Roads2HyCom
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Hydrogen and Fuel Cells - A Handbook for Communities

Volume A: Introduction

October 2007

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EUROPEAN COMMISSION
Community research

The European Commission is supporting the Coordination Action "HyLights" and the Integrated Project "Roads2HyCom" in the field of Hydrogen and Fuel Cells. The two projects support the Commission in the monitoring and coordination of ongoing activities of the Hydrogen and Fuel Cell Platform (HFP), and provide input to the HFP for the planning and preparation of future research and demonstration activities within an integrated EU strategy.

The two projects are complementary and are working in close coordination. HyLights focuses on the preparation of the large-scale demonstration for transport applications, while Roads2Hycom focuses on identifying opportunities for research activities relative to the needs of industrial stakeholders and Hydrogen Communities that could contribute to the early adoption of hydrogen as a universal energy vector.

Further information on the projects and their partners is available on the project web-sites www.roads2hy.com and www.hylights.org.

Members of the Roads2Hycom project contributed to the contents of this volume and commented on draft versions.
Their input is gratefully acknowledged.

Element Energy (editors)
October 2007

CORE GROUP

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Volume A

Energy is an increasingly dominant issue on the global stage. Pressure is increasing to reconsider dramatically, the production and consumption of energy. Two of the drivers behind this are climate change, mainly caused by burning coal, gas and oil, and security of energy supply.

Hydrogen as a fuel may provide part of the solution. It can be produced from energy sources which are local, renewable and carbon-free. It could provide a full range of energy services – heat, electricity and transportation – efficiently and without emissions. In particular, it could facilitate a reduced dependence on oil, since its main application is likely to be transportation.

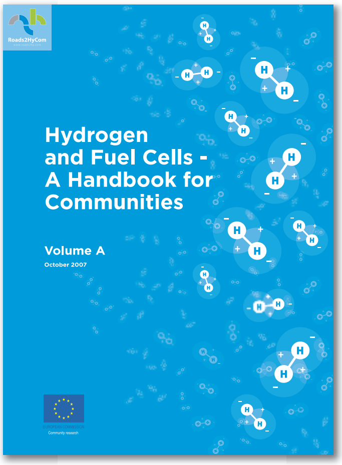
The benefits of hydrogen energy are significant, but so are the challenges. If it is to be achieved, many stakeholders will need to work together with a common vision. Community representatives are key stakeholders. Communities such as cities or regions can play a crucial role in transforming hydrogen and fuel cells from pre-commercial technologies into globally significant energy mechanisms. Communities provide an early end-user of hydrogen technology, and can nurture the hydrogen and fuel cell industries.

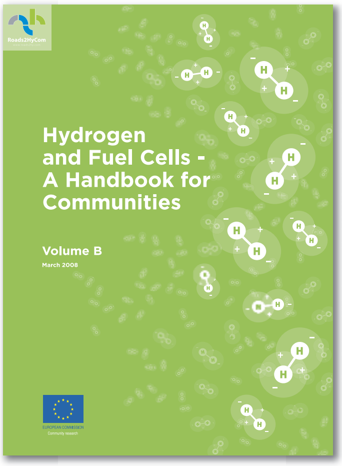
The European Parliament, among others, has proposed to establish a Green Hydrogen Economy and a third industrial revolution in Europe through a partnership with committed regions and cities, SMEs and civil society organisations[1].

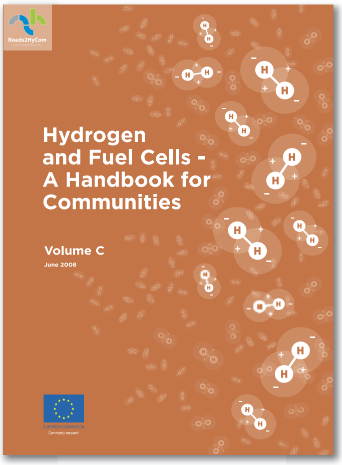
This handbook aims to explain the principles of hydrogen and fuel cell technology and economics and in particular to advise community actors whether to engage with hydrogen, and how to run a successful hydrogen community[2]. The handbook is published in three volumes:

[1] www.europarl.euopa.eu, REF.: 20070516IPR06751

[2] For the purposes of this document, the term ‘hydrogen community’ includes communities using fuel cells.







- **Volume A** introduces hydrogen and fuel cell technologies, and places them in the context of global energy issues. It also introduces the concept of a ‘hydrogen community’ and the role such communities can play in the development of hydrogen technology. This volume is aimed at a reader who is new to hydrogen and who wishes to understand whether early engagement in the sector will be beneficial.

- **Volume B** looks more closely at the roles communities are able to play. Illustrated with case studies, it examines regional characteristics and strategies which lead to successful hydrogen communities. This volume should help the reader define an informed strategy for engagement with hydrogen energy system.

- **Volume C** is a detailed guide to implementing and running a successful sustainable hydrogen community. It addresses aspects such as financing, partnering, procurement and publicity/dissemination.

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1. A Vision of a Hydrogen Energy Economy

1.1 Introduction to hydrogen as an energy vector

Interest in hydrogen is driven by a number of factors. Hydrogen is able to offer:

- Reduction of CO_2 emissions, helping to mitigate climate change
- Reduction of energy imports
- Diversification of energy supplies, reducing dependence on fuels such as oil
- Improved local air quality
- Assistance in the introduction of new fuel cell technologies which offer high efficiencies

These attributes arise because hydrogen has the potential to be produced from energy sources which are carbon-free, local and renewable. Hydrogen can provide a range of energy services, from electricity to transport, while emitting only water.

Given these characteristics, hydrogen fuel, together with fuel cell energy converters may offer a unique opportunity to create a clean and efficient energy system based on sustainable primary energy sources. The investment required to develop these new energy systems means that there is the additional prospect of developing new industries.

What is hydrogen?

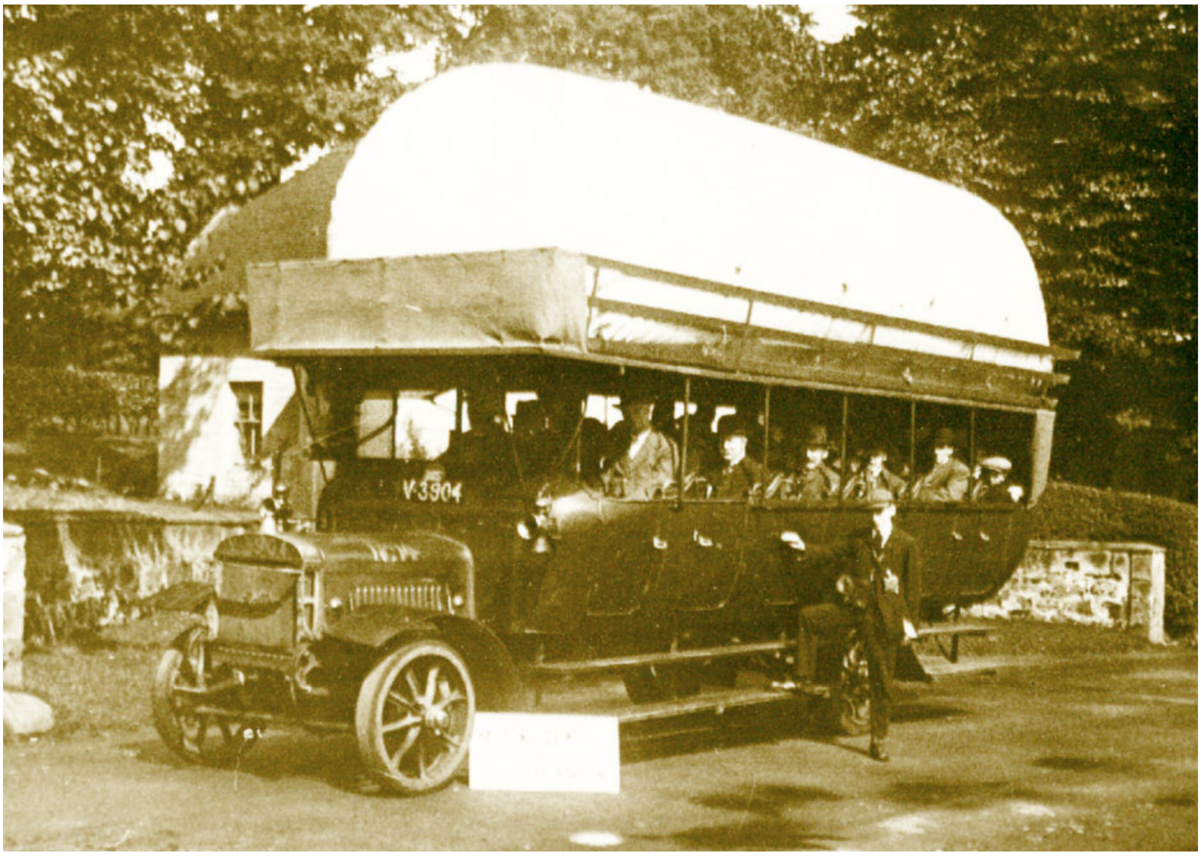
Hydrogen is a chemical element – it is colourless, odourless and a gas at room temperature. It reacts with oxygen, generating both water and energy. Hydrogen can be used as a fuel in combustion engines or to generate electricity in novel fuel cells (see pg.8). In many ways it can be thought of as similar to natural gas, with two important differences; hydrogen cannot simply be mined like methane; and when hydrogen is burned (reacted with oxygen) it does not produce carbon dioxide.

