Hydrogen: An Energy Vector for the Future?

Used today in various industrial sectors including refining and chemicals, hydrogen is often presented as a promising energy vector for the transport sector. However, its balance sheet presents disadvantages as well as advantages. For instance, some of its physical characteristics are not very well adapted to transport use and hydrogen does not exist in pure form. Hydrogen technologies can offer satisfactory environmental performance in certain respects, but remain handicapped by costs too high for large-scale development. A great deal of research will be required to develop mass transport application.

Hydrogen Today

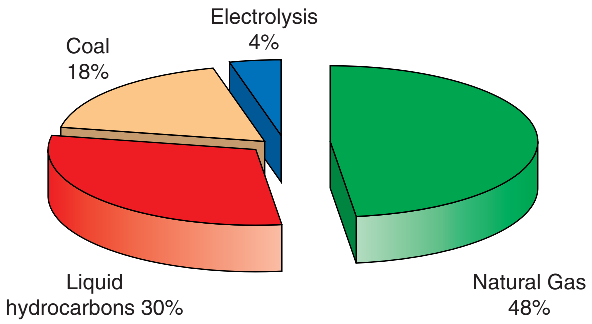
Production

Hydrogen is one of the most plentiful natural elements on earth. Unlike hydrocarbons, it is not found in accumulations that lend themselves to direct extraction. In Nature, hydrogen is nearly always found in combination with other elements (oxygen in water, carbon in natural gas).

To produce hydrogen, one needs an hydrogen source (natural gas, water, etc.) and an energy source. They can be the same, such as when hydrogen is produced from natural gas. They can also be different, as illustrated by the production of hydrogen by electrolysis of water. In the latter case, electricity is the energy source and water is the hydrogen source.

Currently, nearly 96% of all hydrogen production uses fossil fuels, with natural gas being by far the most frequently used energy (cf. Figure 1). The steam reforming of natural gas is the most used process.

Fig. 1 Key energy sources currently used in world hydrogen



It is possible to use heavier hydrocarbons, such as coal, in association with partial oxidation processes, but the capital investment required is higher for this solution than for the steam reforming.

Most hydrogen is currently produced in refineries as a co-product of catalytic reforming, an important stage in the formulation of gasoline (octane number).

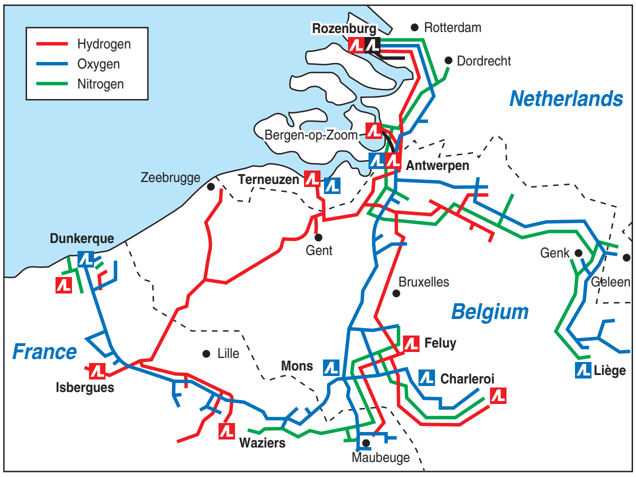
The implementation of electrolytic hydrogen technology, which costs significantly more, remains marginal.

Transmission and Distribution

Hydrogen is a very light gas, which is a handicap for storage and transmission. It is usually delivered compressed in cylinders or pipes, or else as a liquid (–253°C).

The most commonly used system of transmission is the pipeline, with the world network totaling over 2,500 km. Most pipe systems are located in Europe (1,500 km) and the United States (900 km). One of the largest network operators is Air Liquide (cf. Figure 2).

