fuelled by hydrogen or methane
- Develop recommendation for policy priorities and strategies for dealing with these gaps and problems
- Identify the investment needs and the amount of short term subsidies required for a critical quantity of infrastructure that corresponds to a sustainable market demand.

- **EIHP**

In the first 2-year phase of EIHP (2001—2004), proposals for harmonised draft regulations for the approval of hydrogen fuelled road vehicles were developed.
EIHP2, the 3-year follow-up to EIHP provides input for regulatory and standardisation activities on a European and global level facilitating the safe development, introduction and daily operation of hydrogen fuelled vehicles on public roads and their associated refilling stations. The main focus of EIHP2 is on refuelling stations. A final report was published in April 2004.

- **PREMIA**

PREMIA is a Specific Support Action under the 6FP. It investigates the effectiveness of support programmes to facilitate and secure the market introduction of alternative motor fuels in the European Union. Focus is on biofuels (biodiesel - bio-alcohol - biogas – biomass-to-liquid fuels) and hydrogen for transport. The Cute project will for example be evaluated by PREMIA.

- **HYPOGEN & HYCOM**

To stimulate the built-up of experience with hydrogen the European Union will invest the next ten years two lighthouse projects: HYCOM and HYPOGEN. Within the HYCOM framework regions will be developed where the hydrogen comes from all kind of renewable energy. The objective of HYPOGEN is large-scale coproduction of electricity and hydrogen from fossil fuels while the CO_2 is captured and sequestrated. In this way low-emission hydrogen will be available for cars, busses and other applications. HYPOGEN can be based on existent technologies. Social acceptance and juridical aspects around CO_2 captation will be important hurdles.

2.1.3 Demonstration projects in the United States

- **Heat and electricity cogeneration: Siemens Westinghouse**

Siemens Westinghouse develops, as part of the US Department of Energy's advanced fuel cell research program, high temperature fuel cells of the SOFC-type[7]. Apart from a special fuel cell geometry it is interesting that they put a microgasturbine in series with the fuel cell to increase the efficiency.

Their first commercial prototype of the cogeneration system was installed in the Netherlands in the neighbourhood of Arnhem in 1998. It is a 100 kW system operated by the Dutch utility NUON. The system has a peak power of 140 kW, typically feeding 109 kW into the local grid and 64 kW of hot water into the local district heating system, and is operating at an electrical efficiency of 46%. It has shown no performance degradation while it operated for 16,667 hours. In 2001 the system was moved from the Netherlands to a site in Essen, Germany for operation by the German utility RWE.

In 2001 Siemens Westinghouse commissioned the first SOFC/gas turbine hybrid system at the utility Southern California Edison. The system has a total output of 220 kW, with 200 kW from the SOFC and 20 from the microturbine generator. It demonstrated 53% electrical efficiency. Siemens Westinghouse expect that SOFC/gas turbine hybrids should be capable of electrical efficiencies of 60-70%.

Figure 2-11: The 100 kW SOFC cogeneration system placed in the Netherlands and the 220 kW SOFC/ gas turbine hybrid placed in California.

- **Long Island Power Authority**

Long Island Power Authority is a large utility in the state New York and is strongly involved in clean energy production[8,9]. The projects are carried out as part of the 'Clean Energy Initiative', an initiative of the governor of New-York. In this context it invests heavily in fuel cells. Since 2001 they installed already 166 fuel cell units from PlugPower. The fuel cell is 5 kW of the PEM-type. It is the same fuel cell as used in Europe (see 2.1.1), but the units around are developed for American conditions. Long Island Power Authority uses units fed with hydrogen and units fed with natural gas.

In 2001 the utility installed 75 units on a special site to feed the electricity grid. See Figure 2-12. Since then another 45 units have been placed there. The other fuel cell units have been placed at customer locations. According to the utility the fuel cells help against the occurring power failures and they are an important component of an alternative energy mix for Long Island or, as they say, the units provide "environmentally sensitive electric redundancy".

Figure 2-12: 75 fuel cell units acting as an electricity plant at Long Island Power Authority.

- **California Fuel Cell Partnership**

The California Fuel Cell Partnership started in 1999 and is committed to promoting fuel cell vehicle commercialisation[10]. Automobile companies and fuel suppliers have joined together to demonstrate fuel cell vehicles under real day-to-day driving conditions. In addition to testing the fuel cell vehicles, the partnership is examining fuel infrastructure issues and beginning to prepare the California market for this new technology. See Figure 2-14. Its headquarter houses individual indoor garages for vehicles maintenance by the different auto manufacturers.

The partnership consists of auto manufacturers (DaimlerChrysler, Ford, General Motors, Honda, Hyundai, Nissan, Toyota and Volkswagen); energy providers (Air Products, BP, ChevronTexaco, ExxonMobil, Pacific Gas and Electric Company, Praxair, Proton Energy Systems, Shell Hydrogen, Stuart Energy (nowadays Hydrogenics) and Ztek); technology companies (Ballard Power Systems and UTC Fuel Cells); government agencies (California Air Resources Board, California Energy Commission, South Coast AQMD, US Department of Energy, US Department of Transportation, US Environmental Protection Agency, National Automotive Center and the Institute of Transportation Studies at UC Davis); and bus transit agencies (AC Transit, Santa Clara Valley Transportation Authority and SunLine Transit Agency).

Figure 2-13: The headquarter with indoor garages. The cars of the auto manufacturers are shown in front.

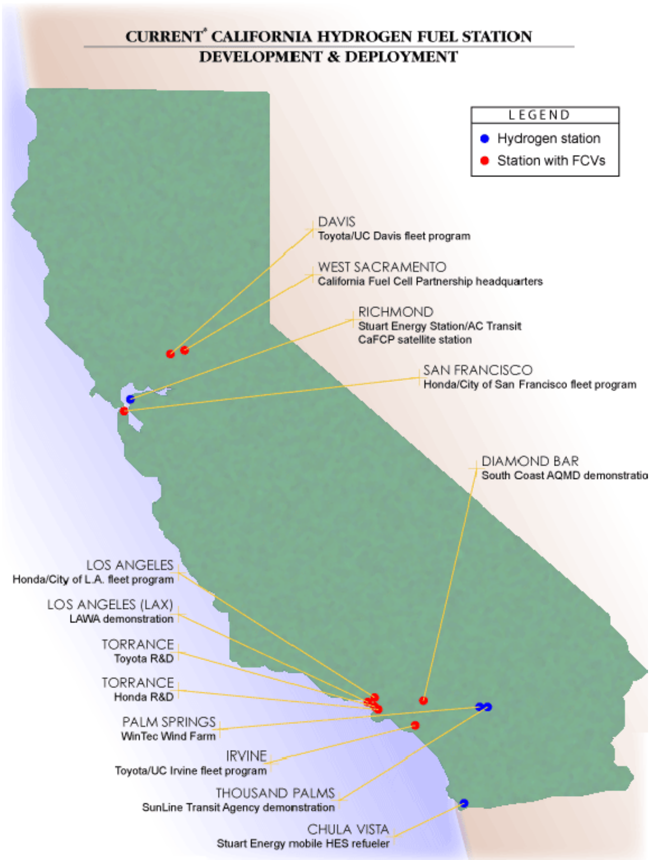

Figure 2-14: The hydrogen stations in California.

2.1.4 Demonstration projects in Japan

- **WE-NET**

In 1993 Japan launched the first major, national R&D programme on hydrogen and fuel cells: WE-NET, the International Clean Energy Network Using Hydrogen Conversion[11]. Initially it focussed R&D on core technologies necessary for establishing a hydrogen infrastructure (e.g., electrolysis, liquefaction, storage: phase 1) and in 1999 on the utilisation of hydrogen and construction of fuelling stations (phase 2). Figure 2-15 represents the task items in the project. The project was lead by the former Ministry of International Trade and Industry (MITI).

The ten-year programme yielded achievements including:
- Hydrogen production: Development of a PEM electrolyser with an efficiency rating of greater than 90% , and the development of high performance cell technologies.
- Transportation and storage: Obtained data of thermal conductivity for insulation panels and LH_2 pumps.
- Metal hydride: Developed 2.6 wt% at <100°C.
- Cryogenic materials: Established data on properties of weld and base metals in LH_2.
- Hydrogen diesel engine: Tested a 100 kW single cylinder engine.
- Hydrogen fuel cells: Developed a 30 kW PEM FC power plant.
- FC vehicles fuel tank systems: Conducted safety test of MH fuel tanks and quick refuelling test for MH tanks.
- Hydrogen filling station: Developed three H_2 filling stations (PEM electrolysis, natural gas reforming and by-product hydrogen system).

The second phase in WE-NET was completed one year ahead of schedule in 2002.

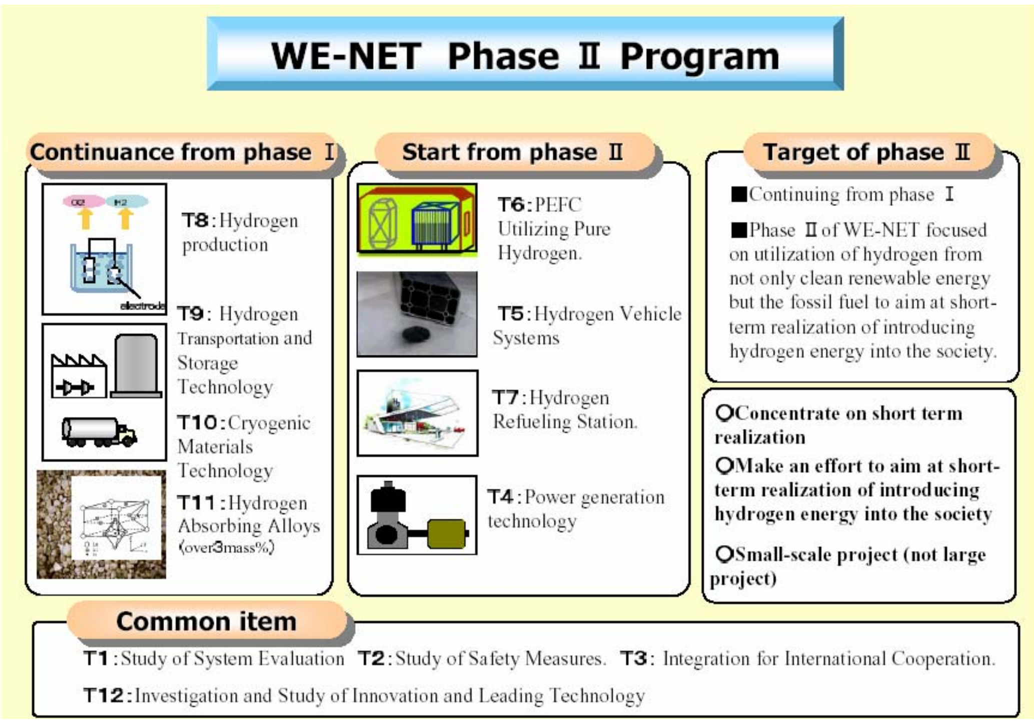

Figure 2-15: Overview of the task items in WE-NET.

- **Japan Hydrogen & Fuel Cell Demonstration Project**

An eye-catching project is the "Japan Hydrogen & Fuel Cell Demonstration Project" (JFHC)[11,12]. The project is situated in the Kanto area (around Tokyo). Centrally there is the JHFC Park, a complex with a FCV showroom, garage, service centre, and hydrogen station. Furthermore there are ten filling stations. Figure 2-16 gives an overview. The demonstration project consists of road test demonstrations and the operation of hydrogen refuelling stations. In this project, ten hydrogen stations with various fuel sources will be tested, such as de-sulphurised gasoline reforming, naphtha reforming, LP Gas reforming, liquid-hydrogen from coke-oven gas as by-product of steel making), methanol reforming, mobile stations, water electrolysis, sulphurous kerosene reforming, natural gas reforming and high-pressure storage (from by-product of sodium hydroxide, NaOH). These stations will be operated and evaluated along with the fuel cell vehicles that participate in this project. Moreover, forty-eight fuel cell cars and five fuel cell buses are participating in this project and various data such as driveability, environmental characteristics, fuel consumption is obtained for evaluation.

In the project there are auto manufacturers (Toyota, Nissan, Honda, DaimlerChrysler, General Motors, Hino, Mitsubishi and Suzuki); energy providers (Eneos, Cosmo Oil, Showa Shell Sekiyu, Tokyo gas, Sinanen, Itochu Enex, Idemitsu Kosan and Toho Gas); industrial gas providers (Iwatani International, Japan Air Gases and Nippon Sanso) and other companies (Nippon Steel, Tsurumi Soda, Kurita Water Industries and Babcock-Hitachi)

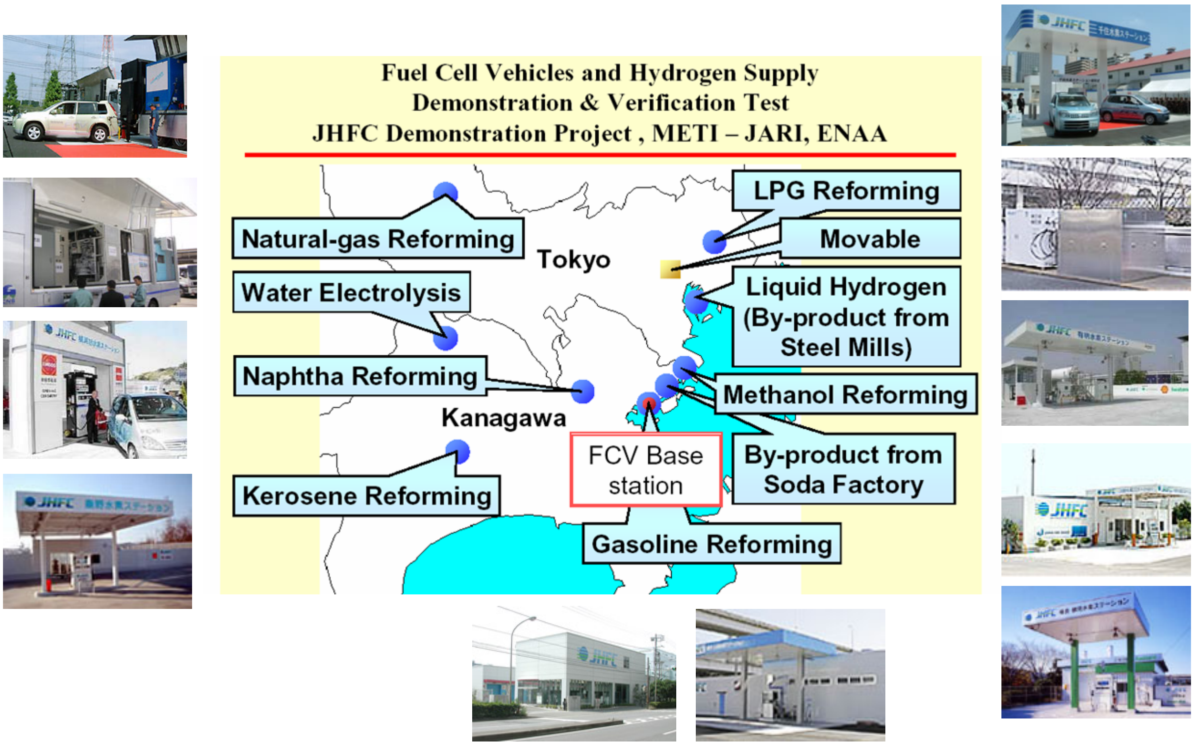

Figure 2-16: The filling stations in the JHFC project with the hydrogen sources.