Space shuttles such as the Atlantis used hydrogen to fuel their rockets. Photo: NASA

Although hydrogen atoms are part of many familiar substances (notably water, but also most organic matter) pure or 'elemental' hydrogen – the kind that is useful in energy systems – is very rare on Earth. Nevertheless, hydrogen has been manufactured for a variety of purposes, including:

- The gas inside early airships
- Combustible 'town gas' used in vehicles, lamps and stoves in the early 20th century

and continues to be used as a rocket fuel and as a chemical feedstock in the fertiliser, petroleum, metal, and food production industries.



During World War I, oil shortages forced the conversion of vehicles to hydrogen-rich 'town gas' made from coal. This is a town gas-fuelled bus in Scotland. The inflatable bag on the roof stores the gas. Photo: East Renfrewshire Council Library and Information Services: Local Studies Collection.

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How is hydrogen used as a fuel?

Like any combustible fuel, hydrogen can be burned in air, producing heat. This could be used to heat a house or cook food. However, hydrogen is more often envisaged as being used in one of the following:

- **Internal Combustion Engine (ICE).** Hydrogen can be burned in an internal combustion engine (very similar to petrol or gas-fired engines) to produce mechanical energy without producing CO_2 at the point of use.
- **Fuel cell.** Fuel cells are devices which use a chemical reaction to generate electricity – rather like batteries. They differ from batteries in that the reactants (the chemicals which combine to produce electricity) are stored outside the device. See 1.2 below for more details. Hydrogen can combine with oxygen in a fuel cell to produce electricity, heat and water. Fuel cells are able to operate with much higher efficiencies than combustion-based engines.

INFO BOX

The most common fuel for fuel cells is hydrogen, but different types of fuel cells exist which can run on other fuels such as natural gas or alcohols. If methanol (wood alcohol) or another hydrocarbon is used as the fuel, carbon dioxide will also be generated alongside electricity and water.

Where does hydrogen come from?

Elemental hydrogen is very rare on Earth, and has to be manufactured using a source of energy (such as electricity or heat) and a source of hydrogen atoms (such as water or hydrocarbons). The two most common methods are:

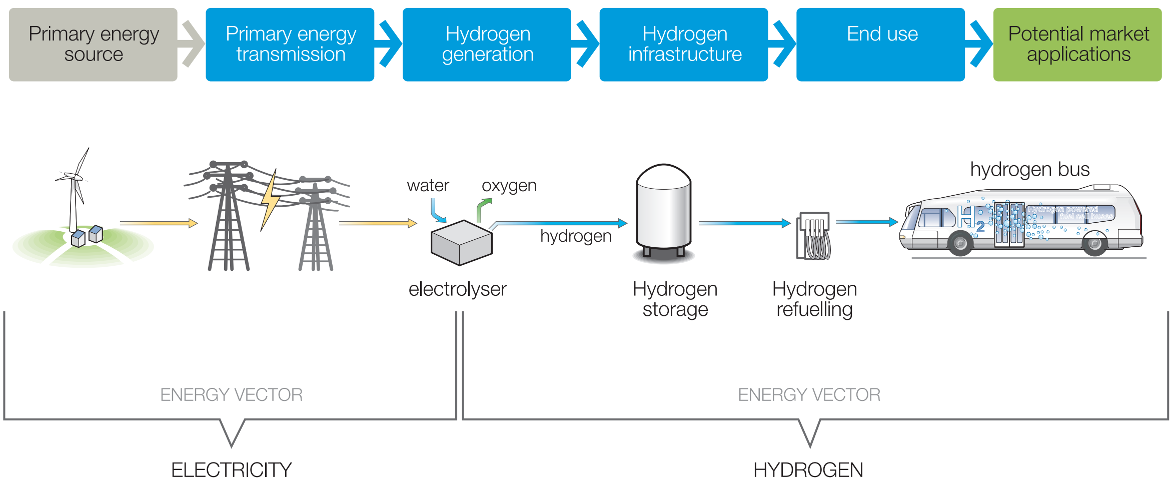
- Hydrocarbon reforming – Chemically converting hydrocarbons (such as gas, oil, or coal), water and oxygen into hydrogen and carbon dioxide. The energy comes from the hydrocarbon.
- Electrolysis – Splitting water into hydrogen and oxygen with an electric current.

Other methods for hydrogen generation do exist, although they are less well developed. More details are given in section 1.2.

In all cases, the energy used in manufacturing the hydrogen must be more than the energy obtained when using the hydrogen at its point of end-use. Each stage of conversion usually has some energy losses associated with it.

Hydrogen is an 'energy vector', not an energy source

Hydrogen is often referred to as an 'energy vector' or ('energy carrier'). The term refers to the fact that hydrogen is not something that can be mined from the ground. Rather, it is used to carry energy from one place to another, or to store it. An example of another energy vector is electricity, which carries energy (through power lines) from a power plant to a house. One of electricity's weaknesses is that it is difficult to store (as is hydrogen).



Electricity is the energy vector carrying energy from the wind to the electrolyser. Hydrogen is then the energy vector carrying energy from the electrolyser, to storage, to the refuelling station, and finally to the hydrogen bus on the road.

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What are prospective applications of hydrogen and fuel cells?

Hydrogen and fuel cells (H2&FC) can be used wherever there is a need for heat or power. The following is a list of the commonly imagined uses for H2&FC.

Note that the applications divide quite easily between those with a clear "social good", such as emissions reduction and energy security, and those which are simply a practical and market driven application of new technology, largely indifferent to wider energy concerns.

The 'market only' applications are relevant to this document insofar as there is synergy between them and the "social good" applications. For example, if direct methanol fuel cells become commercially successful, this is likely to help to lower the cost of PEM fuel cells in vehicles. The 'market only' applications may be still relevant to communities who wish to develop economic growth in relevant industries.

Socially driven applications are important to this document, for it may be that public and community stakeholders value some of the "social good" benefits and can use this as a basis for early engagement in the development or deployment of the technology.

This document will make a distinction between transport-based hydrogen, and other applications of hydrogen and fuel cells because of the very different issues involved.

- Transport is the main application where hydrogen is truly used as an 'energy vector'. Its use has wide-ranging implications as the transport sector accounts for a quarter of global energy consumption[3]. The potential benefits are very significant, but so are the difficulties. These include producing such large amounts of hydrogen from renewable sources, establishing a hydrogen generation and distribution infrastructure, increasing hydrogen vehicle performance and reducing cost in order to reach mass markets.
- Stationary fuel cells. There are many types of stationary fuel cell applications and many types of stationary fuel cells. It is difficult, therefore, to discuss them as a single class. The following is a list of important examples:

[3] IEA World Energy Statistics 2004

- **Storage mechanism for intermittent power.** In situations where either electricity supply or demand is intermittent, some energy storage may be useful to soak up excess energy when supply exceeds demand. Hydrogen has been proposed for this energy storage role, though it is a less efficient storage mechanism than, say, batteries or pumped hydroelectric storage. It would be manufactured at times of high electricity supply, and used in a fuel cell to generate electricity at times of high electricity demand.
- **Combined heat and power.** In homes and other buildings, fuel cells could produce power and use the 'waste' heat for space and hot water heating. Energy chain analysis suggests that in almost all cases, natural gas, rather than hydrogen, would be the fuel of choice.
- **Centralised Power generation.** Fuel cells offer higher efficiency than heat-based generators. Large centralised natural gas fired fuel cells could be a more efficient use of primary energy than the existing technology such as gas turbines.
- **Pre-combustion carbon capture and storage.** One way of using fossil fuels in large power plants, while avoiding large emissions of CO_2 is to reform coal or natural gas into hydrogen and CO_2 before combustion. The resulting CO_2 can be captured and stored underground, and the hydrogen can be used for power generation.

The relevance of these technologies to the wider 'hydrogen economy' is quite variable:

- Micro-CHP and centralised power generation use similar technology to one another (high temperature fuel cells) but have little to do with hydrogen.
- The hydrogen in 'storage mechanism for intermittent power' and 'pre-combustion CCS' is produced and consumed in a closed loop, and therefore may not play a significant role in developing a hydrogen economy, except where it advances technology – reforming, electrolysis, fuel cells.

Application	Likely conversion device	Likely Fuel	Main Driver
Transport	Fuel cell/ICE	Hydrogen	Social
Storage mechanism for intermittent energy	Fuel cell	Hydrogen	Social
Portable electronics – fuel cells could provide the same function as a battery, while being lighter and faster to refill.	DMFC Fuel cell	Methanol	Market
Centralised power generation – Fuelcells running on natural gas could bea more efficient way of generatingelectricity than conventional gas power plants.	High temperature Fuel cell	Natural gas	Social
Carbon-capture-and-storage (CCS) power generation. One way of capturing emissions of CO_2 from coal is to convert the coal to hydrogen, capturing the consequent CO_2. The hydrogen is then used to generate electricity.	Hydrogen gas turbine	Hydrogen	Social
Backup power (uninterruptible power supply – 'UPS')	PEM Fuel cell	Hydrogen	Market
Micro combined heat and power – Fuel cells could generate on-site electricity for a house or district, using the waste heat to warm peoples' homes and hot water instead of a conventional gas boiler.	High temperature/ PEM fuel cell	Natural gas	Social
Auxiliary power systems for, e.g., caravans	DMFC/PEM Fuel cell	Methanol	Market
Off-grid power generation e.g. unmanned communications towers	DMFC/PEM Fuel cell	Methanol	Market

How does hydrogen fuel for vehicles compare with other potential oil replacements?