Fig. 2 One example of a hydrogen transmission system: the Air Liquide network in Northern Europe



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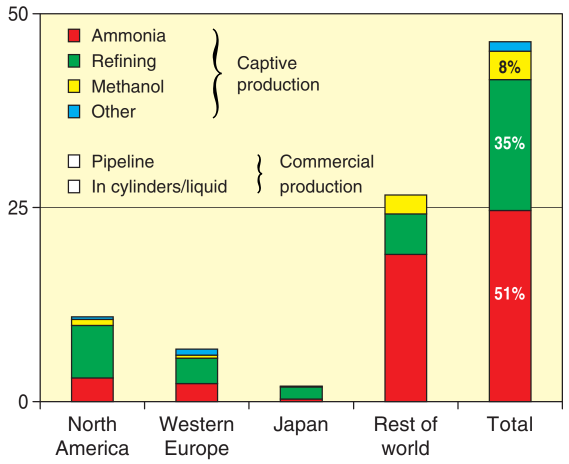
Uses

For the most part, hydrogen is a gas used in industry to produce ammonia, refine petroleum products and methanol (cf. Figure 3). The industrial facilities often build their own hydrogen production unit nearby to ensure its supply. Thus, the hydrogen market today is almost exclusively a "captive" market.

Fig. 3 Key hydrogen markets (in millions of tons)



World hydrogen consumption stands at about 50 million tons, which represents nearly 140 million toe, less than 2% of world energy consumption.

The significance of these figures transcends their absolute value. They show that if hydrogen is to become the main energy vector for the planet colossal capital sums will need to be invested in production and distribution.

Is Hydrogen a Likely Energy Vector for the Future?

Mostly used for chemical applications, hydrogen has taken center stage on the energy scene. Used in association with fuel cells, it could replace the conventional duo formed by hydrocarbons and combustion systems (engines, turbines, etc.).

The benefits of such a breakthrough would be to:

- Decrease pollution in urban areas;
- Sharply reduce greenhouse gas (GHG) emissions;
- Increase the energy independence of oil consuming countries.

But hydrogen cannot be compared directly with fossil energies, because it is only an energy vector and not an energy source. As such, it simply makes it possible to transmit a given quantity of energy from the place of production to the place of consumption.

Hydrogen is being considered as a potential energy vector in two sectors, transport and electricity generation. The latter could be accompanied by the production of heat. However, the only sector covered in this report is road transport.

In the electricity generation section, the first application of the hydrogen system + fuel cell may be to replace batteries in computers, cell phones and other mobile electronic devices to boost their power reserve; however, these applications should not represent very large quantities of hydrogen. Furthermore, most of the development underway rely on fuel cells supplied directly by methanol.

In the longer term, the decentralized production of electricity, with or without heating, for single- or multiple-family housing or industrial parks (small and medium sized enterprises, light industry, etc.) could also be a significant outlet, given the excellent energy efficiency of the fuel cell used (supplied with hydrogen or directly with natural gas). However, many technologies are competing in this sector, among them wind power and micro-turbines.

In the transport sector, hydrogen has one advantage over conventional motor fuels in that it combines readily with oxygen in the air to yield energy and, under the most favorable conditions, only one by-product: water.

There is little advantage to using hydrogen in an internal combustion engine from the perspective of energy consumption or polluting emissions (nitrogen oxide emissions continue to be a problem). Things look different, however, when considering hydrogen fuel cell applications. As a matter of fact, the future of hydrogen in the transport sector appears to be closely related to that of the fuel cells.

Launched in the early 1990s by the Canadian company Ballard, relayed by Daimler Chrysler, Proton Exchange Membrane Fuel Cells (PEMFCs) have received extensive media coverage. Based on the reverse principle of electrolysis of water, these membrane systems produce electrical energy when supplied with hydrogen and air. This conversion takes place without any other emission besides water vapor. The electricity generated is used to drive an electric motor. In other words, it represents a solution equivalent to the battery-powered electric vehicle as a "zero emission" automobile.

Here, we might note that the relative failure of electric cars as a credible solution to urban pollution in the 1990s was partially responsible for reviving the fuel cells and bringing it into the spotlight. While offering the same emissions advantage as its battery-powered competitor, the fuel cells vehicle is said to be free of specific problems associated with all-electric applications (long recharge times, excessively short ranges).

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The most important barriers to the development of these alternatives today, besides cost, are the absence of production infrastructure and distribution networks, as well as the difficulties encountered in developing on-board hydrogen storage technologies.

Two storage alternatives are currently under review:
- the storage of compressed hydrogen at 350 or 700 bar;
- the storage of liquefied hydrogen (–253°C).

Even if most automobile manufacturers are leaning towards high-pressure storage for their demonstration operations, neither of these solutions is fully satisfactory. Using compressed hydrogen storage limits vehicle range. Difficult for the general public to implement, storage in liquid form is also energy-intensive: at best, the operation consumes 35% of the energy available in the tank (not counting the energy required to produce electricity for the liquefaction unit).