Figure 2-17: The vehicles participating in the Japan Hydrogen & Fuel Cell Demonstration Project

- **Stationary Fuel Cell Demonstration Project**

The Stationary Fuel Cell Demonstration Project will test small stationary fuel cells of the PEM type in houses that produce electricity and hot water. It has to estimate the efficiency and to identify the problems of commercialisation, especially for regulation improvement. The project operates 31 stationary fuel cells in various sites such as residential areas, heavy traffic areas, and seaside areas. It will also evaluate various fuel types, i.e. natural gas, LP Gas and kerosene.

Taking an averaged electric demand of households in Japan, the rated output power is selected to be 1 kW and 60°C hot water. The 1 kW range is notably smaller than their North American counterparts. In part this reflects the lower power consumption of the average Japanese household. More importantly, however, Japanese systems are smaller because they are being designed to operate in urban areas and provide power in parallel with the grid. In North America, in contrast, bigger units are being developed as stand-alone power sources for remote locations.

The project is organised by the Japan Gas Association. This involvement reflects the key part that Japanese gas companies are set to play in the commercialisation of residential systems in Japan. The Japanese gas companies, Tokyo Gas, Osaka Gas and Toho gas have put a lot of effort in making reformers for natural gas and LP gas. These technologies have been incorporated in the stationary fuel cell system. There are many Japanese manufacturers of 1 kW PEM systems: Ebara Ballard, Fuji Electric, Ishikawajima-Harima Heavy Industries (IHI), Kyocera, Matsushita Electric Industries, Matsushita Electric Works, Mitsubishi Heavy Industries, Takagi Industrial, Sanyo Electric, Toshiba International Fuel Cells (TIFC) and Toyota.

Over 400 units will be installed. In the first half year of 2005 the installation began with 175 systems. The units costs 10 M¥ (70,000 €) in 2005 and are subsidized with 6 M¥ (40,000 €). The project continues up to 2007 installing new systems. Every year the subsidy lowers. The objective is to have a price of 1 to 2 M¥ in 2007. The maximum obtained efficiency is 81.3 % (32.7 $\%_{electric}$ and 48.5 $\%_{heat}$ (HHV)). The efficiency must be very sensitive to the demand on each residence. Usually the efficiency is 30 $\%_{electric}$ and 40 $\%_{heat}$ (HHV). Tokyo Gas proposes a new contract to customers. For 8000 € it will lease a 1 kW CHP with maintenance of all the gas equipment in the residence for 10 years and with collection of data.

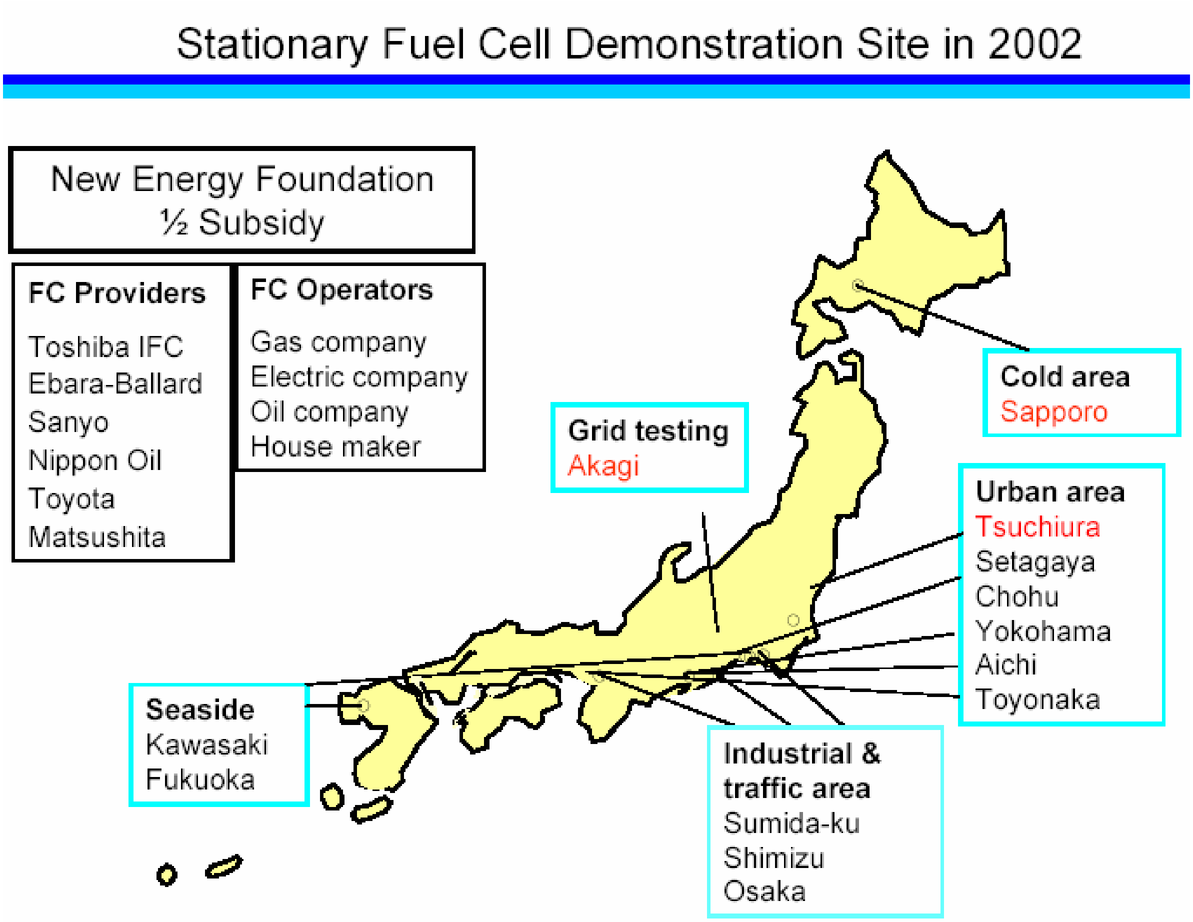

Figure 2-18: The sites for the Stationary Fuel Cell Demonstration Project

- **Demonstration Project on Distributed Power Generation and Grid Connection**

In order to introduce distributed energy systems, such as solar, wind and fuel cell, it is necessary to optimize the fluctuation of the output. Therefore, this project operates solar, wind and fuel cell (typically MCFC) simultaneously by using information technology (IT) and establishes technologies for minimizing fluctuations.

2.1.5 Other related activities

- **Controlled Hydrogen Fleet and Infrastructure Demonstration and validation Project**

The Department of Energy in the United States has a recently launched an initiative in which car manufacturers together with fuel or gas suppliers have to build a network of fuelling stations and to deliver hydrogen-powered vehicles.[13]

In this context Ford teamed up with BP to deliver 26 cars (Ford Focus FC) and to construct a network of fuelling stations in Sacramento, Orlando and Detroit. Daimler Chrysler announced that they will join the initiative while the hydrogen will also be supplied by BP. Daimler Chrysler will build 33 fuel cell vehicles (A-Class "F-Cells" and a Sprinter delivery van). Nine potential fuelling station locations include Sacramento and Los Angeles, CA, and Michigan. Another partnership is ChevronTexaco with Hyundai-Kia. The latter provides 32 fuel cell vehicles (SUVs) while five cities in California for fuelling stations are foreseen. GM works together with Shell producing 40 fuel cell vehicles (Opel Zafira). Potential fuelling station locations include Washington, DC; Ft. Belvoir, VA; Southern and Northern, CA; Detroit, MI; and New York City Metropolitan area, NY.

2.2 Hydrogen Programs and policies

Virtually all of the countries of the OECD reported investment in preparing policy studies[14]. In some cases, the policy work is broad in nature, setting out general goals and objectives for hydrogen and fuel cell work over the long run. In this chapter the main countries are reviewed indicating the major programmes and institutions.

2.2.1 Hydrogen Programs and policies in the United States

- **Hydrogen Fuel Initiative**

The President of the US has formulated several initiatives as part of his National Energy Policy, of which the Hydrogen Fuel Initiative is most explicit on behalf of hydrogen[15]. This initiative stems from the State of the Union in 2003 where it was announced that the United States will do research and develop infrastructure in order that a large number of Americans will choose for fuel cell vehicles by 2020. The initiative has to improve America's energy security by significantly reducing the need for imported oil. At the same time, it is a key component of the President's clean air and climate change strategies.

It builds on the FreedomCAR Partnership, launched in 2002 by the Energy Secretary, that is "a partnership with automakers to advance high-technology research needed to produce practical, affordable hydrogen fuel cell vehicles that American consumers will want to buy and drive". The President's Hydrogen Fuel Initiative and the FreedomCAR Partnership will develop, in parallel, technologies for hybrid components, fuel cells, and hydrogen production and distribution infrastructure needed to power fuel cell vehicles. The Hydrogen Fuel Initiative is sometimes also called FreedomFUEL.

To reduce the need for imported coal, the hydrogen has to come from renewables and nuclear energy as they offer the promise of zero emissions. With carbon capture and storage technologies, hydrogen production from America's abundant coal resources will also make a carbon emissions-free future possible. In this way the Hydrogen Fuel Initiative reduces the greenhouse gas emissions from transportation drastically. According to the initiative additional emissions reductions could be achieved by using fuel cells in other applications, such as generating electricity for residential or commercial uses.

The Department of Energy published in March 2004 the Hydrogen Posture Plan in which it outlines the activities, milestones, and deliverables to support the shift to a hydrogen-based transportation energy system. The Posture Plan integrates research, development, and demonstration activities from the DOE renewable, nuclear, fossil, and science offices, and identifies milestones for technology development over the next decade, leading up to a commercialization decision by industry in 2015.

To fill in the Initiatives and the Posture Plan the Department of Energy launched the "Hydrogen, Fuel Cells and Infrastructure Technologies Program" that incorporates evaluation points through 2010. Success depends on fulfilling the following conditions (for the transport sector):

1. Hydrogen storage systems enabling a vehicle range more than 300 miles while meeting identified packaging, cost and performance requirements;
2. Hydrogen production to safely and efficiently deliver hydrogen to consumer at prices competitive to gasoline without adverse environmental impacts;
3. Fuel cells enabling engine cost less than $50 per kW while meeting performance and durability requirements.

Besides this programme it has set up an International Partnership for the Hydrogen Economy (IPHE) to connect international research.

- **International Partnership for the Hydrogen Economy**

The IPHE is a partnership launched by the US Department of Energy[16,17]. The IPHE was signed in November 2003 by 15 countries and the European Union. Its goal is to efficiently organise, evaluate and coordinate multinational research, development and deployment programmes that advance the transition to a global hydrogen economy. Besides the RD&D it also provides a forum for advancing policies, and common codes and standards that can accelerate the cost-effective transition to a global hydrogen economy to enhance energy security and environmental protection.

Participants in the IPHE are: Australia, Brazil, Canada, China, European Commission, France, Germany, Iceland, India, Italy, Japan, Korea, Norway, Russia, United Kingdom, and United States.

The ultimate goal of the IPHE is to enable Partner countries' consumers to have by 2020 the practical option of purchasing a competitively priced hydrogen powered vehicle that can be refuelled conveniently. This goal can be realized by achieving the following benchmarks:

– Hydrogen powered vehicles are competitive with conventional vehicles.
– Hydrogen is safely and efficiently produced and delivered to consumers at prices and availability competitive with conventional fuels, without adverse environmental impacts.
– Fuelling and storage infrastructure enables ready access to fuel for hydrogen vehicles.
– Hydrogen fuel cells provide stationary and portable power.
– Storage technologies ensure hydrogen vehicle systems operate at the same levels of safety, performance and range as conventional vehicles.
– An internationally consistent system of safety codes and standards related to hydrogen utilization is developed and adopted.

Figure 2-19: The IPHE logo with the flags of the members.

2.2.2 Hydrogen Programs and policies in Europe

Research and development on hydrogen at European level is mainly coordinated by the Directorate-General for Transport and Energy and the Directorate-General for Research. To get support and vision for their policies they launched a High Level Group on Hydrogen and Fuel Cells.

The reasons why Europe must work on developing and deploying hydrogen and fuel cell technologies are[18]:

– Sustainable Development - Hydrogen and electricity are expected to play an increasingly important role as interchangeable energy carriers in a future sustainable energy economy. Together they provide a promising transition pathway towards gradually becoming less dependent on fossil fuels, reducing greenhouse gas and pollutant emissions, and increasing the contribution of renewable energy sources. In the long term, hydrogen could play a key role in adapting energy supply to energy demand as it has the potential for large-scale, even seasonal, energy storage.

– Security and Reliability of Supply – The EU currently imports 50% of its coal, oil and gas; if nothing is done, this figure will rise to 70% in 20-30 years time. Hydrogen would open access to diversified primary energy sources and could therefore help us to reduce our dependence on imports of fossil fuels, thereby contributing to a dynamic and sustainable energy economy in Europe.