The case for hydrogen in transport needs to consider not just how it compares with the incumbent, but how it compares with other alternatives to fossil fuels in vehicles. It is generally acknowledged that there are two other principal alternatives to fossil fuel in vehicles – biofuels and battery electric technology.

Biofuels are hydrocarbons produced from organic material. As they are not fossil in origin, their use does not result in a net increase in atmospheric CO_2. Biofuels are appealing as – once they are produced – they require limited changes in infrastructure. The performance and cost of a vehicle powered by biofuel would not differ substantially from a fossil fuel powered vehicle.

A concern with first generation biofuels is that the arable land area constrains the amount of biofuel which can be produced. Biofuels compete with crop production and may increase food prices. While emerging biofuel (second generation) production technologies may lessen the problem it would not be removed completely.

Battery electric vehicles (BEV) could provide another zero-carbon solution, if renewable electricity is used to charge the batteries. However, the size and weight of existing batteries compared with the amount of energy they store heavily constrains the range of battery-powered cars, limiting their suitability to largely urban operation[4]. Long recharging times, high cost and scarcity of some metals are further constraints on this option.

The main attraction of this option is that the "fuel supply" infrastructure (electricity) already exists. If battery performance was to improve markedly and cost was to reduce, BEVs could represent a complete solution to decarbonising transport. However at this time both are a significant challenge.

Hydrogen technology is the third alternative for decarbonising transport. It too has significant challenges. Hydrogen is difficult to store in useful quantities and like batteries, this has limited

Biofuel production requires arable land –a limited resource which is often needed for growing food crops.

[4] "Status and Prospects for Zero Emissions Vehicles Technology", State of California Air Resources Board Sacramento, California 2007

the range of some vehicles. Technological immaturity and lack of mass-production means hydrogen vehicles are very expensive. Also, hydrogen will require a new fuel supply infrastructure to be developed. However, if these challenges are overcome, hydrogen vehicles could perform as well as fossil fuel vehicles, but without CO_2 emissions.

	Cost	Infrastructure/ RTD needed	Performance	Energy source
Biofuel fuelled vehicles	Almost cost-neutral today	Little further infrastructure or RTD required	Equivalent performance to current vehicles	Resource is limited. Socio-economic and environmental implications.
Battery electric vehicles	Remains expensive	Further RTD needed	May have insurmountable problems with range and recharging time.	Can use any primary source
Hydrogen vehicles	Remains very expensive	Much more infrastructure and RTD needed	Close to being performance-competitive. Potentially better performance than existing vehicles	Can use any primary source, though with lower efficiency than BEVs

Table comparing strengths and weaknesses of different replacements for fossil fuel powered vehicles. Red boxes indicate areas of weakness.

1.2 Hydrogen Energy Chains

An 'energy chain' is a way of thinking about how energy flows from a source to its final use (see diagram above). Typically, at each stage in a chain, energy is converted from one form to another. Generally, complex energy chains will involve energy losses and expensive equipment at each conversion stage. For this reason it is important to carefully consider the production, transport, storage and end-use of hydrogen.

Production

Hydrogen can be produced using a variety of methods. The energy that is eventually produced by the hydrogen cannot be greater than the amount of primary energy originally used to produce it – and may be significantly less.

- **Electrolysis.** Passing an electric current through water can produce hydrogen and oxygen. The efficiency of the process is currently around 70%, but is expected to improve. This method of hydrogen production is relatively expensive, but is seen as a long term option for producing hydrogen from renewable sources.
- **Hydrocarbon reformation.** Hydrocarbons can be chemically converted into hydrogen and CO_2. The hydrocarbon feedstock can be natural gas, oil, coal, or biomass. It is currently the cheapest and most common method of hydrogen production. Carbon dioxide is released during the process, but there might be the potential to capture and store it, rather than releasing it to atmosphere.

Air products reformation plant, New Orleans. Photo: Air products

- **High temperature thermo-chemical processes.** There are some chemical processes which can use extremely high temperature heat to produce hydrogen from water. The high temperature heat could come from nuclear or solar sources. This technology is not yet available commercially, and research is being conducted into materials able to withstand high temperatures.

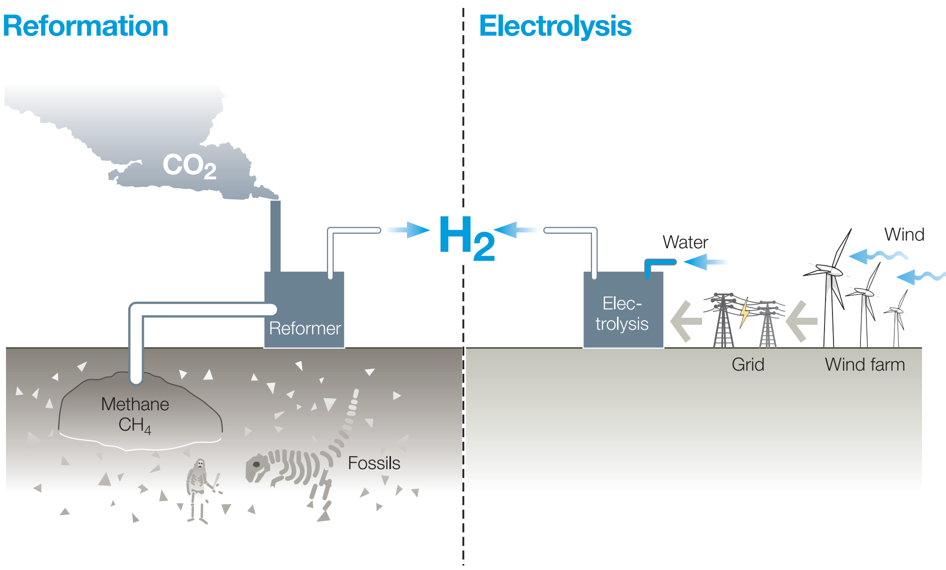


Diagram of electrolysis and reformation processes.

Transmission and storage of hydrogen

Hydrogen is a gas at normal temperatures and pressures, so storing it in useful quantities is a technical challenge. It is usually stored as either a compressed gas in cylinders, or as an ultra-cold liquid in cryogenic tanks and transported on trucks. There is also research into storing hydrogen within other solids. Pipelines offer a means of both storage and transport.

The important challenge of hydrogen storage is to achieve high energy density without high cost. In other words, it is important that for a given quantity of hydrogen, the storage system is neither too bulky nor too heavy, nor too costly. Currently, hydrogen storage systems are much larger and heavier than their petrol equivalents.

Space required by energy storage systems

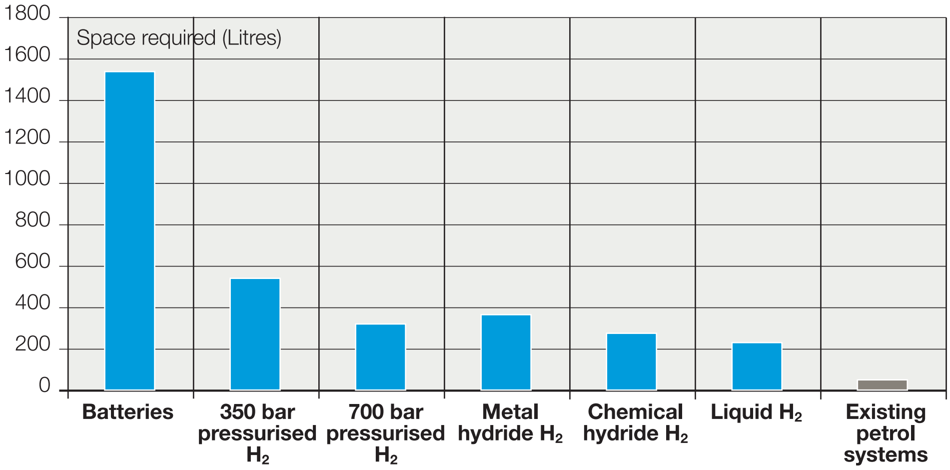


Diagram showing the amount of space needed to store the energy contained in a typical passenger car petrol tank today. Data from US DOE.

- **High pressure gas in cylinders.** Pressurising hydrogen allows more of it to be stored in a given volume, but it also uses up energy, and demands high strength materials. In industry, hydrogen is usually stored in stainless steel cylinders at 200 bar. There is no consensus as to what the optimum storage pressure for vehicles will be. Pressures are anticipated between 350bar and 700bar.
- **Cold liquid in tanks.** Liquid hydrogen has similar (gravimetric) energy density to petrol, but only exists at temperatures below -253°C. Cooling to these temperatures requires significant expenditure of energy and sustaining the temperature requires super-insulated cryogenic tanks. Inevitably, some heat will penetrate the tanks, resulting in some hydrogen ‘boil-off’ that must be vented and most likely lost.

