Parliamentary Office of Science and Technology

postnote

October 2002 Number 186

PROSPECTS FOR A HYDROGEN ECONOMY

There is increasing interest in the use of hydrogen as the basis for an energy system with low carbon dioxide emissions. Hydrogen could be used as a fuel for road transport, distributed heat and power generation, and for energy storage. This has led to discussion of a 'hydrogen economy' – widespread and diverse production and use of hydrogen. This briefing outlines the basis of interest in hydrogen and examines technologies for its production, handling and use. Policy issues surrounding technology and market development of hydrogen are also considered.

Background

Hydrogen is a commonly used industrial gas, which is produced for use in the chemical and other industries, and in refineries for fuel processing. The idea of using hydrogen for energy is not new. It has been used both industrially, domestically (town gas, used in the UK until the 1950s, comprised 50% hydrogen) and as rocket fuel. Interest in hydrogen as a vehicle fuel dates back to the 1800s, but heightened during the oil crises of the 1970s and with technological advances in the 1980s.

Current interest in hydrogen stems from environmental and energy policy concerns including global climate change, local air quality, noise and security of energy supply, together with breakthroughs in fuel cell technology (see page 2). Hydrogen can provide power with minimal air pollutant and zero carbon dioxide emissions at the point of use. For instance the Energy Saving Trust (EST)[1] has referred to the use of hydrogen in fuel cell vehicles as *'the most promising option for zero carbon road transport'*. Also, because there are many possible production routes and uses for hydrogen, it could enhance security of energy supplies.

An energy carrier

Unlike oil, gas and coal, hydrogen does not exist in large quantities in nature in a useful form. Like electricity, it is an 'energy carrier', which must be produced using energy from another source. Hydrogen has an advantage over electricity, however, in that it can be stored more easily. This allows its use as a vehicle fuel, for electricity and heat generation and as a storage medium for electricity generated from intermittent renewable sources.

Production

Hydrogen can be produced from a wide range of sources by a number of different routes (see box on page 2). These include:

- from hydrocarbons such as coal, oil and natural gas
- from biomass and wastes
- by electrolysis of water, using electricity produced from fossil fuels, nuclear, or renewable energy.

While hydrogen has minimal environmental effects where it is used, there may be impacts associated with its production. For instance, production of hydrogen from fossil fuels leads to carbon dioxide (CO_2) emissions, the principal cause of global climate change, and also to resource depletion. The overall CO_2 emissions may be lower than if conventional technologies (such as a petrol internal combustion engine) were used[2], and there are also lower emissions of local air pollutants.

It may be possible to capture and store the CO_2 produced in biological or geological sinks, such as forests or underground reservoirs. However, CO_2 emissions would be negligible if hydrogen were produced by electrolysis using nuclear energy, or renewable energy sources.

Hydrogen production technologies

- **Steam reforming** – this is the most common method Here, a hydrocarbon gas, often methane, is mixed with steam at a high temperature and pressure, in the presence of a catalyst, to produce hydrogen and carbon dioxide. The hydrocarbon gas can also be produced from biomass products by heating to high temperatures with little oxygen present (gasification).
- **Partial oxidation** – hydrogen can be produced by reacting heavier hydrocarbons such as oil, coal, and some biomass products, with oxygen and steam. This is a commercially available process and is of interest for countries with large coal resources.
- **Electrolysis** – an electric current is used to split water into hydrogen and oxygen. Alkaline electrolysis, the most common form, has been used industrially for over 80 years, but is now used on a large scale only where cheap electricity (e.g. from hydroelectric schemes) is available. There is significant interest in very small scale (e.g. domestic) electrolysers.
- **Biological methods** – several types of algae and bacteria can produce hydrogen by photosynthesis or by fermentation. Some methods may have commercial potential, but most are at the R&D stage.
- **More prospective technologies** – these include photoelectrolysis, the use of a solar cell that splits water directly, without use of electricity.

Hydrogen storage technologies

Compressed gas

Compressed hydrogen is generally stored in cylindrical tanks at pressures of around 200 bar (around 200 times atmospheric pressure). Low pressure storage, either in tanks or underground, can be used for very large volumes. On-board storage systems for vehicles have been demonstrated at pressures of up to 700 bar, using tanks made from composite materials. Compressed storage is the cheapest method, however storage density is low. Higher storage pressures increase the storage density, but also the costs of the system and the safety requirements.

Liquid hydrogen

Hydrogen can be stored as a liquid at -253 °C in insulated pressure vessels. The liquefaction process itself is energy intensive, but liquid hydrogen has a very high energy density, over three times that of petrol. Highly insulated tanks are needed to minimise evaporation, and these can make on-board liquid storage relatively bulky and heavy.