– International Competitiveness – Various market studies forecast that the potential market for hydrogen and fuel cell technologies in the future may be very large. At present the world leaders in the field are the US and Japan, where well financed, co-ordinated programmes to develop and market the necessary technologies are already in place. In contrast European hydrogen and fuel cell R&D is uncoordinated, under-funded and fragmented.

- **High Level Group on Hydrogen and Fuel Cells**

The High Level Group on Hydrogen and Fuel Cells started on 10th October 2002[19]. It was launched by Vice President of the European Commission de Palacio, responsible for Energy and Transport, and Research Commissioner Busquin. The group is made up of 19 prominent stakeholders from a variety of backgrounds and from different countries, with the aim of formulating an integrated EU vision on the possible role that hydrogen and fuel cells could play in achieving sustainable energy. It will also address what would be required to achieve global leadership in this field in the next 20 to 30 years.

The first result of the group is a report "Hydrogen Energy and Fuel Cells - A vision of our future", supported by the Commission. The report aimed to capture a collective vision and agreed recommendations. It formulates five actions to a hydrogen energy future:

– A political framework that enables new technologies to gain market entry within the broader context of future transport and energy strategies and policies.
– A Strategic Research Agenda, at European level, guiding community and national programmes in a concerted way.
– A Deployment Strategy to move technology from the prototype stage through demonstration to commercialisation, by means of prestigious 'lighthouse' projects which would integrate stationary power and transport systems and form the backbone of a trans-European hydrogen infrastructure, enabling hydrogen vehicles to travel and refuel between Edinburgh and Athens, Lisbon and Helsinki.
– A European roadmap for hydrogen and fuel cells which guides the transition to a hydrogen future, considering options, and setting targets and decision points for research, demonstration, investment and commercialisation.
– A European Hydrogen and Fuel Cell Technology Partnership, steered by an Advisory Council, to provide advice, stimulate initiatives and monitor progress – as a means of guiding and implementing the above, based on consensus between stakeholders.

The members are: Rolls-Royce (UK), Nuvera (I), Johnson Matthey (UK), Solvay (B), Siemens-Westinghouse (D), Ballard Power Systems (D), Air Liquide (F), Vandenborre Technologies (nowadays Hydrogenics) (B), Renault (F), Daimler-Chrysler (D), Shell (NL), Norsk Hydro (N), Sydkraft (S), CEA (F), ENEA (I), CIEMAT (E), FZJülich (D), Icelandic New Energy (IS), UITP (D).

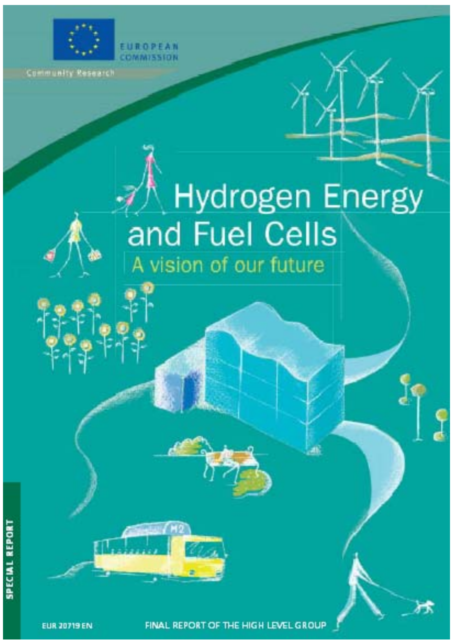

Figure 2-20: Cover page of the High Level Group's report "Hydrogen Energy and Fuel Cells - A vision of our future".

- **European Hydrogen and Fuel Cell Technology Platform**

The European Commission has facilitated the establishment of a European Hydrogen and Fuel Cell Technology Platform aimed at accelerating the development and deployment of these key technologies in Europe[20]. The platform should assist in the efficient co-ordination of European, national, regional and local research, development and deployment programmes and initiatives and ensure a balanced and active participation of the major stakeholders (i.e. industry, scientific community, public authorities, users, civil society). It should help to develop awareness of fuel cell and hydrogen market opportunities and energy scenarios and foster future co-operation, both within the EU and at global scale. The technology platform and all its activities should contribute to an integrated strategy to accelerate the realisation of a sustainable hydrogen economy in Europe. Regular annual or bi-annual meetings of platform participants will ensure shared ownership and a common vision.

Figure 2-21 represents the organisational structure of the platform and displays its logo. At the top is an Advisory Council and at the bottom there are Initiative Groups. The Advisory Council sets the overall direction, strategy and vision of the platform. It comprises 36 senior executives with expertise and direct responsibilities in the field of hydrogen and fuel cells. The Member State's Mirror Group is actively involving the EU Member States as regards furthering the European Research Area in hydrogen and fuel cells. This Group will aim to ensure closer coordination and co-operation between Member States, regional research programmes, high-level representatives within administrations of Member States and the platform.

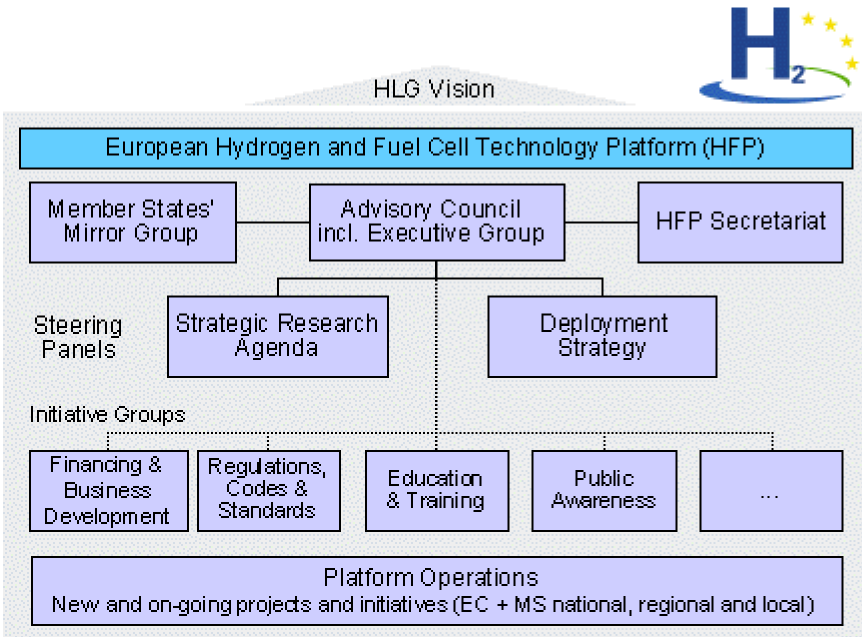

Figure 2-21: The organisational structure of the European Hydrogen and Fuel Cell Technology Platform.

The European Commission wants to copy this idea of a technology platform to other domains to foster effective public-private partnerships : "The role of Technology Platforms in stimulating more effective RTD, particularly in the private sector, can contribute directly to achieving the Lisbon objectives, developing the European Research Area and increasing investment in R&D towards the 3% of GDP target". In the mean-time several platforms are emerging, for example on biotechnology, photovoltaics and sustainable chemistry. [21]

The steering panels for the technology platform have to define a research & deployment strategy including:
– A prioritised 10 year research and demonstration programme, with targets aligned with the deployment strategy
– A deployment strategy indicating milestones and market penetration goals - 'Snapshot 2020'
– A mid-term outlook until 2030 and a long-term, strategic view until 2050

It also defines priorities for investment in R&D, demonstration and deployment in the context of Europe's strengths and weaknesses, and later industrial exploitation.

- **Deployment Strategy**

The European Hydrogen & Fuel Cell Platform prepared a strategy for developing and exploiting a hydrogen-oriented energy economy for the period up to 2050.[22] For this purpose it developed an intermediate milestone: 'Snapshot 2020', it identified milestones for the Strategic Research Agenda for 2015 to enable a mass-market implementation in 2020 and proposed a Development Strategy.

The Snapshot 2020 is a target setting and coordination of the development of hydrogen and fuel cells. Figure 2-22 gives the deployment status for applications in 2020. It is expected that fuel cells in portable applications, especially in computers and in generators, will be an established market in 2020. The market for stationary fuel cells will be growing and road transport applications will be at the threshold of mass market implementation. To reach the targets a considerable cost reduction of the fuel cell system and a significant improvement in lifetime are needed.

The deployment strategy focuses on short-term (2010) actions. These include:
– 'Light-house Projects'
– Programmes for market introduction and cost reduction
– Regulation, codes and standards
– Policy framework to encourage hydrogen and fuel cell deployment
– Development of early niche markets.

The 'Light-house Projects' will be integrated research and demonstration projects towards commercialisation and the public framework (regulations and sustainability criteria). They have to be in line with carbon-lean energy sources. The Light-house Projects will be developed in certain pilot regions across the EU. The Light-house resemble at a proposal from the European Initiative for Growth: HYCOM & HYPOGEN. HYCOM will be pilot areas to demonstrate fuel cell applications, while HYPOGEN will be combined plants for electricity and hydrogen generation from fossil fuels (mainly coal and natural gas) with carbon capture and sequestration.[23]

Key Assumptions on Hydrogen & Fuel Cell Applications for a 2020 Scenario[3]

	Portable Fuel Cells For handheld electronic devices	**Portable Generators & Early Markets**	**Stationary Fuel Cells** Combined Heat and Power (CHP)	**Road Transport**
EU H2/FC Units Sold per Year projection 2020	~ 250 million	~ 100,000 (~ 1 GW_e)	100,000 to 200,000 (2-4 GW_e)	0.4 million to 1,8 million
EU Cumulative Sales projections until 2020	n.a.	~ 600,000 (~ 6 GW_e)	400,000 to 800,000 (8-16 GW_e)	1- 5 million
EU Expected 2020 Market Status	**Established**	**Established**	**Growth**	**Mass market roll-out**
Average Power Fuel Cell System	15 W	10 kW	<100 kW (Micro CHP) >100 kW (industrial CHP)	80 kW
Fuel Cell System Cost Target[4]	1-2 €/ W	500 €/kW	2.000 €/kW (Micro CHP) 1.000-1.500 €/kW (industrial CHP)	< 100 €/kW (for 150.000 units per year)

[3] These projections are discussed in detail in the DS Foundation report.
[4] The primary reasons that automotive fuel cells are expected to be produced at a significantly lower cost than stationary fuel cells are discussed in detail in this Foundation report.

Figure 2-22: Deployment status for applications in 2020 according to the Deployment Strategy

For the Light-house Projects the Deployment Strategy steering panel gives the following recommendations:
- Focusing on a limited number of large-scale projects, primarily addressing transport applications, plus other relevant applications for maximum synergy
- In addition, establishing selected "hydrogen communities" with early markets and stationary fuel cell applications as the main driver
- Networking and co-ordinating activities in different regions and clusters in order to demonstrate and comprehensively benchmark "real world behaviour"
- Including appropriate existing demonstration sites that support the above targets and allow a quick start and expansion
- Fostering progressive growth and expansion to other European regions
- Designing appropriate financial mechanisms and instruments to facilitate this key development
- Building co-operation with complementary initiatives, such as the International Partnership for the Hydrogen Economy (IPHE).

The total of plans, from deployment strategy focuses on short-term, together with the foreseen market development and policy framework has been graphically represented as shown in Figure 2-23.

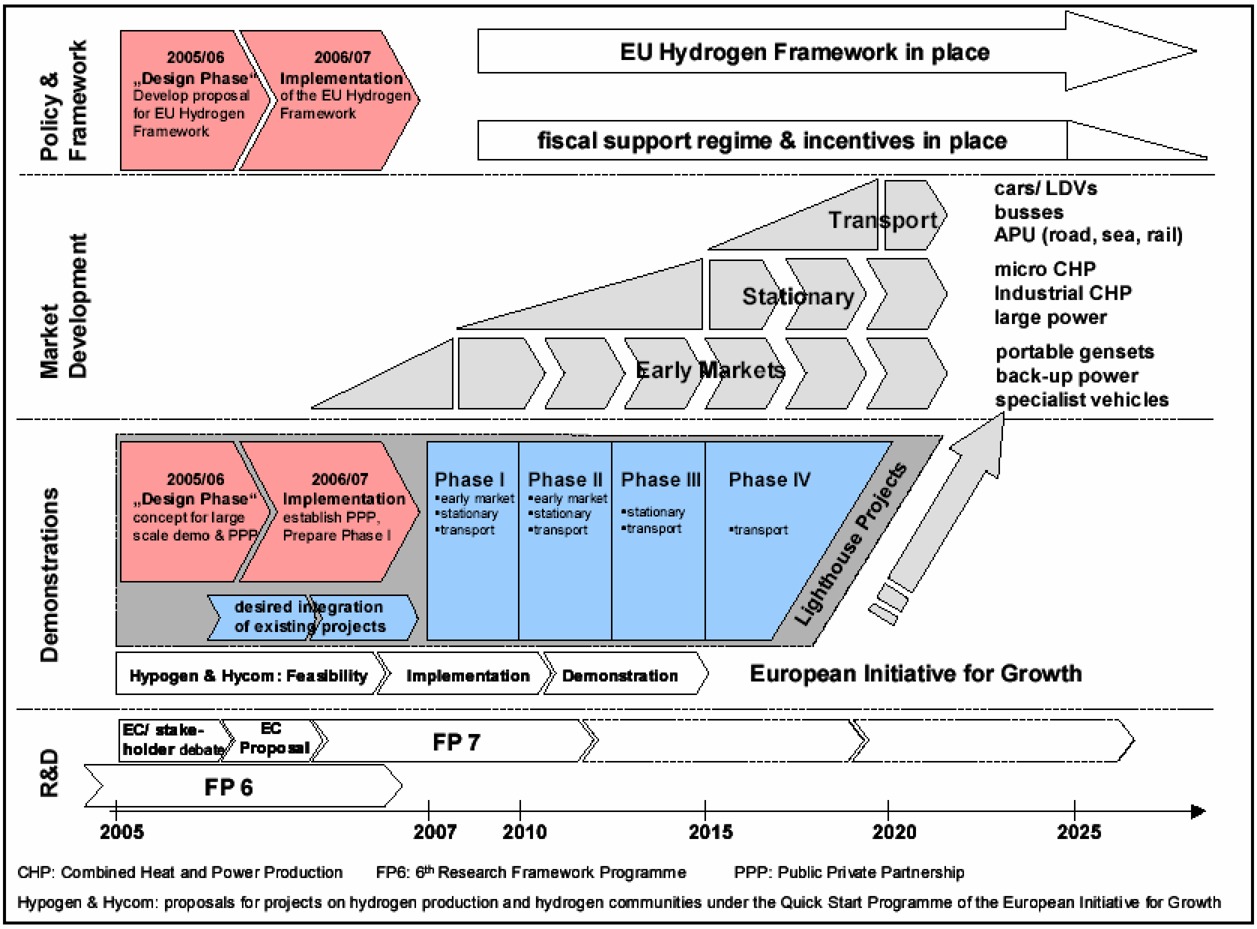

Figure 2-23: The schedule for the Deployment Strategy on Hydrogen & Fuel Cells.