Challenging the "on-board reformer" Solution

Seeking to get around the constraints associated with hydrogen storage/distribution, several research teams set out to adapt fuel cell systems to run on liquid motor fuels (e.g. methanol or gasoline) that would be easier to store on board. They did this by associating to a fuel cells an hydrogen production unit (reformer) compatible with these motor fuels.

Methanol was the easiest to implement. Hydrogen is generated from this alcohol at a temperature of about 300°C. But methanol is not a widely distributed motor fuel and its toxicity is problematical for large-scale application. Other research programs then undertook to explore the development of small "reformers" using petroleum motor fuels. These projects have encountered major development difficulties: the start-up time is still long (several minutes); energy consumption is high at start-up; the management of transient operating conditions continues to be difficult; and the problems related to the emission of CO_2 and pollutants (NOx, etc.) have not been solved.

In 2004, research programs covering these areas and financed by the US Department of Energy will come to a turning point. They may even be stopped. Last summer, General Motors announced that it was abandoning its research activities in this field.

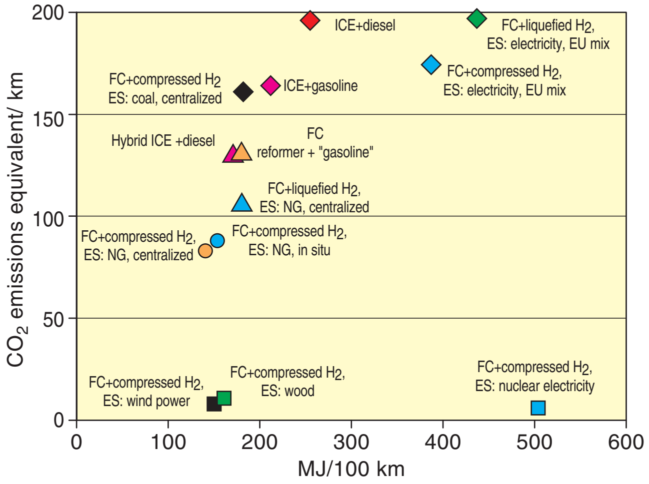
Environmental Impact

To evaluate potential hydrogen technology benefits in the absolute with reference to energy efficiency, cost and environmental impact, a global balance sheet must be established, covering every step of the energetic patway from production to end use, including transmission and storage.

For instance, let's consider the production of hydrogen from electricity and water (electrolysis). Only a portion of the initial energy used to produce the electricity ends up in hydrogen form. In other words, the benefits of the electrolytic technology vary, depending on how the electricity is initially produced.

Several studies aimed for greater accuracy in pinpointing the advantages of hydrogen solutions with respect to GHG emissions and energy consumption has been done. Figure 4 contains the principal results of a European study carried out by three partners: JRC (the Joint Research Center of the European Commission), CONCAWE (the European association dealing with environmental issues, for oil companies) and EUCAR (the R&D arm of the European Automakers association). The graph gives the "well to wheel" performance per 100 km and per km (energy consumption and CO_2 emissions equivalent respectively) for various technologies.

Fig. 4 "Well to wheel" results for key hydrogen technologies



ICE: internal combustion engine; FC: fuel cell; ES: energy source; NG: Natural Gas.

Source: "Well-to-wheels analysis of future automotive fuels and powertrains in the European context", EUCAR, JRC, CONCAWE, November 2003

Several significant results emerge from this analysis:
- The fuel cell vehicle (FCV) running on compressed hydrogen generated from wind power(1) or biomass(2) obtains the best results in terms of GHG emissions. For energy consumption, these alternatives are among the best-performing solutions even if the gains remain low, especially compared to hybrid vehicles (equipped with both an internal combustion engine and an electric motor).

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(1) Electrolysis of water using wind-generated electricity.

(2) Hydrogen production based on the gasification of wood.

Both of these options present the same disadvantage: the potential volume of hydrogen production remains limited.