Liquid hydrogen storage is commonly used to transport hydrogen over long distances. Photo: Linde.

- **Pipelines.** Hydrogen like other fluids can be transported by pipelines. Hydrogen causes brittleness in some metals, and leaks more easily than natural gas. Therefore hydrogen pipelines are more expensive than natural gas pipelines. There are in existence 1600 km of hydrogen pipelines in Europe[5]. Pipelines have an additional advantage in providing a store for hydrogen as well as a transport mechanism; excess hydrogen can be stored in pipelines by allowing the pressure to rise. Pipelines become economically feasible at high levels of hydrogen demand.

Hydrogen pipelines could transport large volumes of hydrogen, but require considerable capital expenditure. Photo Courtesy of Linde.

[5] "European Hydrogen Infrastructure Atlas" Roads2HyCom deliverable 2.1

- **Solid-state storage.** There are currently experimental systems involving hydrogen stored in solid structures – metals or carbon nanotubes. Solid storage could offer advantages particularly in terms of safety, but the technology has some way to go before it is ready for use in mainstream vehicles.

An image of the raw material for a metal hydride system. Photo: GfE

- **Chemical storage.** Chemicals such as sodium tetrahydroborate and lithium hydride offer the potential to store hydrogen at usefully high energy densities. Difficulties remain over how to distribute fresh, fully charged chemicals to the end users, and how to recycle the chemical once the hydrogen is used up.

End-use

There are two major ways hydrogen can be used for energy – in fuel cells or in combustion engines.

Fuel Cells

Fuel cells combine hydrogen with oxygen to produce electricity, water and some waste heat. The hydrogen is separated from the oxygen by an electrolytic membrane, which only allows ions to pass through. In order for the hydrogen and oxygen to combine to produce water, an electric current must pass from one electrode to the other to balance the charges.

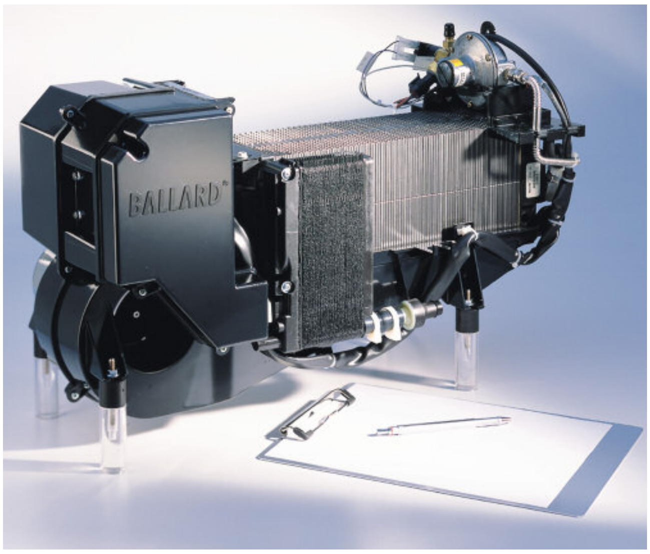


Photo of a 1.2kW fuel cell system. Photo: Ballard

There are many types of fuel cells, with different characteristics – including operating temperature, fuel, and efficiency. Some of the most common fuel cells are:

- Proton Exchange Fuel Cell (PEM)
- Molten Carbonate Fuel Cell (MCFC)
- Solid Oxide Fuel Cell (SOFC)
- Alkaline Fuel Cell (AFC)
- Direct Methanol Fuel Cell (DMFC)
- Phosphoric Acid Fuel Cell (PAFC)

These can generally be characterised as either low or high temperature.

The low temperature fuels cells (PEM, AFC and PAFC) have the following properties.

- Rapid response; short start-up times.
- Requirement for high purity hydrogen.
- Requirement for precious metal catalysts, such as platinum, which add to costs.
- Susceptibility to poisoning by impurities such as sulphur and carbon monoxide, which can quickly shorten lifetimes.

The above are likely to be suitable for mobile/transport applications and small (<50kW) stationary applications.

The high temperature fuels cells (SOFC and MCFC) have the following properties.

- Slow response; long start-up times.
- Ability to use a variety of hydrocarbon fuels.
- Requirement for high specification materials to withstand temperatures.
- Requirement for thermal management systems.
- Production of high grade heat, which can be used in thermal cycles to produce more electricity.

Due to their weight and complexity, these are likely to be suited to large scale stationary power generation (100kW to 10MW).

Combustion

Hydrogen burns in oxygen similarly to other combustible substances. A standard internal combustion engine requires limited modification in order to be suitable to run on hydrogen. This makes hydrogen internal combustion (H2ICE) powered cars much cheaper than their fuel cell counterparts.

Compared with fuel cells, a downside of internal combustion engines is their relative inefficiency. At an average efficiency of around 20-30%[6] they require more primary energy than equivalent fuel cell vehicles. They also require more onboard hydrogen storage in order to travel the same distance, which has its own technical difficulties.

H2ICE vehicles are seen as providing a 'stepping stone' in the path to a hydrogen economy (see section 2.2).

[6] "Well-to-Wheels analysis of future automotive fuels and powertrains in the European context TANK-to-WHEELS Report"; Version 2c, March 2007. Concawe, EUCAR, EC Directorate-General Joint Research Centre. http://ies.jrc.ec.europa.eu/WTW

It should be noted that H2ICE vehicles do produce some emissions. Some oxides of nitrogen (NOx) are produced, and tiny amounts of CO_2 are produced due to the combustion of the engine's lubrication oil.

Hydrogen internal combustion engines are a relatively mature and inexpensive technology. The above image shows BMW's 6L V12 engine which can run on hydrogen or petrol. Photo: BMW

To conclude, there are various potential energy chains which could offer the potential to establish more sustainable energy systems in Europe. There are technical difficulties with many components of these chains.

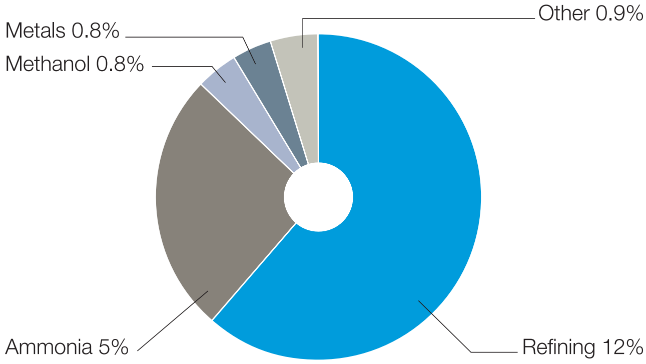
1.3 The Current State of Hydrogen and Fuel Cells

Hydrogen as an energy carrier is at the pre-commercialisation stage. It exists in demonstration projects and laboratories. The cost of hydrogen technologies is still prohibitively high for typical commercial consumers.

Hydrogen production

Hydrogen is produced in large volumes for industrial processes. The following chart shows the quantities of hydrogen used by the major industries in Western Europe. The total is 19 million tonnes of oil equivalent per year. In energy terms, this is approximately equivalent to 0.5% of the world's annual oil consumption.

Annual hydrogen consumption by Western European industry Mtoe



Graph showing breakdown of today's hydrogen consumption in Europe. Source: Roads2HyCom

Some hydrogen is produced as a by-product in certain industries but is vented to the atmosphere. This surplus hydrogen is estimated to be between 1.3 and 3.6 Mtoe, theoretically enough to supply 3 – 6 million vehicles, or 3% of Europe's car fleet, although much of this hydrogen would need to be purified before use[7].