- **Strategic Research Agenda**

Together with the Deployment Strategy a Strategic Research Agenda has been defined by the European Hydrogen & Fuel Cell Platform (the cover is shown in).[24] The Strategic Research Agenda proposes an aligned, prioritised and benchmarked technology development plan for the period 2005- 2015 in line with the market penetration levels envisaged in 'Snapshot 2020' from the Deployment Strategy.

The long-term outlook is the basic motivation for the R&D initiative: "In 2050, oil will very likely no longer be cheap and, certainly, Europe's internal reserves will be exhausted. It is inferred from today's stock assessments that an increasing proportion of primary energy production will be drawn from CO_2 lean resources.
Hydrogen will be one of the three energy vectors, besides electric power and liquid biofuels. As it can be produced from a great variety of primary energies and consumed by an even greater variety of applications, it will form an energy hub – much like electric power today.
By 2050, hydrogen is expected to be widely available in industrial nations, at competitive cost. Indeed, it can realistically be expected to serve as a major transport fuel for vehicles, with a share of up to 50%."

The document touches all issues on hydrogen and fuel cells. For every aspect a research budget has been defined, benchmarks given and targets set up to 2015. Table 2-2 gives an overview of the research areas and the proposed budget shares. In the document each area has been worked out regarding actual status, benchmarks and research budget priorities.

Figure 2-24: Cover page of the "Strategic Research Agenda" from the European Hydrogen & Fuel Cell Technology Platform.

Table 1: Proposed Budget Shares for Hydrogen & Fuel Cell Targeted R&D

Research Area	Budget Share	Key Considerations
Transport applications	27%	Technologically crucial for environmentally friendly transport solutions and the driving force for fuel cell development
Hydrogen production	22%	Essential for the technological development of the entire sector. Increase of CO_2-lean production is targeted. Carbon capture and sequestration are of the essence, yet are expected to be covered within other European R&D programmes
Stationary applications	20%	Important for CO_2 reduction via highly efficient cogeneration. Provides an opportunity for early markets
Hydrogen storage & distribution	18%	Storage density is crucial for effective storage – particularly for transport and portable applications
Portable applications	10%	Important for early markets. Fit ever increasing market needs to fuel gadgets and small transport applications
Socio-economics	3%	Long-term guidance for technological development
Total Hydrogen & Fuel Cells	100%	

Table 2-1: Proposed budget shares in the Strategic Research Agenda for the different research areas.

- **The framework programmes**

Research funding from the European Union is organised in Framework Programmes[25]. The last one was the Fifth Framework Programme. Here the EU was contributing €145 million to support 70 projects, see also Figure 2-25.

The Sixth Framework Programme (FP6) differs significantly from previous ones. One key difference is its role in contributing to the creation of the European Research Area (ERA) in sustainable energy systems. This means that the aim is to assemble a critical mass of resources, to integrate research and related efforts by pulling them together in larger, more strategic projects, and to make this research more coherent on the European scale. Hydrogen and fuel cells research cuts across a number of the Thematic Priority Areas in FP6:
– Priority 6.1 'Sustainable energy systems'
– Priority 6.2 'Sustainable surface transport'
– Priority 4 'Aeronautics and space'
– Priority 3 'Nanotechnologies and nanosciences, …'

Currently 100 M€ of EU funding, matched by an equivalent amount of public and private investment, is being awarded to research and demonstration projects for hydrogen and fuel cells in the FP6. In Figure 2-26 the approved projects from the first round are listed.

This will be reinforced via further calls for RTD and demonstration proposals worth an expected public and private investment of the order of 300 M€, of which about half would be funded by the EU.

Table 1: EU support (in million €) to hydrogen and fuel cell RTD in FP5 for the period 1999-2002

	Hydrogen	FC technology acquisition[1]	FC stationary applications	FC transport applications	FC portable applications	Total
Medium and longer term RTD	23.6	22.4	12.1	28.0[2]	8.4	94.5
Short term (Demonstration and benchmarking)	6.9	-	16.8	26.5[3]	-	50.3
Total	**30.5**	**22.4**	**28.9**	**54.5**	**8.4**	**144.8**

1. Includes generic fuel cell development for stationary, transport and portable applications;
2. Approximately €19 million devoted to projects related to fuel processing;
3. €18 million for fuel cell bus demonstration project CUTE;

The EU is thus contributing some €145 million to support 70 projects in the field of hydrogen and fuel cells.

Figure 2-25: Support of the European Union to hydrogen and fuel cells in the Fifth Framework Programme.

Table 2: *Hydrogen* contracts awarded, or under negotiation, after the first calls for proposals in the Sixth Framework Programme (FP6)

Area	Project acronym	Type of action or instrument*	Topic or title	EU indicative funding (€ million)	Coordinator	Contact details
H_2 production	CHRISGAS	IP	Hydrogen rich gas from biomass	9.5	Växjo University, Sweden	Mr Sune Bengtsson sune.bengtsson @power.alstom.com
	SOLREF	STREP	Solar Steam Reforming of Methane Rich Gas for Synthesis Gas Production	2.1	DLR, Germany	Dr Stephan MÖLLER stephan.moeller@dlr.de
	HYTHEC	STREP	Hydrogen THErmochemical Cycles	1.9	CEA, France	Mr Alain LE DUIGOU aleduigou@cea.fr
	Hi_2H_2	STREP	Highly Efficient, High Temperature, Hydrogen Production by Water Electrolysis	1.1	EDF, France	Dr Philippe STEVENS philippe.stevens@edf.fr http://www.hi2h2.com
	SOLAR-H	STREP	Hydrogen production from renewable resources			
H_2 storage	STORHY	IP	Hydrogen Storage Systems for Automotive Application	10.7	Magna Steyr Fahrzeugtechnik, Austria	Dr Guenter KRAINZ guenter.krainz @magnasteyr.com
H_2 safety, regulations, codes & standards	HYSAFE	NoE	Safety of Hydrogen as an Energy Carrier	7	Forschungs-zentrum Karlsruhe, Germany	Dr Thomas JORDAN thomas.jordan @iket.fzk.de
	HARMONHY	SSA	Harmonisation of Standards and regulations	0.5	Vrije Universiteit Brussels, Belgium	Prof. Gaston MAGGETTO gmagget@vub.ac.be
H_2 pathways	HYWAYS	IP	Elaborating a European Hydrogen Roadmap	4	L-B System-technik, Germany	Dr Ulrich BUENGER buenger@ibst.de
	HYCELL-TPS	SSA	Development and implementation of the European Hydrogen and Fuel Cell Technology Platform Secretariat	1.8	Kellen Europe, Belgium (Alfons Westgeest & Patrick Maio, Brussels)	Mr Alfons WESTGEEST awestgeest @kelleneurope.com secretariat @HFPeurope.org www.HFPeurope.org
	NATURALHY	IP	Investigating infrastructure requirements for H_2 and natural gas mixes	11	Gasunie, The Netherlands	Mr Onno FLORISSON o.florisson@gasunie.nl
	INNOHYP-CA	CA	Innovative high temperature production routes for H_2 production	0.5	CEA, France	Dr Paul LUCCHESE Paul.lucchese@cea.fr

Area	Project acronym	Type of action or instrument*	Topic or title	EU indicative funding (€ million)	Coordinator	Contact details
	HY-CO	CA	Co-ordination Action to Establish a Hydrogen and Fuel Cell ERA-Net	2.7	Research Centre Jülich (FZJ), Germany	Dr Hans-Joachim NEEF h.j.neef@fz-juelich.de
	WETO-H2	CA	World Energy Technology Outlook-2050	0.39	ENERDATA, France	Bertrand CHATEAU bertrand.chateau @enerdata.fr
	CASCADE MINTS	STREP	Case Study Comparisons and Development of Energy Models for Integrated Technology Systems	0.95	ICCS/NTUA	Pantelis Capros kapros@central.ntua.gr
H_2 end-use	ZERO REGIO	IP	H2 FC fleet demonstration	7.5	INFRASERV, Germany	Dr Heinrich LIENKAMP heinrich.lienkamp @infraserv.com
	HYICE	IP	Optimisation of the Hydrogen Internal Combustion Engine	5	BMW, Germany	Hans-Christian FICKEL hans.fickel@bmw.de
	PREMIA	SSA	Effectiveness of demonstration initiatives	1	VITO, Belgium	Ms. Leen GOVAERTS leen.govaerts@vito.be
			Total EU funding:	**€67.7 million**		

** Type of action or instrument: IP : Integrated Project, NoE: Network of Excellence, STREP: Specific Targeted Research Project, CA: Coordination Action, NEST: New and Emerging Science and Technology, ERA-Net: Support for the coordination of activities, SSA: Specific Support Action*

** Type of action or instrument: IP : Integrated Project, NoE: Network of Excellence, STREP: Specific Targeted Research Project, CA: Coordination Action, NEST: New and Emerging Science and Technology, ERA-Net: Support for the coordination of activities, SSA: Specific Support Action*

Table 3: *Fuel cell* contracts awarded, or under negotiation, after the first calls for proposals in the Sixth Framework Programme (FP6)

Area	Project acronym	Type of action or instrument*	Topic or title	EU indicative funding (€ million)	Coordinator	Contact details
High Temperature Fuel Cells	Real-SOFC	IP	Realising Reliable, Durable, Energy Efficient and Cost Effective SOFC Systems	9	Research Centre Jülich (FZJ), Germany	Dr Robert STEINBERGER-WILCKENS r.steinberger @fz-juelich.de
	BIOCELLUS	STREP	Biomass Fuel Cell Utility System	2.5	TU Munich, Germany	Dr Juergen KARL karl@ltk.mw.tum.de
	GREEN-FUEL-CELL	STREP	SOFC fuelled by biomass gasification gas	3	CCIRAD, France	Dr Philippe GIRARD philippe.girard@cirad.fr
	SOFCSPRAY	STREP	Porous material for Solid Oxide Fuel Cells/High power applications (industry, power stations)	0.6	Nuevas Tecnologias para la Distribucion Activa de Energia S.L., Spain	Mr. Carlos Martinez Reira

Area	Project acronym	Type of action or instrument*	Topic or title	EU indicative funding (€ million)	Coordinator	Contact details
Solid Polymer Fuel Cells	HYTRAN	IP	Hydrogen and Fuel Cell Technologies for Road Transport	8.8	Volvo, Sweden	Mr Per EKDUNGE Per.Ekdunge @volvo.com
	FURIM	IP	Further Improvement and System Integration of High Temperature Polymer Electrolyte Membrane Fuel Cells	4	Technical University of Denmark (DTU)	Prof. Niels Janniksen BJERRUM njb@kemi.dtu.dk
	PEMTOOL	STREP	Development of novel, efficient and validated software-based tools for PEM fuel component and stack designers	1	Bertin Technologies SA, France	Mr Clement KIRRMANN
	INTELLICON	STREP	Design and prototyping of intelligent DC/DC converter/ fuel cell hybrid power trains	0.5	HIL Tech Developments Limited, UK	Mr. John HOLDEN
	DEMAG	STREP	Integration of a PEM fuel cell with ultra-capacitors and with metal hydrates container for hydrogen storage (prototype)	0.65	Labor S.r.l., Italy	Mr. Alfredo PICANO
Portable applications	MORE-POWER	STREP	Compact direct (m)ethanol fuel cell for portable application	2.2	Geesthacht Research Centre (GKSS), Germany	Dr Suzana PEREIRA NUNES nunes@gkss.de
Area	**Project acronym**	**Type of action or instrument***	**Topic or title**	**EU indicative funding (€ million)**	**Coordinator**	**Contact details**
	FEMAG	STREP	New product = fuel cell + components + expert system/Small vehicles (non automotive)	0.65	AGT S.r.l., Italy	Prof. Filippo UGOLINI
General	ENFUGEN	SSA	Enlarging fuel cells and hydrogen research co-operation	0.23	Labor S.r.l., Italy	Mr Alfredo PICANO a.picano @labor-roma.it
			Total EU funding:	**€33.13 million**		

** Type of action or instrument: IP : Integrated Project, NoE: Network of Excellence, STREP: Specific Targeted Research Project, CA: Coordination Action, NEST: New and Emerging Science and Technology, ERA-Net: Support for the coordination of activities, SSA: Specific Support Action*

Figure 2-26: The approved projects in the first round of the sixth Framework Programme.

2.2.3 Hydrogen Programs and policies in Japan

Japan has high expectations of fuel cells[11,26,27]. It has few indigenous energy resources and very high energy import. For Japan hydrogen may offer an opportunity to achieve energy self-sufficiency. Japan has been an early leader in hydrogen and fuel cell technology development.

The Ministry of Economy, Trade and Industry (METI) is pushing forward hydrogen and fuel cell development by defining programmes and budgets. The important organisation is the New Energy and Industrial Technology Development Organization (NEDO). It is researching and developing hydrogen energy technologies in a joint industry-government-university effort, aiming at worldwide deployment by the year 2030.