- The fuel cell vehicle powered by hydrogen ex-electricity (via electrolysis) presents contrasting results. If the origin of the electricity is nuclear, the result is excellent for GHG emissions, but much more mediocre for overall energy consumption. If the electricity originates from a European mix of current production modes (average breakdown), then there is no advantage with respect for GHG emissions or energy consumption. This conclusion could change only if the electricity production systems in Europe underwent substantial modification, with as for example the large-scale development of renewable energies or the wide dissemination of CO_2 capture and geological storage technologies.
- The balance sheet for FCVs using natural gas as the energy source is good: they reduce energy consumption by 30% and GHG emissions by nearly 50% compared to the reference diesel. Compared to the hybrid system, the gains are obviously much lower: the reduction amounts to 35% for GHG emissions and about 15% for energy consumption. In addition, we might note the adverse effect of liquefaction, which penalizes this solution by nearly 30% compared to the “compressed hydrogen” technology, both for energy consumption and GHG emissions. Moreover, the “greenhouse effect” balance sheet for these NG-based options could be improved if the capture of the CO_2 generated and its storage in geological reservoirs were included.
- FCVs with an on-board reformer offer very few advantages over ICE applications.
- Generating hydrogen from coal presents very few advantages compared to the reference gasoline or diesel. To be considered as a long-term solution, these applications must include the capture of the CO_2 generated and its storage in geological reservoirs.

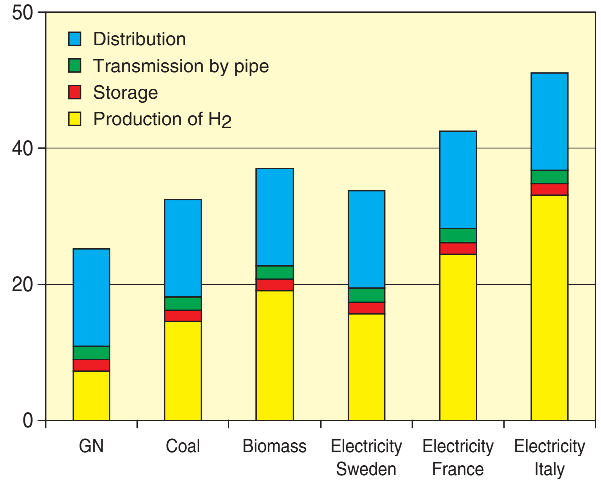
Economic Aspects

Although specific hydrogen FC applications represent a net environmental gain in terms of GHG emissions over conventional solutions, these applications are by far the most costly (cf. Figure 5).

From a strictly economic perspective, it is hard to choose between the on-board storage solutions (compressed or liquefied hydrogen). They obtain comparable results: for the storage of liquid hydrogen, energy consumption is high but costs are lower than for storage at high pressures (350 or 700 bar). Since automakers have primarily geared their demonstrators to the latter, we will only examine this option.

Figure 5 indicates that, for compressed hydrogen technologies, the “well to fuel tank” cost ranges from 20 to €50/GJ. The most economical solution uses natural gas as the raw material; the cost of applications based on coal and biomass (in this case, wood) is 30% and 50% higher, respectively. The highest costs (€35-50/GJ) are associated with the electrolysis of water. Of course, this ranking could change in the event of tension affecting natural gas prices. By comparison, conventional oil-based motor fuels obtain a “well to fuel tank” price of €8/GJ, given a crude price of $25/bbl.

Fig. 5 Estimated “well to fuel tank” costs of compressed hydrogen technologies, as a function of the raw material price in €/GJ. (In the case of electrolysis, the price of electricity indicated dates to July 2002)



In the future, gains should be possible all along the hydrogen supply chain, especially at the distribution stage, which is a major expense item (unlike for conventional motor fuels). Research undertaken in the United States shows that non-negligible gains could be made by developing small hydrogen production units located at service stations. This would also, at least initially, obviate the need for heavy investment in a dense hydrogen pipe network. The US Department of Energy has set an objective of $12.50/GJ by 2010 for this type of system.

But the cost of hydrogen “from well to fuel tank” is not all. It must be determined whether vehicle consumption can compensate for the elevated cost of hydrogen. Considering the high level of uncertainty surrounding the evaluation of fuel cell costs and long-term trend forecasts, a best-case assumption is made, i.e. that the cost of purchasing and maintaining a fuel-cell vehicle is the same as for a conventional vehicle. Table 1 gives the cost per 100 km.

This analysis shows that, for hydrogen FC applications, the cost per 100 km is higher (by 15% to over 100%) than for conventional solutions and modified versions thereof.