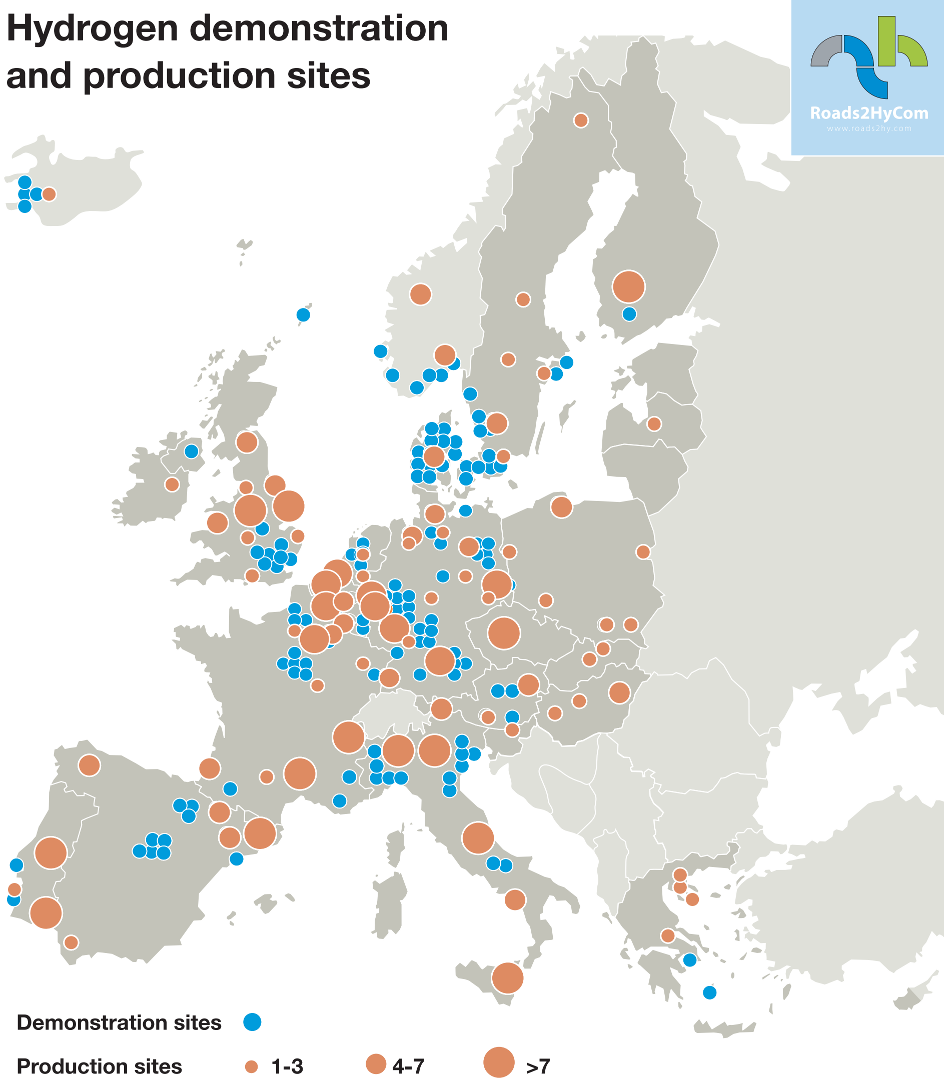
The potential long-term methods for producing renewable or carbon neutral hydrogen, as discussed above, are at various stages of development, and only electrolysis from renewable electricity has been used to date.

Hydrogen and fuel cell technology – status and notable achievements

Most H2&FC end use technologies today are bespoke rather than mass produced, and are operated in the context of demonstration projects rather than on a commercial basis.

Many of the large automobile manufacturers have hydrogen research programs. The companies each have their own research focus, producing one-off vehicles for demonstration projects. Since road-testing a prototype is advantageous for the company as well as the consumer, vehicles may be sold at prices below their production costs. The following is a map of hydrogen and fuel cell demonstration projects in Europe.

[7] "Industrial excess hydrogen analysis" Roads2HyCom deliverable 2.1a



Demonstration sites in Europe are gradually adding to the hydrogen infrastructure developed by industry. Source: Roads2HyCom

Some notable recent achievements of the hydrogen/fuel cell industry are:

Transport – demonstration

The GM sequel has a range of 300 miles per refilling. Photo: GM

- The GM Sequel fuel cell vehicle has demonstrated a 300 mile range on a single tank[8]
- BMW 7 Series H2ICE vehicles have reached 100 units of production[9]
- Honda claims 60% efficiency for its next-generation FCX Concept fuel cell vehicle[10]
- The CUTE project across Europe operated hydrogen buses for over 60,000 combined hours[11]

Transport – niche markets

Fuel cell forklifts are an important early market. Photo: General Hydrogen

- Plug Power has acquired Cellex and General Hydrogen to sell fuel cell-powered electric forklifts[12]
- Wal-mart has successfully conducted beta trials of Cellex forklifts[13]

[8] www.gm.com
[9] www.bmwgroup.com
[10] http://world.honda.com/
[11] www.hfpeurope.org
[12] www.plugpower.com
[13] www.cellexpower.com

Stationary

- SFC Smart Fuel Cell AG has sold 2,372 fuel cells in the first half of 2007[14]
- Fuel Cell Energy had 10.9 MW of orders, year to date by June 2007[15]
- UTC Power's stationary 200kWe scale fuel cell CHP fleet has reached 8 million hours of field operation[16]

Portable

- CMR Fuel Cells, a UK compact fuel cell specialist has entered a joint development agreement with Samsung to produce direct methanol fuel cells for portable electronics devices.[17]

[14] www.investor-sfc.com/
[15] www.fuelcellmarkets.com
[16] www.fuelcellmarkets.com
[17] www.cmrfuelcells.com

Summary: A vision for a Hydrogen Energy Economy

- Reducing CO_2 emissions and improving security of energy supply are the two main drivers for hydrogen fuel.
- An important advantage of hydrogen is that it can be produced from a range of primary energy sources, either fossil fuels or renewable.
- Hydrogen can be used to generate electricity using fuel cells, or motion using the simpler but less efficient internal combustion engine.
- While hydrogen could be used as a fuel in a wide range of applications, it is in the transport sector where its benefits are most clear.
- Other than hydrogen, there are two main alternatives to fossil oil in vehicles – biofuel powered vehicles and battery electric vehicles. Each has its associated difficulties.
- As well as in vehicles, fuel cells have a number of stationary energy applications, from portable electronics to large scale electricity generation.
- Hydrogen energy technology – production, storage, transport and end-use – is at the pre-commercialisation stage, and significant technical and financial challenges remain.
- One of the main technical challenges is to transport and store hydrogen cheaply and easily.
- Costs are high in part because most fuel cells are made in small numbers. Nevertheless, inroads are starting to be made in niche applications such as forklifts.

2. The Road to a Hydrogen Economy

The previous section illustrated possible visions for a hydrogen economy. In this section, we consider some of the barriers to this vision and how these might be overcome.

Factories able to mass-produce hydrogen cars at a low cost per unit will only be built once there is sufficient demand for hydrogen cars

2.1 Barriers to use of hydrogen:

Cost of technology

Costs of hydrogen technologies today are much higher than their fossil-fuel counterparts. This is the biggest barrier to the uptake of hydrogen technology.

The reasons for high cost have to do with technological maturity. The biggest factor, however, is the lack of economies of scale. Mass-commercialisation is needed for hydrogen to be competitive with conventional technologies:

- **Technological maturity** – Unlike combustion engines, which have had a century to be improved and refined, hydrogen technologies are relatively immature. Researchers are working on improving performance, and developing cheaper methods of production.
- **Critical mass, economies of scale** – Hydrogen vehicles today are not produced in any great number (ca. 100 pa. worldwide). They have to be designed and manufactured virtually bespoke. This results in very high unit costs, when compared with conventional cars, which are produced in their millions. A critical mass – a minimum number of units produced and delivered – is needed to bring costs down and to demonstrate feasibility, preparing for self-sustaining development.

This 'chicken-and-egg' relationship between production and consumption is one of the most fundamental challenges of commercialising a technology that competes with a mass-produced incumbent.

Supply chain/infrastructure

The lack of refilling stations, or other easy access to hydrogen presents another 'chicken-and-egg' problem. Refuelling stations will only provide hydrogen if there is enough demand.

Early petrol infrastructure developed much more easily, since petrol can be stored and transported easily. Also it did not have to compete with and attempt to displace an existing energy infrastructure. As a model for developing infrastructure, the success of compressed natural gas vehicles in some countries (Argentina and Bangladesh) may be more appropriate.

Regulation/standards

It was shown above that hydrogen is in common use as a feedstock in a range of industries. Its use here is tightly regulated, and safety is paramount. However its use in energy systems is still very novel, and appropriate regulations and standards have not yet been developed. Significant efforts are underway to develop regulations and harmonise these across countries. The lack of internationally recognised codes, regulations and standards slows down the development of new hydrogen and fuel cell products and projects.

Public acceptance

There is a concern that people will be reluctant to adopt hydrogen technologies, even once they meet cost and performance-competitiveness, due to unfamiliarity and fears about safety. How serious this concern really is remains unclear. But it is clear that the public will need to be trained and educated as hydrogen technologies require different operational procedures – refuelling a hydrogen car is different to filling a petrol car.

Hydrogen production and distribution

The uptake of hydrogen technology is limited by the availability and price of the hydrogen itself. Currently, hydrogen is significantly more expensive than petrol.

There is also the issue of obtaining hydrogen from low-carbon sources. It shouldn't be forgotten that this is the principal reason for using hydrogen in the first place. Carbon-free energy sources need to be harnessed to supply increasing need for hydrogen.

Finally, if centralised production is desired, distribution routes to take hydrogen from a production plant to a filling station's forecourt need to be established.

2.2 Possible pathway to a hydrogen economy

The barriers outlined in the previous section might be overcome in a number of ways. This section illustrates today's thinking on how to reach the hydrogen economy. The analysis pertains mostly to hydrogen in transport, rather than to other uses for hydrogen and fuel cells.

Consumer uptake

The common theme to the barriers described above is the 'chicken-and-egg' dilemma. Ordinary consumers, who comprise the largest section of the market, won't buy, for example, hydrogen cars until they are cost and performance-competitive with conventional cars, and there is sufficient refilling infrastructure. But this won't happen until there are enough cars being produced and on the roads.

The solution generally envisaged is for H2&FC technologies to gradually enter the market in 'niche' areas, where high costs and lack of infrastructure are less of a barrier than they are in the conventional market. Pioneering consumers and users will take the risk – and be rewarded by status and first mover advantages. Their purchases will facilitate continued investment and development in fuel cell and hydrogen technology. In turn, this will improve performance and reduce costs, making the technology attractive to a larger number of consumers. This virtuous circle can ultimately lead to mass market applications.