In 1993 Japan launched the first major, national R&D programme on hydrogen and fuel cells: WE-NET, the International Clean Energy Network Using Hydrogen Conversion. See section 2.1.4 for a description. The METI has now launched the "New Hydrogen Project" for the commercialisation of hydrogen fuel cells in 2020. It integrates the development of fuel cells, hydrogen production, hydrogen transportation and storage technologies, together with demonstration programmes, vehicle sales, construction of refuelling infrastructure, establishment of codes and standards, and a general push to enlarge the consumer market for fuel cells and fuel cell vehicles. *The demonstration projects mentioned in section 2.1.4 are part of it.*

A public organisation have been established in March 2001 where all stakeholders' concerns are discussed and consensuses are reached for the coordinated actions by industry and government: Fuel Cell Commercialization Conference of Japan (FCCJ).

- **Fuel Cell Commercialization Conference of Japan**

The Fuel Cell Commercialization Conference consists of companies and parties active in fuel cell technologies including fuel cell manufacturers, gas and electric utility companies, automotive companies, petroleum companies. It resembles the European Hydrogen and Fuel Cell Technology Platform. The FCCJ is to have close and frequent contacts with METI and its related organisations like NEDO, but not to have financial assistance from government

Figure 2-27 shows the organisation, while Figure 2-28 shows the relation of the Fuel Cell Conference with other organisations in Japan. The objectives are:
– To identify specific issues in commercialization & widespread use of FCs,
– To submit policy proposals to resolve the issues to the government
– To Contribute to FCs commercialization and promotion, establishing FC industries in Japan

It developed in 2002 a detailed road map for R&D of FC related technologies which is displayed in Figure 2-29.

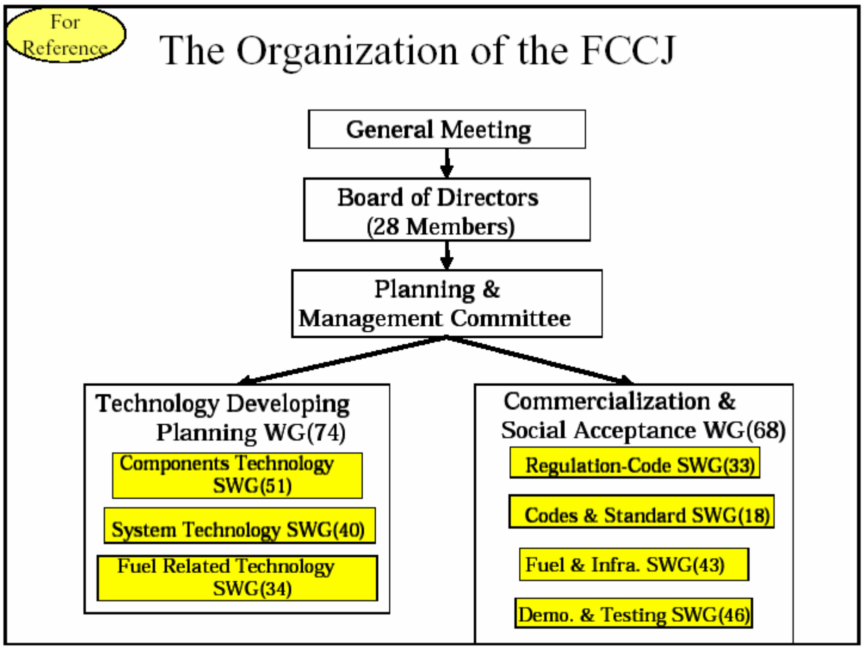

Figure 2-27: Organisational diagram of the Fuel Cell Conference of Japan.

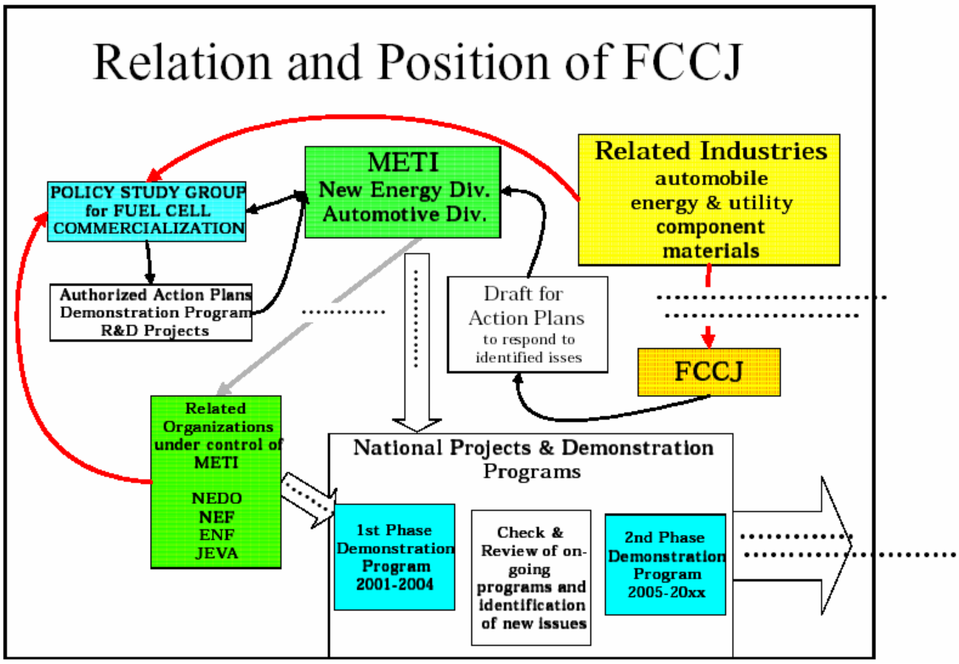

Figure 2-28: The relation of the Fuel Cell Conference with other organisations in Japan.

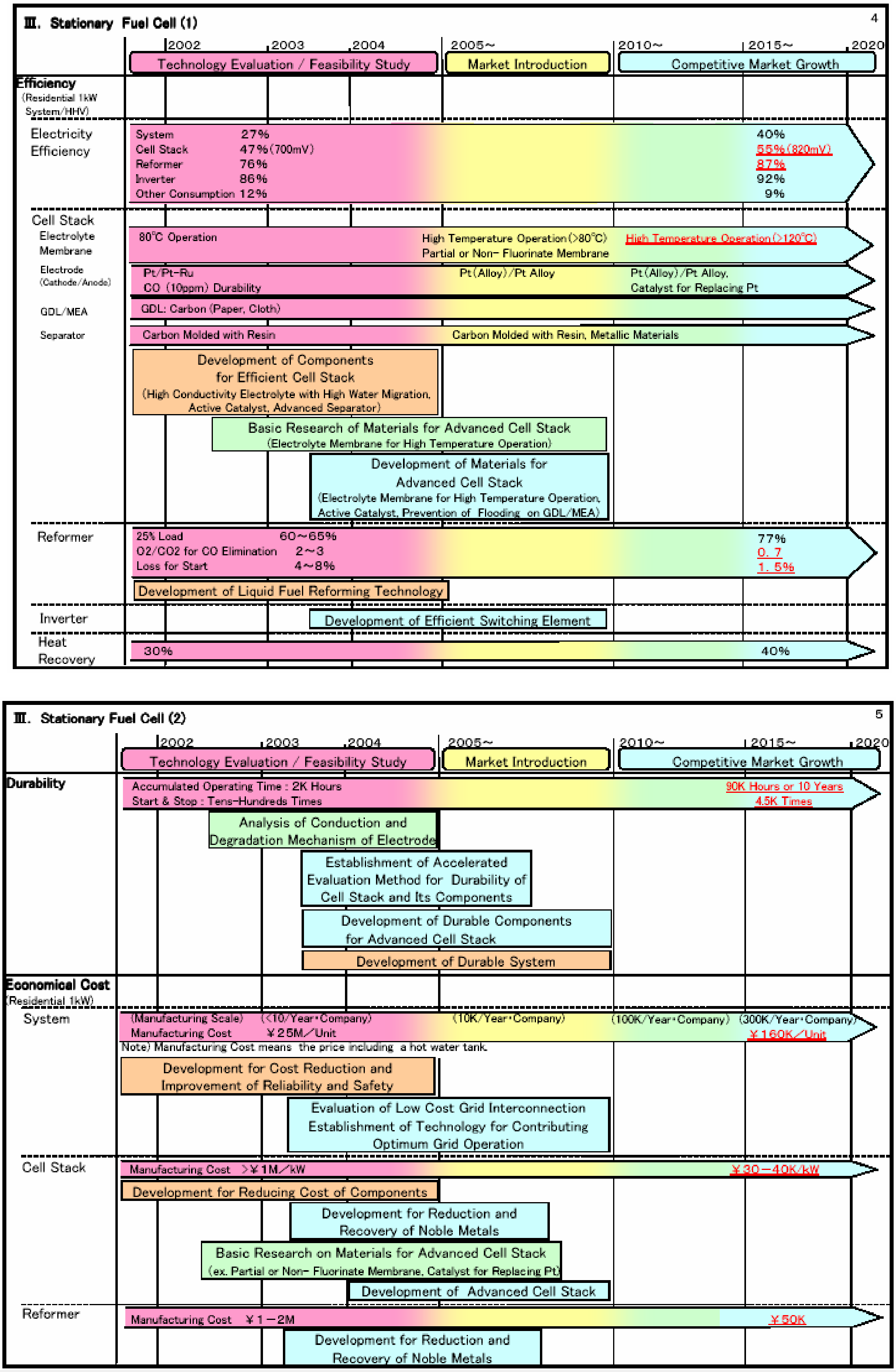

Figure 2-29: Road map for R&D of FC related technologies as prepared by the FCCJ.

2.2.4 Other countries and regions

- **Germany**

In Germany, the Federal Ministry of Economy and Labour (BMWA) supports research and demonstration of fuel cells and hydrogen within the "Federal Programme for Energy Research and Technologies". Intensive RD&D on hydrogen technologies started in Germany in 1988 and focused on electrolysis, hydrogen storage and larger projects to demonstrate the complete chain of solar hydrogen energy production (HYSOLAR and the Solar-Hydrogen-Bavaria Project BAYSOLAR). This work ended in 1995/1999 with the conclusion that main components were developed and functioning but commercial viability was not proved. As a consequence, since 1995 RD&D efforts were concentrated on fuel cells projects focused on new materials, improved components, and system integration. The "Programme on Investment into the Future" (ZIP) was initiated in 2001 as part of the Energy Research Programme with the main priorities on fuel cell development and demonstration. Some projects related to hydrogen technology, such as demonstration of infrastructure for fuel cell buses are included in this programme. Within ZIP more than 40 additional projects are being funded by BMWA. Several 250 kW MCFC projects, one plant with SOFC tube concept technology, and several PEMs (2 – 5 kW) for house applications are in operation or in a planning phase. Projects for the demonstration of fuel cell buses (Stadt Barth, Berlin) and the development of a fuel cell car (AUDI) are also included. Under the EU CUTE project the demonstration of hydrogen infrastructure for the DaimlerChrysler fuel cell bus NEBUS/Citaro is being co-financed within ZIP.

Other examples are the *Clean Energy Partnership* in Berlin, an initiative of the Federal Ministry of Traffic, Building and Housing (BMVBW) for demonstrating a hydrogen service station and hydrogen powered vehicles. Another key initiative is the so called Transport Energy Strategy (TES) aiming at developing a strategy for the introduction of a new energy carrier to the transport sector.

Noteworthy programmes include Bavaria's "Hydrogen Initiative" and the North-Rhine Westphalia "Hydrogen and Fuel Cell R&D Programme". In 2003, BMWA established an advisory council on hydrogen technologies with the objective to draw up a new vision on future RD&D demand. Also Baden-Württemberg and Saxony are playing an active role.

- **France**

The French Réseau Paco provides and example of a national network developed to promote cooperation between R&D institutes and companies, with the major themes focussed primarily on PEM, SOFC, hydrogen storage and on-board reforming. Additionally, France features innovative research on the development of high-temperature processes for hydrogen production, coupled with future nuclear energy.

France's Petroleum Institute (IFP) and the Atomic Energy Commission (CEA) will contribute to the *Hyfrance* project, whose main goal is to build a hydrogen roadmap for France.

- **Canada**

Canada has a long-standing involvement in the development of hydrogen and fuel cell technologies, focussing on fuel cells for transportation and stationary power, including off-grid applications[28]. Programme activities are oriented toward the development of technologies with short-to-medium term commercial potential. The R&D program focuses on fuel cell commercialisation and the development of coordinated hydrogen and fuel cell standards that will be required for hydrogen to be a safe and cost-effective energy carrier. Canada is currently focusing on the development and demonstration of various PEM fuel cell technologies, along with developing DMFC for portable, stationary and automotive applications, and on fundamental and applied research to develop novel materials and architectures for high temperature fuel cells and micro fuel cells. The program is managed by Natural Resources Canada, National Research Council, Natural Sciences and Engineering Research Council, Department of National Defence and Environment Canada.

In October 2003 the Canadian government announced to capitalise heavily on the use of hydrogen and fuel cells and stated three strategic priorities:

- Early adoption of hydrogen technologies through integrated demonstration projects undertaken by partnerships that will showcase a working model of the hydrogen economy in real-world settings;
- Improved performance and reduced costs of hydrogen technologies, and extension of Canadian leadership through research and development of innovative new applications in strategic areas of the hydrogen value chain; and
- Initiatives to establish a hydrogen infrastructure through Sustainable Development Technology Canada, building on the foundation's success in establishing successful, partnership projects.

Canada also works on the development of a Canadian Hydrogen Installation Code for hydrogen fuelling stations: a study to establish appropriate clearance distances for hydrogen fuelling stations, the "Virtual Fuelling Station".

2.3 Roadmaps

Many countries define roadmaps with their view on the hydrogen and fuel cell development[14] Often they are defined by government in cooperation with industry platforms. The first countries with a roadmap were the United States and Japan. Many countries, as Germany and France, will come in 2005 with a roadmap. The roadmap can be part of a broader view on CO_2 reduction and renewable energy strategy like in Austria.

2.3.1 Roadmap of the United States

The US "National Hydrogen Energy Roadmap" (November 2002), describes the principal challenges to be overcome and suggests ways the US can achieve the national vision for hydrogen[15]. The roadmap stresses the need for parallel development of model building codes and equipment standards to enable technology integration into commercial energy systems, along with outreach programs to effectively educate local government officials and the public, who will determine the long-term acceptance of these technologies.