This conclusion is based on the best-case scenario, whereby the cost of FC and ICE applications is the same. But this does not reflect the existing situation, far from it. Today, the cost of fuel cells manufactured in a limited series exceeds €3,000/kW, compared to €30-50/kW for mass-produced conventional ICEs. But even assuming that fuel cells could be manufactured on a large scale (several hundreds of thousands), the ICE would still be more advantageous, because it would still cost 100-200 €kW(3) to manufacture fuel cells, which is three to four times more than a conventional motor (and this does not account for the electrical motors needed to power the vehicle).

Table 1
Hydrogen applications: cost per kilometer driven

	Consumption (MJ/100 km)	Motor fuel cost (€/GJ)	Cost (€/100 km)
ICE + gasoline	224	8	1.8
ICE + diesel	184	8	1.5
Hybrid ICE + diesel	141	8	1.1
FC + compressed H_2, energy: NG	84	25	2.1
FC + compressed H_2, energy: coal	84	32	2.7
FC + compressed H_2, energy: biomass	84	37	3.1
FC + compressed H_2, energy: electricity (France)	84	42	3.5

Source: IFP based on “Well-to-wheels analysis of future automotive fuels and powertrains in the European context”, EUCAR, JRC, CONCAWE, November 2003

According to Directed Technology, the most expensive fuel cells components are the membrane and the platinum (Pt), i.e. the catalyst that makes this type of energy conversion system work. Between 50 and 100 grams of platinum are needed to make a membrane technology fuel cell operate at low temperature and under satisfactory conditions with respect to durability, efficiency and performance. Many think that this range of values is much too high. For instance, if fuel cells were to be generalized on the French market (about 2 million vehicles a year), this alone would generate demand of 100 to 200 tons/year of platinum, close to the world’s annual consumption of this precious metal.

Beyond the question of the platinum availability, if fuel cells were to become an unregulated success in the transport sector, especially in the short term (2010), the result could be tensions on the market for this metal, whose production is highly concentrated: South Africa is responsible for nearly 75% of world output, followed by Russia, whose market share amounts to about 15%. If the fuel cell is to become the energy conversion system of the future, its platinum content will have to be reduced; a good objective would be to reduce it by a factor of 10. In addition, work would have to start immediately on planning and implementing appropriate recycling processes.

But the fuel cell itself is not all. On-board hydrogen storage is still a high-cost factor. The most favorable costs to be announced are in the vicinity of €1,000/kg(4) of stored hydrogen. Some sources mention values that are four times as high. But it would take 4 to 5 kg of hydrogen to ensure a satisfactory range (400 to 500 km) to a vehicle. In other words, it would cost something like €4,000-5,000 to store hydrogen on board a HFCV. In comparison, it only costs €125 for a 40-liter tank of a conventional vehicle.

Mass production would reduce the tank cost, but only in the range of €200-500 per kg of hydrogen, says the DOE, which observes that major progress is required in this area. Thus, even if the technical aspects of on-board hydrogen storage have been mastered, a great deal of research is still needed, especially to bring the cost down. In this field, the DOE has set very ambitious targets: by 2015, the cost of on-board hydrogen storage should be about €66/kg.

Conclusion

For nearly a century, oil and gas technologies have dominated the transport sector and enjoyed the benefits of scale effects, and of on-going technological improvement and optimization. Given this monopoly situation, it is difficult to develop alternative technologies, which are much less mature. This is particularly true of the hydrogen technologies, which offer undeniable environmental benefits but are heavily penalized by excessive costs.

Under these circumstances, the use of hydrogen in the transport sector should remain relatively limited in the short run. The production of electricity (stationary fuel cell) and the storage of energy for mobile equipment (cell phones, laptops, etc.) should be the first applications of this type of technologies to emerge in the years to come.

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(3) Source: Department of Energy and Directed Technology, Inc., "DFMA Cost Estimates of Fuel-Cell/Reformer Systems at Low/Medium/High Production Rates", Brian D. James, Greg D. Ariff, Reed C. Kuhn, Future Car Congress 2002, June 4, 2002.

(4) Source: S. Rau, Dynetek, Deutscher Wasserstoff Energietag 2002, Essen, November 13, 2002.

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In the 21st century, transport systems will have to meet major challenges. It is conceivable that, considering its strong environmental characteristics (certain solutions are especially promising for GHG emissions) and the need to diversify energy sources, hydrogen could eventually play a key role. Nevertheless, it will not provide the only answer to the problem of the transport energy of the future. Such applications, which still need substantial research to reduce the cost, continue to be possibilities among others. Interest in these applications would decline sharply, for instance, if a breakthrough in electricity storage technology is to be found.

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