Early markets will be ones where hydrogen's current weaknesses are less of a barrier, and where its strengths are more relevant. Some examples of characteristics which satisfy these criteria are:

Early market – Police fleets are an example of public fleets who are hoped to become early adopters of hydrogen.

- **Transport applications which are geographically localised.** Vehicles which are restricted to an area or route don't require widespread refilling infrastructure. Example: buses.
- **Applications with high daily usage.** When a piece of equipment is used heavily, its capital cost plays a less important role than its operating and fuel costs.
- **Luxury/high performance applications.** Cost is less relevant, or where the cost of the power system is a small component of the overall cost. Examples. CCTV, military, consumer electronics.
- **Transport applications where vehicles need to stop and start regularly.** Fuel cells operate well even at partial load, so have an advantage over internal combustion engines. Examples: delivery vans, taxis.
- **Fleets.** Consumers who purchase many vehicles have the advantage of being able to make bulk purchases.
- **Publicly owned vehicles.** Public-sector consumers have the additional benefit of being more interested in the long-term benefits of hydrogen, and in local air pollution.
- **Indoor applications.** Where a moving power source is required where emissions must be zero, the incumbent technology is generally battery powered. Fuel cells can compete with batteries on both cost and performance already. Examples: forklift trucks, airport buggies.
- **Remote areas with high energy demand.** It is possible that areas may be able to exploit local energy resources by manufacturing hydrogen to meet local transport energy demands. How competitive hydrogen will be relative to other solutions remains to be seen.
- **Where the existing market is small.** Hydrogen cars have to compete with the mass-production efficiencies of petrol cars. In applications where the incumbent technology is manufactured on a small scale, hydrogen's competitive disadvantage is lessened.

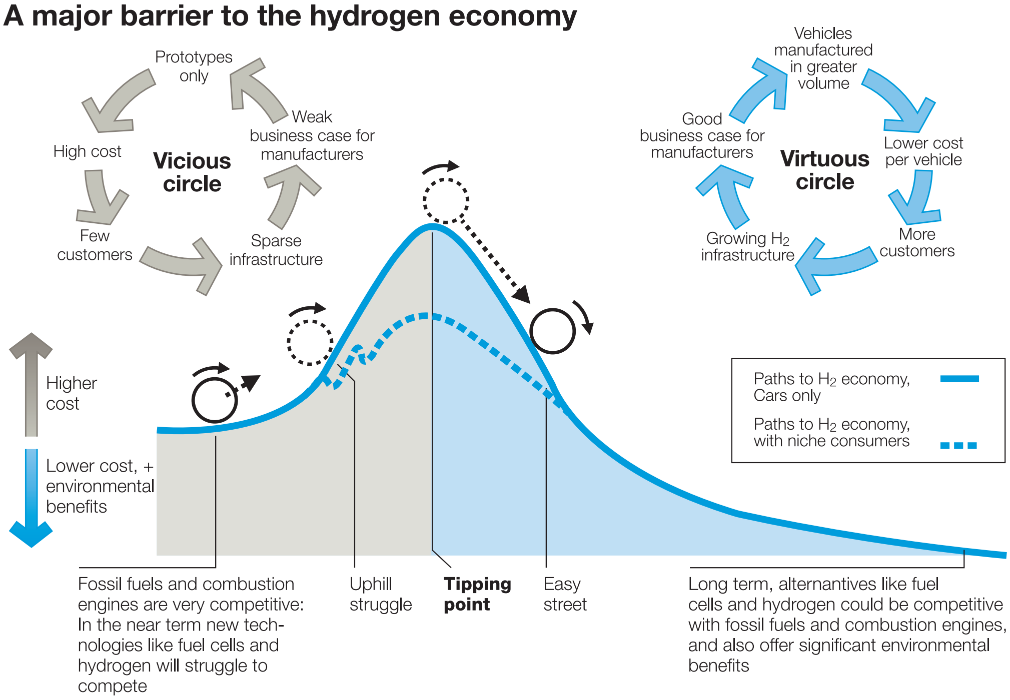
Early market – Buses are high-use, public fleets which are produced in smaller numbers than cars. They are seen as a significant early market.

Early market – As high-tech electronic devices call for higher power, fuel cells can offer a superior power solution to batteries.

In the "niche" model, hydrogen refuelling infrastructure will need to be installed to match demand. Oversizing of supply infrastructure would allow other end users to start using hydrogen. Hybrid cars able to run on either hydrogen (ICE) or petrol could provide an important 'stepping stone'. Once a reasonable demand for hydrogen is established, it will be sensible for companies to complete their networks of refilling services.

As the market expands, prices will fall, and infrastructure will be more accessible. Hydrogen vehicles will become attractive to an increasingly wide range of consumers.

A major barrier to the hydrogen economy



Development of technology and industry

More research is needed to improve costs and performance for hydrogen technologies. Some areas where improvement is envisaged:

- Fuel Cell lifetime. Currently, PEM fuel cells only have operating lifetimes of around 2,000 hours, more research is required to bring this figure to the 5,000 hours needed for cars[18].
- Fuel Cell cost.
  - Increasing the current through a fuel cell means that more power is available for a given electrolyte area – reducing he effective cost for a certain amount of power.
  - Reducing precious metal (platinum) loading.
  - New manufacturing techniques.
- Hydrogen storage gravimetric density.
- Hydrogen storage cost.
- Improvements in electric drivetrains.

[18] "Implementation plan - status 2006" European Hydrogen and Fuel Cell Technology Platform.

Although we are some distance from achieving these goals, recent developments suggest we can be optimistic regarding fuel cell developments. On the other hand, improvement of hydrogen storage techniques is progressing less quickly[19].

As well as the research-based activities described above, the hydrogen industry itself will need to expand. Infrastructure, manufacturing capacity, and supporting services will all need to develop rapidly. This can be driven by demand as consumer uptake increases. Maintaining the required level of demand, while the technology develops towards a level acceptable to the mass market, is quite a challenge.

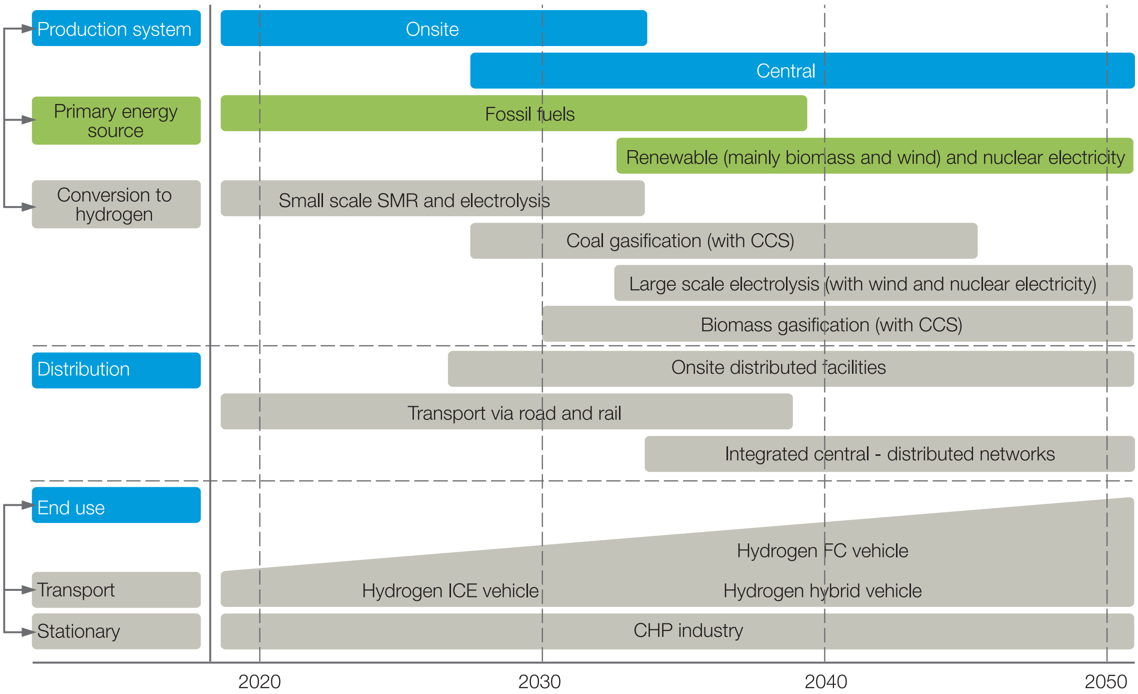
Possible pathways to a hydrogen economy

Early/niche markets
Mass markets
Coverage will, in time become complete.