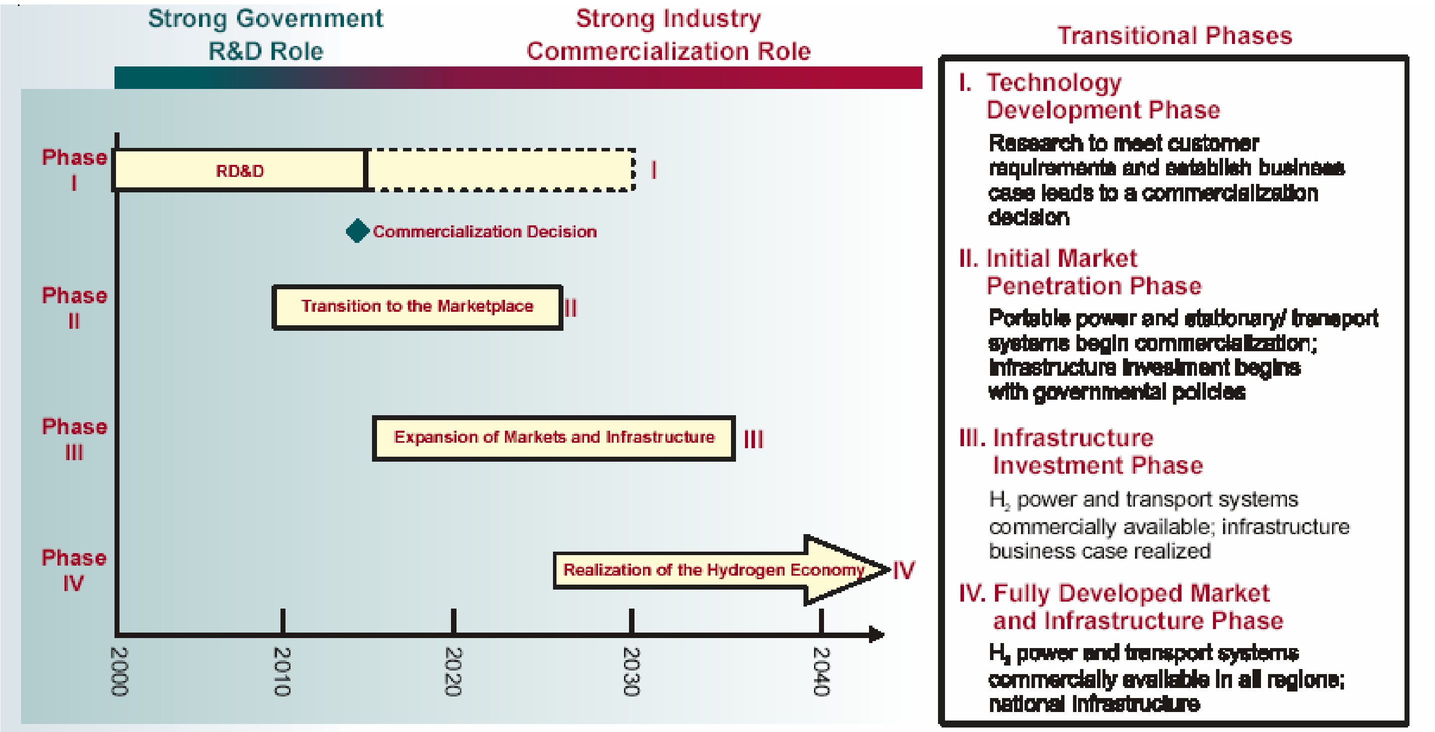

Figure 2-30: Roadmap of the United States

2.3.2 Roadmap of the European Union

The roadmap of the European Union has been drawn up by The High Level Group on Hydrogen and Fuel Cells and published in the report "Hydrogen Energy and Fuel Cells - A vision of our future" (see also the previous section) with the aim to guide the transition to a hydrogen future, considering options, and setting targets and decision points for research, demonstration, investment and commercialisation.[12] In principle this road map is now replaced by the deployment strategy as depicted in Figure 2-23.

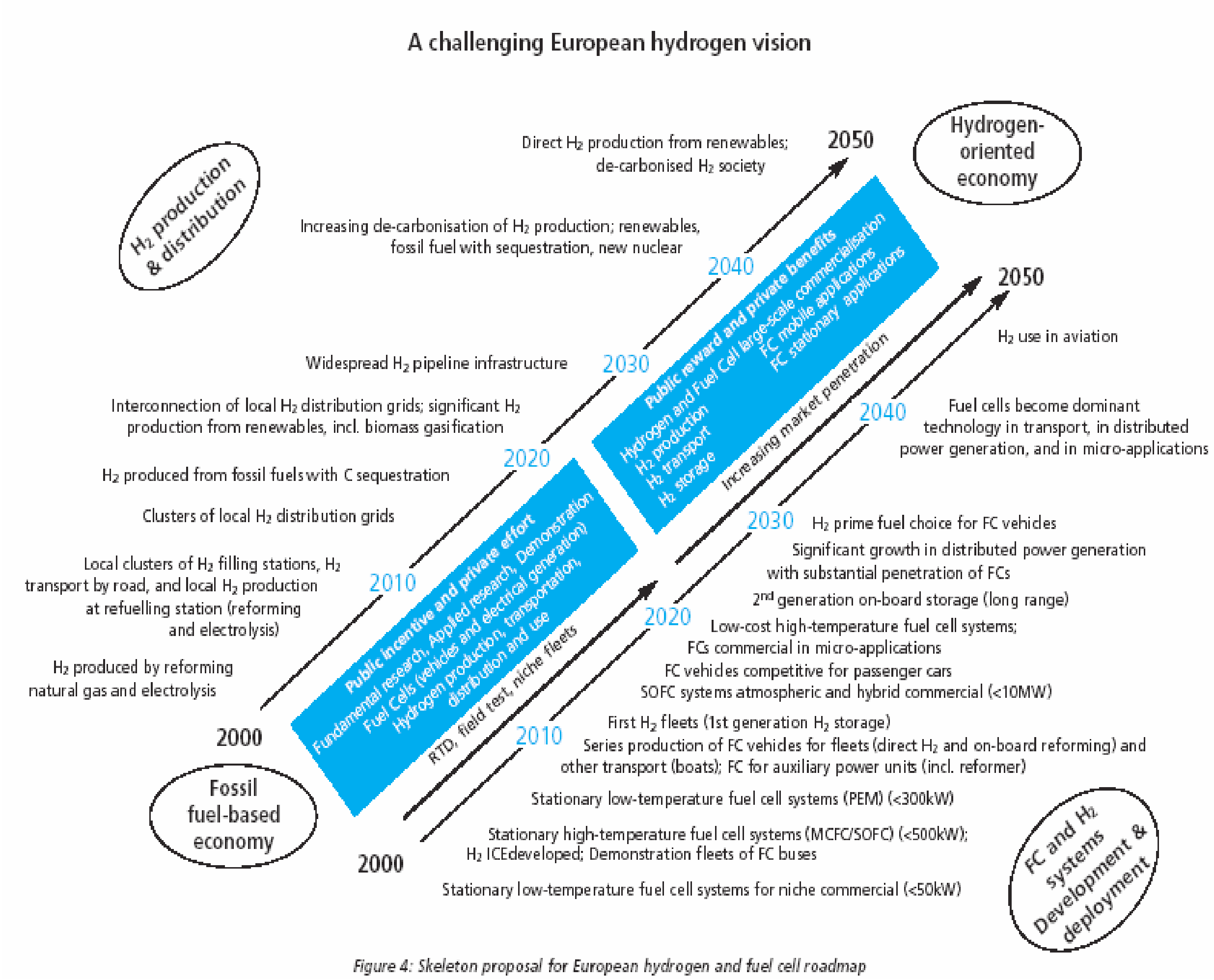

Figure 2-31: Roadmap of the European Union

2.3.3 Roadmap of Japan

In Japan their roadmap, called "Fuel Cell Commercialisation and Diffusion Strategy", was formulated by a study group and later on by the Fuel Cell Commercialization Conference.[28] A strategy emerged for the practical application and implementation of fuel cell technologies. The strategy is based around a three-stage commercialization plan through 2020, which integrates the development of fuel cell, hydrogen production, transportation and storage technologies concurrently with the implementation of demonstration programs, vehicle sales, construction of refuelling infrastructure, establishment of codes and standards, and a general push to enlarge the consumer market for stationary fuel cells and fuel cell vehicles. The ground work phase leads to basic R&D insights and develops demonstration projects, the introduction phase leads to the introduction and gradual establishment of hydrogen supply systems, and the diffusion phase establishes hydrogen-supply systems at a larger scale in order. The roadmap contains quantitative objectives:

– By the end of the "Introduction Stage" in 2010

- 50,000 fuel cell vehicles
- 2.2 GW of stationary fuel cell co-generation systems

– By the end of the "Diffusion Stage" in 2020

- 5,000,000 fuel cell vehicles
- 4,000 hydrogen stations
- 10 GW of stationary fuel cell co-generation systems.

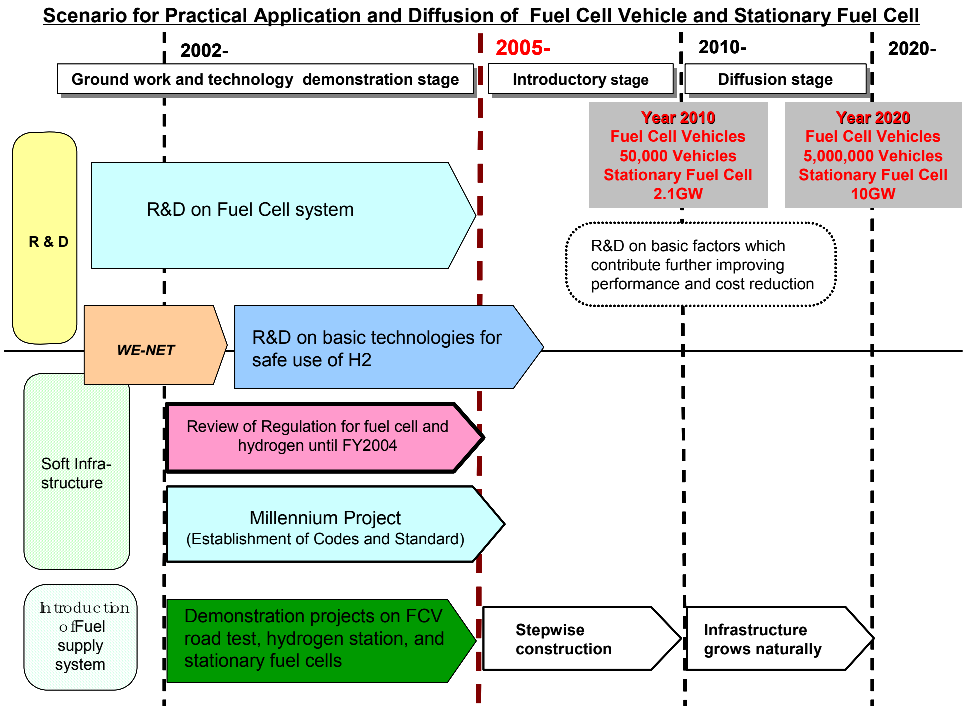

Figure 2-32: So-called "Fuel Cell Commercialisation and Diffusion Strategy" of Japan

2.4 Interesting reports

For the reader interested in some more demonstration projects and countries, two literature titles are amplified.

- **"Hydrogen & Fuel Cells, Review of national R&D programs", IEA**

The International Energy Agency (IEA), an autonomous intergovernmental entity within the Organisation for Economic Cooperation and Development (OECD), created a "Hydrogen Coordination Group". Within this group IEA's member countries filled in an extensive national enquiry from which a book was published in December 2004 entitled "Hydrogen & Fuel Cells, Review of national R&D programs". The book gives an overview on the status of hydrogen and fuel cells research in the countries and the spent budgets.

- **"Assessing the international position of EU's RTD&D on hydrogen & fuel cells", ESTO Research**

The publication "Assessing the international position of EU's RTD&D on hydrogen & fuel cells" by ESTO research contains a review of the European policy on hydrogen and fuel cells and a characterisation of the research, technological development and demonstration outside the EU.[29]

2.5 References

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4 Presentation of Mr. Bardewyck from MTU at a meeting of 'Vlaams Samenwerkingsverband Brandstofcellen', Mol, July 2004

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10 www.fuelcellpartnership.org

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24 "Strategic research Agenda", European Hydrogen & Fuel Cell Technology Platform, 2005
www.hfpeurope.org/uploads/677/686/HFP-SRA004_V9-2004_SRA-report-final_22JUL2005.pdf

25 Brochure "European Hydrogen and Fuel Cell projects", European Communities, 2004

26 Presentation at IEA Hydrogen Coordination Group by METI (Japan) at 18-6-2003

27 Proceedings "Fuel Cells Seminar – RD&D strategies and activities", prof. Ishitani, the Royal Swedish Academy of Eng. Science, 2004

28 "Hydrogen & Fuel Cells, Review of National R&D Programs", IEA, Paris, 2004

29 esto.jrc.es/detailshort.cfm?ID_report=1298

3 ANNEX 3: HYDROGEN PATHWAYS AND INFRASTRUCTURE

Results from the European HySociety project (2003-2005) are revealed in which political, societal and technical challenges for developing a European hydrogen economy have been addressed. The focus in this annex is placed on the assessments of hydrogen pathways and infrastructure. It will appear that no optimal chain can be selected for hydrogen supply. In order to know whether the pathway losses can be overcome by efficient use of H2 fuel, this paper shows calculations based on well-to-tank losses and tank-to-wheel efficiencies of some vehicles. To look into the consequences of introducing hydrogen, a top-down scenario has been worked out. The message is that certainly the handling part has to be improved in order not to loose the emission gain that is obtainable, especially via carbon capture and sequestration. In order to quantify the market development a bottom-up approach has been used, in particular for the transport sector.

3.1 Pathways

The European HySociety project (2003-2005) addressed political, societal and technical challenges for developing a European hydrogen economy. This annex shows results on the assessments of hydrogen pathways and infrastructure. Hydrogen is conceived as a clean fuel, attaining special precautions throughout the entire supply chain. The key question is from which source hydrogen can be produced in a sustainable manner in large quantities. An important aspect is to avoid that hydrogen becomes just a more expensive way of harnessing fossil fuels. We start with showing results of the pathway analysis, making some well-to-wheel calculations to get insight in the chain efficiency and CO2 emissions. Then we reveal the conclusions from a top-down penetration approach in order to assess the influence of a mixture hydrogen pathways on the total energy need. The third and last item is the bottom-up scenario in the HySociety project to get insight in the market-penetration for hydrogen, particularly hydrogen fuelled cars.

In the HySociety project more than 40 plausible supply chains have been quantified[1] Most of the pathways were assessed for transport application but also pathways for stationary and portable applications were addressed. To evaluate the supply chains, three criteria have been examined: primary energy demand, cost expectation and emission index, based on forecasts for 2030 (referring to economical conditions as of year 2000). The pathway losses ('well-to-storage/tank') appear to range from 42% at the best to almost 500% as reckoned from the remaining H2 fuel. This means that in the best case for 1 kWh of H2 1.42 kWh of primary energy is needed. Or otherwise stated the best chain efficiency is 1/1.42 = 70%. In figure 3-1 at the left the nine most efficient hydrogen chains (well-to storage) are presented by the thick line (referring to the left-handed ordinate axis), whereas the right picture compares eight hydrogen chains including carbon dioxide capture. Table 3-1 gives an explanation of the pathways.

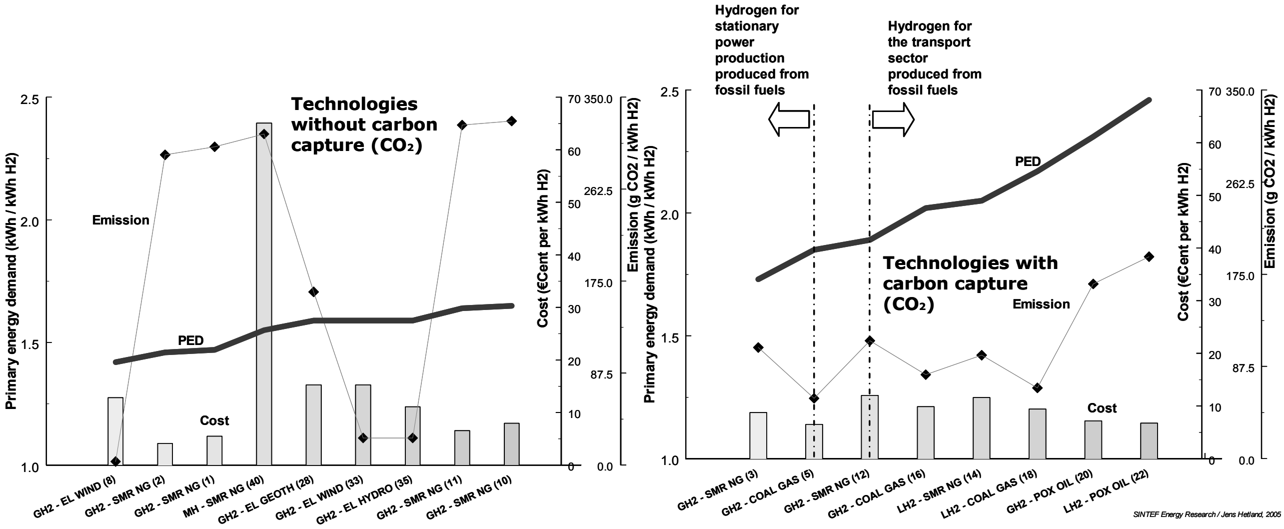


Figure 3-1[a]: Energy supply system in a well-to-storage approach (excluding end-use) as resulting from the HySociety pathways assessment, expressed in terms of cost, emission and primary energy demand (PED). The left picture shows the nine most efficient hydrogen chains, the right pictures shows eight pathways from fossil fuels including carbon capture ranked according to primary energy demand.

GH2 – EL WIND (8)	GH2 via centralised electrolysis with wind power; transport: H2 pipeline; buffer storage: 50 bar	stationary appl.
GH2 – SMR NG (2)	GH2 via centralised reforming of natural gas; H2 transport: pipeline; buffer storage: 50 bar	stationary appl.
GH2 – SMR NG (1)	GH2 via onsite reforming of natural gas; buffer storage: 50 bar	stationary appl.
MH – SMR NG (40)	centralised reforming of natural gas, compression centralised (500 bar); H2 transport: truck / pressure vessels; storage: metal Hydrides	portable appl.
GH2 – EL Geothermal (28)	CGH2 via centralised electrolysis, with geothermal power, H2 transport: pipeline; compression, storage, refuelling on-site; storage: on-board, 700 bar	mobile appl.
GH2 – El wind (33)	CGH2 via centralised electrolysis with wind power; H2 transport: pipeline; compression, storage, refuelling on-site; storage: on-board, 700 bar	mobile appl.
GH2 – El hydro (35)	GH2 via centralised electrolysis with hydro power; H2 transport: pipeline; compression, storage, refuelling on-site; storage: on-board, 700 bar	mobile appl.
GH2 – SMR NG (11)	CGH2 via centralised reforming of natural gas; H2 transport: pipeline; compression, storage, refuelling on-site; storage: on-board, 700 bar	mobile appl.
GH2 – SMR NG (10)	CGH2 via on-site reforming of natural gas; H2 compression, storage, refuelling on-site; storage: on-board, 700 bar	mobile appl.
GH2 – SMR NG (3)	GH2 via centralised reforming of natural gas with carbon sequestration; H2 transport: pipeline; buffer storage: 50 bar	stationary appl.
GH2 – COAL GAS (5)	GH2 via centralised gasification of hard coal with carbon sequestration; buffer storage: 50 bar	stationary appl.
GH2 – SMR NG (12)	CGH2 via centralised reforming of natural gas with carbon sequestration; H2 transport: pipeline; compression, storage, refuelling on-site; storage: on-board, 700 bar	mobile appl.
GH2 – COAL GAS (16)	CGH2 via centralised gasification of hard coal with carbon sequestration; H2 transport: pipeline; compression, storage, refuelling on-site; storage: on-board, 700 bar	mobile appl.
GH2 – SMR NG (14)	LH2 via centralised reforming of natural gas with carbon sequestration; H2 liquefaction centralised; transport: cryogenic truck; refuelling; storage: on-board	mobile appl.
GH2 – POX OIL (17)	LH2 via centralised gasification of hard coal; H2 liquefaction centralised; transport: cryogenic truck; refuelling; storage: on-board	mobile appl.
GH2 – COAL GAS (18)	LH2 via centralised gasification of hard coal with carbon sequestration; H2 liquefaction centralised; transport: cryogenic truck; refuelling; storage: on-board	mobile appl.
GH2 – POX OIL (20)	CGH2 via partial oxidation of residual oil (at the refinery) with carbon sequestration; H2 transport: pipeline; compression, storage, refuelling on-site; storage: on-board, 700 bar	mobile appl.
LH2 – POX OIL (22)	LH2 via CGH2 via partial oxidation of residual oil (at the refinery) with carbon sequestration; H2 liquefaction centralised; transport: cryogenic truck; refuelling; storage: on-board	mobile appl.

Table 3-1: Explication of the abbreviations for the hydrogen pathways in figure 1

The average loss of the study is about 130% reckoned among the 20 most efficient technologies while constraining costs at €20 Cents/kWh H_2. It is 70-150% in pathways that employ carbon capture and sequestration. This loss from well to storage can only be

[a] Figure 9 in [4]

overcome if the end-use is more efficient than nowadays energy services. Since fuel cells are envisaged to give an overall well-to-use gain, high expectation of their efficiencies are roused, or it must be that the local pollution and/or the cost may make up for the additional conversion losses.

A clear message can be drawn: no optimal chain can be selected for hydrogen supply. The best efficiency, cost and emissions is never combined in one pathway. This aspect may become quite decisive when it comes to a large-scale transition to hydrogen in Europe.

In order to know whether the pathway losses can be overcome by efficient use of H_2 fuel, we want to present calculations based on well-to-tank losses and tank-to-wheel efficiencies of some vehicles. In order to compare hydrogen pathways with classical pathways (natural gas and gasoline vehicle) data have been taken from another study (table 3.2-2 in the GM/LBST Well-to-Wheel study[2]). The HySociety study works with pathways assumptions made for 2030. However, we would first like to know what would be the overall consumption and emission index if nowadays cars are used, making us independent of predictions on efficiency increases for vehicles. Table 3-2 shows the calculation. A comparison can be made between using natural gas in a natural gas fuelled vehicle and in a hydrogen fuelled vehicle. A vehicle that operates on compressed natural gas (CNG) has an efficiency of about 18% (using the same efficiency as for a gasoline car assuming a dual-fuel car; a dedicated CNG engine would have a higher efficiency). This means that in order to provide 1 kWh by the wheels, 5.5 kWh has to be in the tank. Multiplying this with the well-to-tank energy demand of 1.2 kWh/kWh, an overall energy demand of 6.6 kWh is required. From the table it can be seen that a fuel cell car would demand about one third less. So, for a fuel cell car the increased well-to-tank loss is compensated by the fuel cell. An internal combustion engine operating on hydrogen, however, would require 60% more primary energy. Looking at the emissions we see also that the fuel cell car results in a lower overall emission index. If the hydrogen was not made from natural gas by steam reforming but via electrolysis based on electricity from wind or from the average European electricity grid, the overall energy use and emissions would be largely influenced from the better to the worse in comparison with natural gas.

If we replace the vehicles in our analysis with upgraded hybrid versions for 2010 (the most modern type of cars in[2]) we see in Table 3-3 that the hybrid internal combustion engines will increase 10% in efficiency (mostly due to hybridisation), and the hybrid fuel cell efficiency increases with 14% (9% due to the fuel cell and 5% due to hybridisation). Table 3-3 shows that the overall energy consumption and emissions come closer to each other. Transforming natural gas into hydrogen and using it in a fuel cell car will still be more efficient than the direct natural gas pathway, but only in a minor amount. Adding CO_2 capture and sequestration (CSS) can make the big difference. In table 3 three pathways with CSS are shown. For natural gas it shows that the primary energy demand goes up, whereas the emissions may drop with as much as 70%.

In HySociety also a cost calculation has been made including the well-to-wheel efficiency[3] The result is depicted by Figure 3-2. It shows that hydrogen pathways can not reach the cost level of conventional paths with today's cost, although the cost of some pathways may come close to nowadays gasoline price in which tax is included. It is again shown that the gain in CO_2 emission depends on the applied feedstock in combination with the pathway chosen.

Remark: Existing cars (2004)

	E wheel [kWh]	eff. (1) [-]	E tank [kWh]	PED [kWh/kWh]	**E primary [kWh]**	Emission index [g/kWh fuel]	Emission [g/kWh wheel]	**Emission (relative)**
FC (GH2 from NG)	1	0,36 (2)	2,8	1,64	**4,6**	324	900	**1**
ICE (LH2 from NG)	1	0,2	5,0	2,15	**10,8**	310	1550	**1,7**
ICE (CNG)	1	0,182	5,5	1,2	**6,6**	240	1320	**1,5**
ICE (gasoline)	1	0,182	5,5	1,15	**6,3**	291	1600	**1,8**
FC (GH2 from EL-wind)	1	0,36	2,8	1,59	**4,4**	26	70	**0,1**
FC (GH2 from EL-EU mix)	1	0,36	2,8	3,67	**10,2**	485	1350	**1,5**

(1) Data from GM/ LBST WtW study.
(2) Opel press releases on the Zafira Hydrogen3. For the Necar4 it is almost the same.

Table 3-2: Well-to-wheel analysis expressed in primary energy demand and emissions for several natural gas pathways, a gasoline pathway for reference and two hydrogen pathways with other energy sources than natural gas. Opel Zafira's are used as reference for car efficiencies (2004). (FC: fuel cell, ICE: internal combustion engine, GH2: gaseous hydrogen, LH2: liquid hydrogen, NG: natural gas, CNG: compressed natural gas, EL: electricity).

Remark: Hybrid versions (2010)

	E wheel [kWh]	eff. (1) [-]	E tank [kWh]	PED [kWh/kWh]	**E primary [kWh]**	Emission index [g/kWh fuel]	Emission [g/kWh wheel]	**Emission (relative)**
FC (GH2 from NG) HEV	1	0,49	2,0	1,65	**3,4**	324	660	**1,0**
ICE (GH2) HEV	1	0,35	2,9	1,65	**4,7**	324	930	**1,4**
ICE NG-HEV	1	0,318	3,1	1,2	**3,8**	240	750	**1,1**
ICE (gasoline) HEV	1	0,286	3,5	1,15	**4,0**	291	1020	**1,5**
Remark: carbon sequestration included								
FC (GH2 from NG) HEV	1	0,49	2,0	1,88	**3,8**	111	230	**0,3**
FC (GH2 from coal) HEV	1	0,49	2,0	1,99	**4,1**	70	140	**0,2**
ICE (GH2 from NG) HEV	1	0,35	2,9	1,88	**5,4**	111	320	**0,5**

(1) Data from GM/ LBST WtW study

Table 3-3: Well-to-wheel analysis expressed in primary energy demand and emissions for several natural gas pathways, a gasoline pathway for reference and three hydrogen pathways including carbon capture. The car efficiencies are those of hybrid Opel Zafira's in 2010. (HEV: hybrid electric vehicle).