[19] "2006 annual progress report" DOE Hydrogen Program, www.hydrogen.energy.gov

Speculative timetable for the commercialisation of hydrogen and fuel cells

(info courtesy of Roads2hycom)



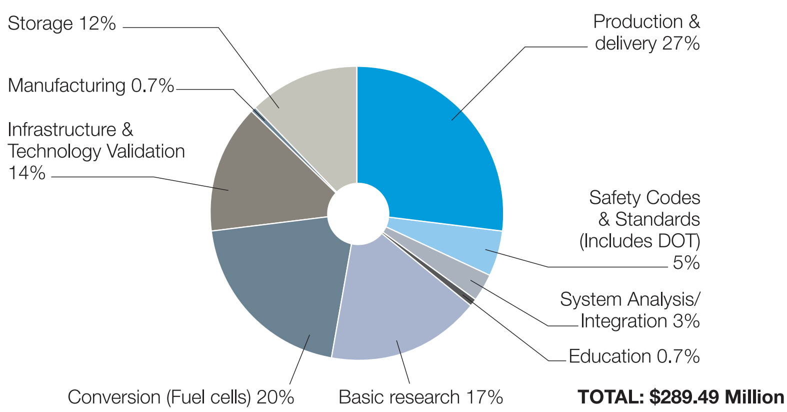
A speculative timetable for the commercialisation of hydrogen and fuel cells (courtesy of Roads2hycom)

2.3 Existing Efforts

Most industrialised countries have hydrogen energy programs. Activity is particularly focused in the US, Western Europe and Japan.

For the funding year 2007, the US's 'Hydrogen Fuel Initiative' requested $290m from the US Government budget, broken down as follows[20]:

US 'Hydrogen Fuel Initiative' budget request $290m (2007)

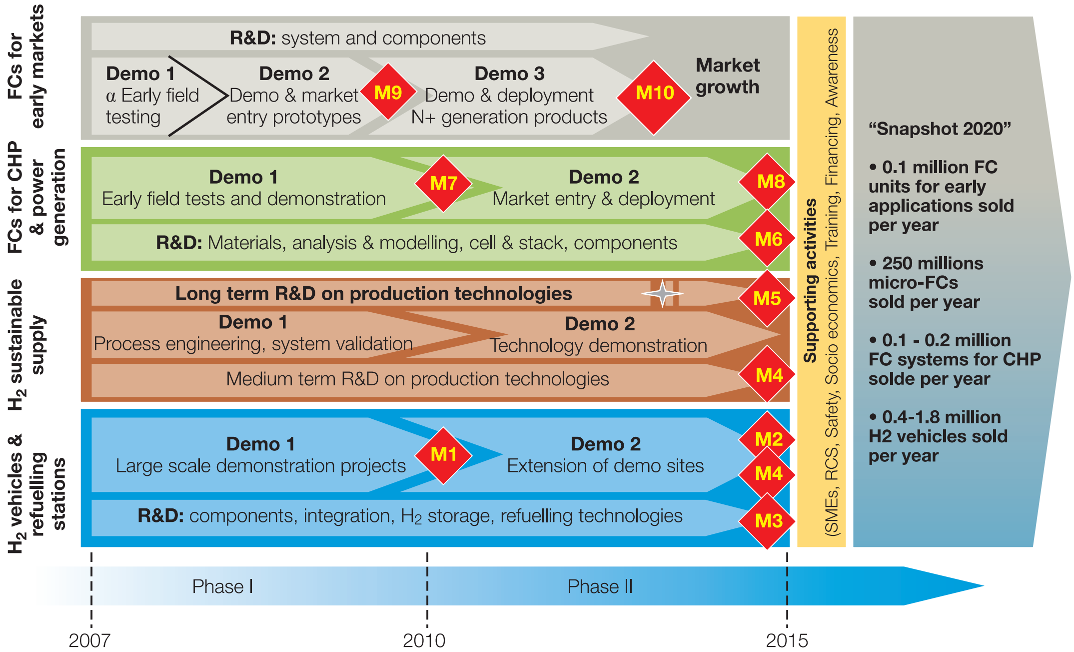


[20] "Hydrogen Posture Plan" US DOE, December 2006.

Public funding in Europe is estimated at €320m – €350m per year. These budgets are dwarfed by the global spending on H2&FC R&D by automobile companies, an estimated €5 billion per year[21].

The EU's 'Hydrogen Implementation plan', written by the 'Hydrogen and Fuel Cell Technology Platform' (HFP) gives the following plan for the timescales of hydrogen deployment.

European roadmap for development and deployment of H2 & FC technologies



[21] "Implementation plan – status 2006" European Hydrogen & Fuel Cell Technology Platform

Summary: The road to the hydrogen economy.

The most significant barriers to the commercialisation of hydrogen and fuel cells are:

- High cost –technological immaturity and the lack of mass production results in cost being a major barrier.
- Requirement for new hydrogen generation and supply infrastructures.
- Some technical hurdles, particularly transporting and storing hydrogen.

The pathway to a hydrogen economy involves the following:

- Niche markets creating a demand for HFC technology to increase production volume, supply chains and infrastructure
- Technical developments to reduce costs and increase performance
- Hydrogen production developing from distributed, fossil-fuel based production to centralised renewable and low carbon production with high volume transport mechanisms such as pipelines.

Achieving widespread uptake of hydrogen energy will not be cheap, and will require the sustained efforts of a range of public and private stakeholders.

The efforts to move to commercialisation of H2FC are currently being undertaken by governments, particularly in the US, Europe and Japan, major car companies, and SMEs developing innovative technology.

3. Hydrogen Communities

3.1 What is a Hydrogen Community?

The Roads2HyCom project is centred around the notion of a 'Hydrogen Community'. The project defines a hydrogen community as follows:

INFO BOX

A Hydrogen Community refers to an early adopter of Hydrogen and Fuel Cell technologies, having the potential to lead to a coordinated, larger-scale adoption of such technologies within a coherent end-user grouping

In practice such communities could be regions, cities, remote locations (such as islands), self-contained entities (airports, seaports, industrial complexes, etc), or distributed entities (hydrogen highways, etc). In a Hydrogen Community, Hydrogen plays a significant role in the community as an energy vector.

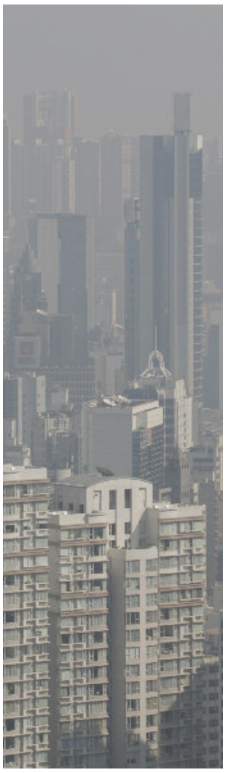
A Hydrogen Community may evolve out of, or in parallel to, large demonstration projects. Possible cluster activities within the Community can include fundamental or applied research and demonstration projects that feed new technology into the Community.

Communities have the opportunity to help address the main challenges discussed above.

- **Consumer uptake** – Acting as consumers, encouraging demand, valuing the "public good" benefits of hydrogen energy.
- **Development of technology and industry** – Assisting RTD, establishing industrial clusters
- **Hydrogen Supply** – Exploiting local energy resources through hydrogen

Here are some indicative examples of how this might work.

- A busy city might embark on a hydrogen bus demonstration program, reducing local air pollution, positively branding the city, and providing a real-world situation to test and advertise hydrogen buses. Eventually it might convert its entire bus fleet to hydrogen, which would allow suppliers to ramp up manufacturing capacity (in



Smog and pollution in cities can be eased by using zero emission hydrogen vehicles alliance with other cities perhaps, to get the advantage of bulk purchasing).

- A region with a strong technology or manufacturing base, but with declining industries, could regenerate itself by becoming a centre for hydrogen technology. This could create jobs and bring money into the local economy. In the longer term, it could allow the region to establish itself as a major innovator/manufacturer of hydrogen technologies. As a technology that is new, and is expected to become very significant, hydrogen represents an attractive option for regional growth.
- A remote community with an abundance of locally generated renewable energy sources but little infrastructure to use it or sell it, could build a hydrogen production facility. This way the island could reach energy independence, or even become an energy exporter, without having to build, for example, electricity transmission lines.

Windy islands can use hydrogen to help harness its energy resource. This is the Norwegian island Utsira (see 3.4) Photo: Hydro

3.2 Why are hydrogen communities important?

Section 2.1 identified some of the main barriers to the hydrogen economy. Community-level action can provide a major part of the solution to these barriers. In particular:

Communities can be early adopters

For the commercialisation of hydrogen and fuel cells, it is essential that the immature technologies are able to be demonstrated in real world conditions. This is also crucial from the point of view of the technologies gaining public acceptance. Purchasing demonstration vehicles for example, could be undertaken on a number of scales – it could be national or on a private individual basis. The concept of a 'community as an end user is very promising.

Communities offer a good end user:

- Building infrastructure (a filling station say, or a supply chain) is more easily done by public bodies. Often the scope of operation of hydrogen technologies will initially be localised to a region or city, it makes sense for this to be the political unit responsible for infrastructure issues.
- Communities can think long term; they are more likely to consider wider social and environment issues than individuals.
- They are generally in charge of certain 'captive fleets' of vehicles (such as buses, police cars), or public projects (see section 2).
- Community fleets are in the public eye and able to be publicised through the established channels for public advertising.
- In cities, hydrogen offers the additional attraction of cleaner air.
- Special needs might make them a niche market – they may require remote power, or may find hydrogen to be the best way of selling energy

Communities can support hydrogen and fuel cell industries

Hydrogen and fuel cells are novel, developing technologies and many regions are interested in claiming some value in some area of the technology supply chain – from research to manufacturing and distribution

Communities are trying to develop 'clusters' where a number of hydrogen technology-related organisations are geographically localised, and are able to benefit from being close to one another. This is seen as a way to promote regional innovation, and contributes to the development of hydrogen technologies.