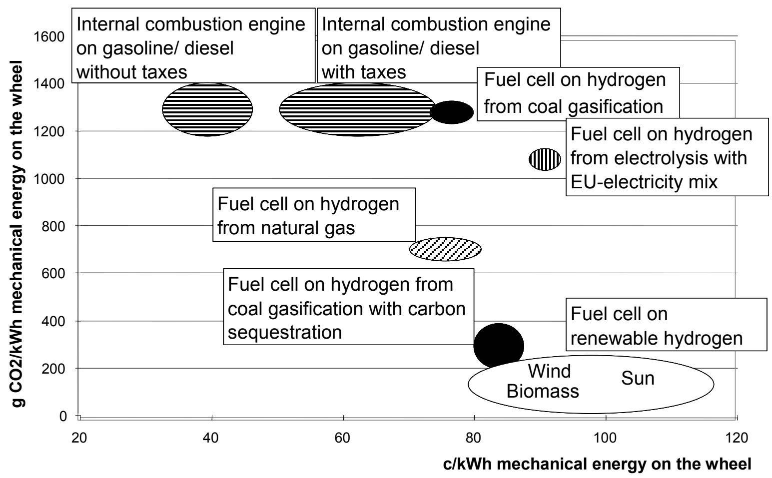


Figure 3-2[b]: comparison of several fuel pathways (well-to-wheel) regarding emission (g CO_2/ kWh) and costs (c/kWh).

b Figure 5 in [3]

3.2 Top-down penetration scenario

In the HySociety project two penetration scenarios have been established in a top-down approach. The most ambitious one presumes that 20 % of the European energy demand is met by hydrogen, both for stationary and transport application. It is further assumed that hydrogen is made from primary energy sources, largely coupled to carbon capture. In the stationary sector electricity is produced from the hydrogen while in the transport sector it is used as a tank fuel. For the stationary sector 20 % of energy demand means that 2 million GWh/yr[c] of electricity is produced which could be realised by some 4000 plants of 100 MW. In the transport sector there will be 85 million vehicles on hydrogen in 2030 (internal combustion engines and fuel cells)[d]. Half of the vehicles are within captive fleets, the others are personal cars.

In the suggested high-penetration scenario of HySociety the hydrogen fuel is produced as follows: 15 % is derived from renewables and 85 % from fossil fuels. Thereof 20 % in small, distributed plants via natural gas reforming. 80 % is produced in centralised plants for which CO_2 capture and sequestration is employed: 70 % by reforming of natural gas, 25 % by gasification of hard coal and 5 % by partial oxidation of residual oil (see Figure 3-3 for a visualisation). For the transport sector 50 % of the hydrogen is supplied in liquid phase and 50 % in gaseous form at refuelling stations. The stationary sector is roughly demanding three times as much energy as the transport sector.

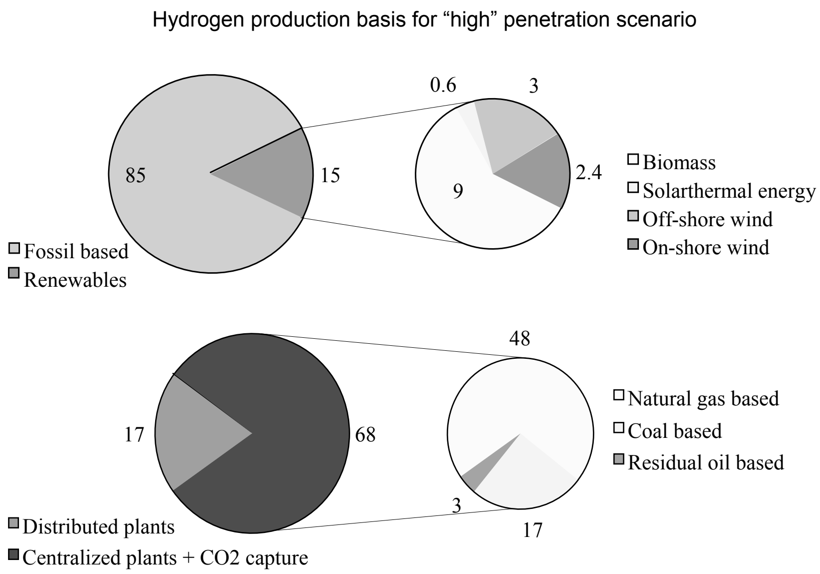


Figure 3-3: The hydrogen production base for the top-down scenario. The upper picture shows the share of fossil fuels and renewables. The lower picture zooms into the 85% of fossil fuels being produced partly in distributed plants and in centralised plants with carbon capture and sequestration.

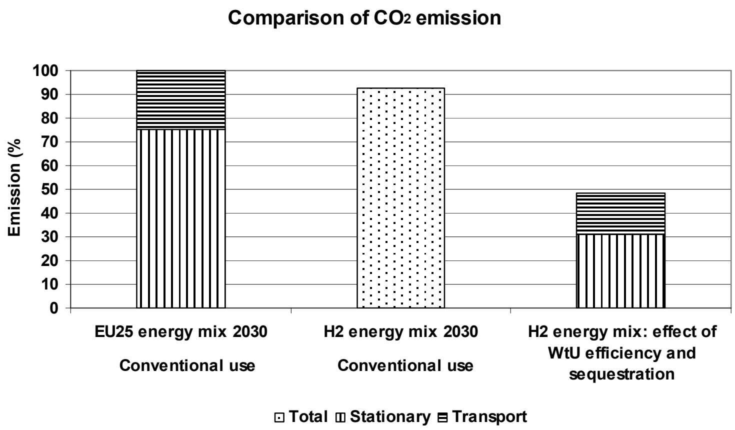
The dependency on fossil fuels requires a warning regarding security of energy supply: hydrogen does not necessarily solve this strategically important issue.

c Table 3 in [4]
d Table 25 in [4]

Based on this scenario one may look further into the consequences of introducing hydrogen, especially for CO_2 emissions. A reference scenario has been formulated using the expected energy mix for the enlarged EU of 25 Member States in 2030 without any provision for hydrogen[4] Figure 3-4 gives a visualisation thereof. The upper picture shows the relative CO_2 emissions from the energy mixtures. The left bar is the emission from the reference case (100 %). The bar in the middle shows that the energy mix from which hydrogen is derived in the scenario would have resulted in approximately the same emissions. However, by means of the hydrogen pathways only 50% of the reference emissions are released as shown by the third bar. This decrease is mostly due to well-to-use technology including sequestration.

The lower picture shows the CO_2 emission chain for the stationary and transport sector respectively. Classically most of the emission is released at the end of the supply chain where combustion of the fuel takes place. In the event of hydrogen, however, the emissions are prone to be pushed towards the supply side owing to the hydrogen production (mainly for distributed plants), carbon sequestration (for centralised plants with carbon sequestration) and handling (distribution and/or refuelling). It must be concluded that for the transport sector far less emission reduction is realized than for the stationary sector. This is caused by the need to distribute hydrogen to the refuelling station and then to the vehicle tank. The latter can be done pressurising hydrogen up to some 800 bar, but also by liquefying hydrogen (as mentioned before, it was assumed that half of the hydrogen amount would be distributed in liquid form). Half of the handling emissions is due to the liquefaction process. The message is that certainly the handling part has to be improved in order not to loose the emission gain that is obtainable via carbon capture and sequestration.

On the total energy demand the hydrogen scenario of 20% share results in an emission reduction of 10%. In the transport sector the hydrogen vector gives a 6% relief. Also an estimation of the costs to establish an infrastructure for the 20% scenario has been made (see Figure 3-5)[3]. This estimation suggests that the deployment cost of the infrastructure corresponds to 0.3% of the EU-25 GDP in 2030. By way of contrast, the estimated annual cost of constructing new motorways in the recent past in EU15 is around six times this amount. Furthermore these investments are to occur gradually and meet the needs of discrete energy chains.



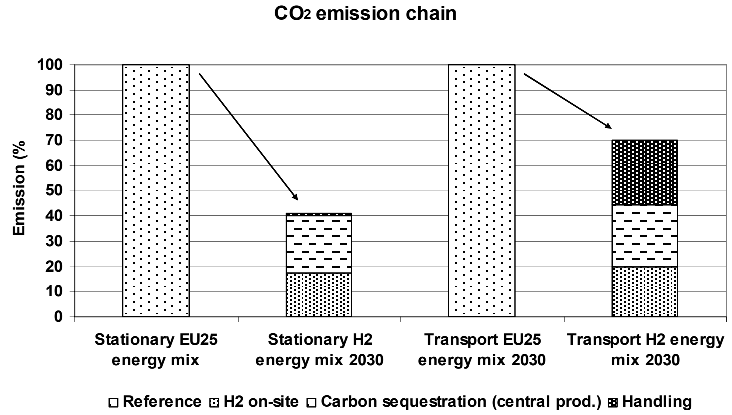


Figure 3-4: CO_2 savings by transition to hydrogen. The first picture shows the emission from the energy mixtures comparing the emission due to conventional use and the emissions from the total of pathways (well-to-user / WtU) as assumed in the top-down approach. The second picture shows the CO_2 emission chain for the stationary and transport sector respectively[e].

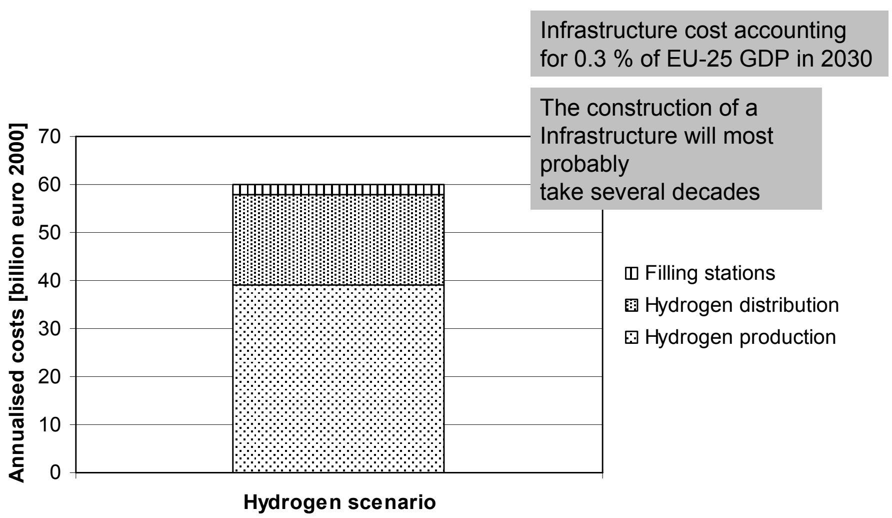


Figure 3-5: Annual hydrogen infrastructure cost of the top-down penetration scenario.

[e] Based on tables 4 and 15 in [7].

3.3 A bottom-up approach

The top-down scenario is probably not very likely. In order to quantify the market development a bottom-up approach may be used.

In the infrastructure section of the HySociety project three main directions have been distinguished[4]:

1. Transport sector: introducing the more efficient and less polluting fuel cell vehicles, and initially also internal combustion engine vehicles.
2. Electric power applications: introducing hydrogen for energy services that require energy storage (island societies), and for some special applications (uninterrupted power supply, auxiliary power units, etc.).
3. For the power sector: large central power plants on primary fuels with capture and storage of CO_2 would be implemented – independent of any European hydrogen infrastructure. Eventually, co-production in the power plant of hydrogen and electricity would become part of the hydrogen infrastructure.

As the transport sector is considered most essential in an European hydrogen economy the strategic approach should particularly address this sector. Figure 3-6 shows that in HySociety it is foreseen that it requires roughly 15 years to reach a population of 1 million fuel cell vehicles reckoned from the infrastructure-deployment launch. In this process the friendly customer approach (i.e. commitments by regions) would be quite essential, especially in the early phase. In 2030 12 million hydrogen vehicles could then be possible. The 1 million cars within 15 years correspond to the recently published EU Deployment Strategy which targets at 1 to 5 million vehicles in 2020[5].

Eventually, hydrogen may also serve as a swing producer for intermittent power generation units especially in connection with wind power parks and solar systems. This concept would be transferable also to island societies. It is recommended to start with two islands of about 10.000 inhabitants. A growth rate has not been given. Here it will be important to improve the efficiency of the swing producer system.

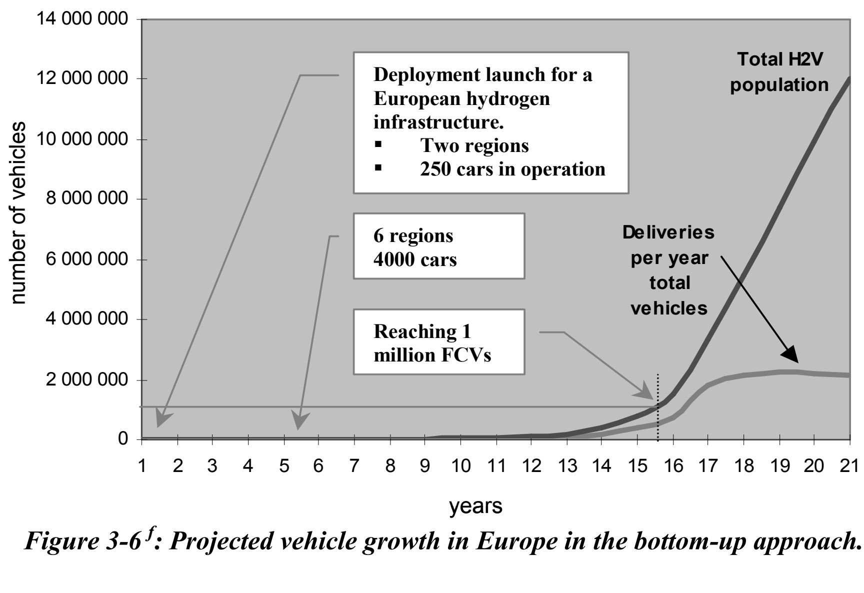


Figure 3-6[f]: Projected vehicle growth in Europe in the bottom-up approach.

[f] Figure 3 in [4]

3.4 Conclusion

When proceeding towards a sustainable hydrogen economy the fuel pathways become very important. Especially for natural gas several pathways have been illustrated in this paper and it was shown that the hydrogen pathway can be better than the classical pathway, but only in combination with fuel cells. The real decrease in emissions comes from CO_2 capture and sequestration. A top-down scenario has shown that hydrogen will mainly be made from fossil fuels, again stressing the important role of carbon capture. This is however not proven technology and scientists regard off-shore storage in geological formations as the only acceptable option that may offer safe long-term storage at the order of thousands of years. This might shed a shadow over hydrogen as an energy vector and may in due course result in conflicts of interest between nations.
The bottom-up approach shows that 1 million fuel cell cars on the road in Europe can be reached in 15 years.

3.5 References

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