Communities can part finance projects

There are a number of motives, including public good and regional economic development, which form the basis for communities contributing to some of the costs of hydrogen and fuel cell development, and demonstration projects. A broad range of instruments are used to provide community part financing. These will be analysed in the subsequent volumes of this handbook. The objective of this analysis will be to identify:

- The full range of instruments used.
- The stated policy drivers.
- The funding sources that are used to meet these drivers.
- Understand if they differ throughout Europe.

Communities can help to establish a hydrogen supply

Remote communities who are energy rich (windy islands for example) may have difficulty exporting their energy as electricity. Hydrogen offers another way to export the energy – providing local benefit and leading to establishment of hydrogen supply chains. Regions with a traditional energy supply (such as gas power stations) can also become hydrogen producers. Low cost gasification processes are seen as one of the promising ways of producing hydrogen in the near term.

3.3 What are the benefits for the community?

Depending on its specific circumstances, there are a number of reasons why communities could be stakeholders in hydrogen projects. The most often-cited ones are:

Innovation and growth benefits – Expertise in cutting-edge technologies like H2&FCs might improve the competitiveness of local firms, or generate new high value organisations. New clusters combining competences on energy, transportation and services may emerge. Aside from business and economic growth the community as a whole would benefit via learning processes and strengthened cooperation between different actors in the field of high-technology (universities, research institutes, public actors etc.). The community would acquire eco-innovative credentials which later on could attract new investments and funding.

New business opportunities – Some towns, cities or regions have a strong economic dependency on industries that are now in clear decline. Engaging with a growth industry like hydrogen can offer a chance to re-invigorate a local economy. This could mean manufacturing hydrogen technologies, producing hydrogen from a local energy source, or expanding research facilities.

Apart from providing platforms for new industries in hydrogen and fuel cell technologies, these technologies could affect existing industries. In the first place they could replace older technologies such as batteries and small combustion engines.

Services are also likely to be needed to facilitate the introduction of a hydrogen economy. These include specialised financial services, insurance, logistics, shipping, truck transportation, retail, surveillance and overhaul and maintenance. Furthermore, hydrogen and fuel cell technologies can be the technological platform for developing totally new services such as energy storage. Some regions might prefer to promote such service industries instead of traditional industrial manufacturing.

Publicity, prestige and 'branding' – With a growing international awareness of climate change, cities are eager to improve their profile by establishing their green credentials. For example, London's bid for the 2012 Olympic Games included displaying its fuel cell buses.

London's CUTE buses were part of its successful 2012 Olympic bid. Photo: Ballard

Clean local air – An indisputable benefit of hydrogen vehicles is their lack of toxic pollutants. In congested, polluted cities this can be a strong driver.

Concern for the global environment – People are beginning to accept the concept that individuals, governments and businesses have a responsibility to look after interests other than just their own, as is evidenced, for example, in the rise of 'corporate responsibility'. Communities may have a genuine desire to promote the long-term humanitarian and environmental good.

Usefulness of H2&FC technology – a community's particular circumstances may make it one of the 'niche consumers' described above, where it becomes economically sensible to make use of what H2&FC has to offer.

3.4 Examples of communities

Although communities may choose to become interested in hydrogen for any reason, the three major categories of hydrogen communities to date are cities, regions, and islands/remote regions.

Cities

Large cities like London, Berlin and Los Angeles have heavily promoted hydrogen-powered urban transport. The reasons have generally been concern for the global environment, local environment and prestige.

- **Berlin** formed the Clean Energy Partnership (CEP) in 2002, an alliance of government and industry aiming to prove the reliability of hydrogen in transport applications and to determine levels of public acceptance. The city now has 17 hydrogen cars, and two filling stations.[22]

A filling station in Berlin. Photo: www.H2stations.org

[22] www.cep-berlin.de

◗ **California** formed a similar public-private partnership, the 'California Hydrogen Highway Network', whose aim is 'to support and catalyse a rapid transition to a clean, hydrogen transportation economy in California' in order to reduce dependence on oil, curb emissions, improve air quality and help grow the Californian economy. There are now 24 hydrogen fuelling stations, 128 hydrogen vehicles and 8 transit buses[23].

California is leading the world in hydrogen filling infrastructure. The focus in California is on private vehicles rather than buses. Photo: Honda

◗ **London.** Since April 2002, the London Hydrogen Partnership (LHP) has been working towards a hydrogen economy for London and the UK. The aim is to improve air quality, reduce greenhouse gases and noise, improving energy security and support London's green economy. London took part in the 'Clean Urban Transport for Europe' ('CUTE') project with 3 hydrogen buses. It is now procuring 11 hydrogen buses and 70 public-sector cars, vans and motorbikes[24].

[23] www.hydrogenhighway.ca.gov
[24] www.lhp.org.uk

Examples of regions

- **North Rhine Westphalia**, Germany, has spent tens of millions of Euros funding 60 fuel cell and hydrogen projects since 2000. The region aims to position itself as an 'internationally recognized location for the fuel cell and hydrogen technology'[25].

- **Tees Valley region.** Steered by 'Renew Tees Valley Ltd', the Tees valley region is aiming to become a centre for renewable energy in the UK. Hydrogen production and storage forms a part of this strategy. The region currently has 75000 tonnes/year of hydrogen generating capacity (for use in industry). It aims to develop coal-based hydrogen production with carbon capture and storage, and wind-based hydrogen production.[26]

Examples of islands/remote areas

- **Utsira** is a small Norwegian island, conducting a demonstration project into using hydrogen as a way of harnessing intermittent power output from wind turbines. The island, which has a number of wind turbines, uses an electrolyser to produce hydrogen when electricity supply outstrips demand, and uses a fuel cell to recover energy from the hydrogen at other times.[27]

- **H2 Seed**, in the Outer Hebrides (UK), will cover the whole value chain of hydrogen technologies: hydrogen production from biogas, hydrogen storage, a hydrogen filling station and hydrogen use in both stationary and transport applications. The project consists of using an electrolyser to absorb the excess electricity generated from an existing biogas generator.[28]

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25 www.innovation.nrw.de
26 www.renewteesvalley.co.uk
27 www.hydro.com
28 www.cne-siar.gov.uk

Summary: Hydrogen communities

The term 'Hydrogen Community' refers to early adopters of H2&FC technology, who have the potential to become large scale adopters. Cities, regions, islands, and industrial zones are examples of potential hydrogen communities.

Communities are important for the commercialisation of H2&FC technologies:

- Providing willing consumers
- Developing H2 infrastructure
- Developing production of H2

Communities may be interested in adopting H2&FC technology, as it can offer:

- Innovation and growth
- Publicity, prestige, branding
- A solution to local air quality
- Reduced CO_2 emissions
- Practical advantages over existing technologies

4. Next steps

The purpose of this document has been to set out briefly, and in simple terms, what the vision for a hydrogen based energy economy might be, what the main challenges to this vision are, and what role communities – amongst a range of stakeholders – will have in attaining this vision. Achieving this vision will require significant and sustained effort, and not every community will be in a position to commit to this.

However, community stakeholder involvement is vital if the vision is to be realised. The purpose of the two remaining volumes in this series, is to add detail to the outlines provided above, helping the reader develop a sensible, informed strategy for engagement in hydrogen energy, and to implement successful projects that benefit all stakeholders.

5. Glossary and list of abbreviations

Roads2HyCom
www.roads2hy.com

BEV Battery electric vehicle

Biofuel Hydrocarbons produced from biological sources in the active carbon cycle

Carbon-free energy source an energy source which doesn't involve emitting CO2 into the atmosphere

CCS Carbon capture and storage, a (yet unproven) process to capture CO2 from a concentrated source and store it (in, e.g. depleted fossil fuel reservoirs) to prevent it contributing to global warming

CCTV Closed circuit television camera

CHP 'Combined heat and power'. Using a fuel to generate electricity while putting the inevitable waste heat to use

CO_2 Carbon dioxide (a greenhouse gas)

CUTE 'Clean urban transport for Europe' a hydrogen bus project involving nine European cities from 2001 to 2006

DMFC Direct methanol fuel cell

FC Fuel cell

H_2 Hydrogen

H2&FC Hydrogen and fuel cells

H2ICE Hydrogen internal combustion engine

HFP "Hydrogen and Fuel Cell Technology Platform", a EU technology platform aiming to accelerate the development and deployment of hydrogen and fuel cell technology in Europe

Hydrogen fuel initiative A heavily funded US government initiative intended to "develop hydrogen, fuel cell, and infrastructure technologies needed to make it practical and cost-effective for large numbers of Americans to choose to use fuel cell vehicles by 2020"

ICE internal combustion engine

PEM fuel cell Proton Exchange fuel cell

RTD research and technical development

SME Small or medium enterprise

UPS Uninterruptible power supply (e.g. grid electricity combined with a backup generator)

US DOE United States Department of Energy