Chemical storage

Metal hydrides are metal alloys that can store hydrogen within their chemical structure. Hydrogen is bonded to the surface of small particles of the material and is only released when heat is supplied. Hydrogen can also be stored within carbon materials and in the form of liquid hydrides.

Storage and distribution

Hydrogen contains more energy on a weight for weight basis than any other substance. However it is also the lightest chemical element, and so has very low energy per unit volume. For example, at 200 times atmospheric pressure, one litre of natural gas contains 5 times more energy than a litre of gaseous hydrogen. The box opposite outlines a number of methods for storing a useful amount of energy in a small volume, e.g. in a vehicle. The most suitable storage method depends on factors including the volume to be stored, the storage time, space restrictions and end-use requirements. For example, in buses, compressed hydrogen can be stored in tanks on the roof.

Hydrogen stored by any of the methods mentioned in the box opposite can be transported by road, rail or sea. Compressed hydrogen can be transported via dedicated pipelines. There has also been discussion of mixing hydrogen into natural gas in the pipeline network.

To refuel vehicles with hydrogen, new dispensing technology will be required, to which consumers will need to adapt. Both gaseous and liquid hydrogen refuelling are sufficiently developed that refuelling could take place in a few minutes, with no leakage. The world's first public liquid hydrogen filling station uses a robotic dispenser, without the driver having to leave the car.

Use

Hydrogen can be used to provide electricity and heat either through use in a fuel cell (see box on page 3) or through combustion. A fuel cell is a device similar to a continuously recharged battery, which generates electricity by combining hydrogen with oxygen from the air. The only byproduct is water. Hydrogen fuel cells are silent, have no moving parts and produce no air pollutants.

Fuel cells can be used to provide electricity on a small scale for homes and businesses, and can be included in combined heat and power (CHP) schemes. Stationary systems have fewer constraints on storage space and system weight than vehicle systems and require less infrastructure development.

For transport, hydrogen can be burned in an internal combustion engine (ICE), in the same way as petrol or natural gas. BMW currently uses this technology to power a fleet of demonstration vehicles. This produces water as the main byproduct, but also small amounts of oxides of nitrogen, an air pollutant. Dual fuel ICE vehicles have been produced to run on both hydrogen and petrol.

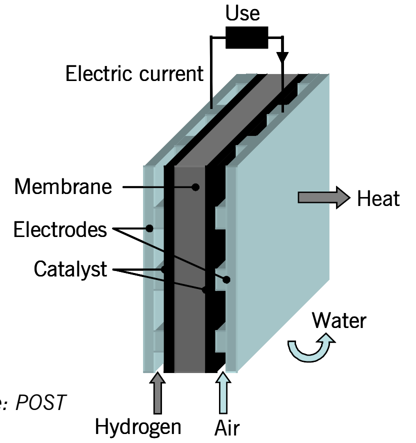
Hydrogen can also be used to power fuel cell vehicles. Using hydrogen in fuel cells is more efficient than combustion, with efficiencies of up to 45%, compared with up to 25% for a dual fuel ICE. Therefore a fuel cell car could travel over twice as far as a dual fuel ICE car on the same amount of hydrogen. Hydrogen ICE and fuel cell cars are currently at the demonstration stage (see box on page 3). Eight major car manufacturers are planning to introduce fuel cell cars by 2004-5. However, there are still issues of cost, reliability and lifetime, such that fuel cell cars are not expected to reach mass markets until after 2015. As there is considerable experience with ICEs, some consider that they may be important in the interim.

Safety

Like most other fuels, hydrogen is flammable, and potentially hazardous if handled incorrectly. It is no more hazardous than other fuels, but has different properties which must be understood in order to store, transport and use it safely (see box on page 3).

Fuel cells

A fuel cell combines hydrogen with oxygen from the air in a chemical reaction, producing electricity. One type of fuel cell for transport, (the *proton exchange membrane* fuel cell) consists of two electrodes, separated by a membrane. Many fuel cells are connected to provide the power needed.



Source: POST

Current projects

Projects demonstrating the use of hydrogen as a vehicle fuel are in operation worldwide. For example, the **Munich Airport Hydrogen Project**, opened in 1999, supplies hydrogen to cars and airport buses. The **California Fuel Cell Partnership**, also established in 1999, comprises 28 government and industry groups, testing and promoting fuel cell vehicles. The EU **Clean Urban Transport for Europe** project will provide fuel cell buses in 10 European cities in 2003, including 3 in London. In the UK, projects include a stationary hydrogen fuel cell used in Woking to provide heat, power, cooling and clean water for a leisure complex, with hydrogen generated by reforming of natural gas. The **Urban Solar Hydrogen Economy Realisation Project** in Cambridge will use electricity from a photovoltaic system to produce hydrogen for buses. **Iceland** intends to become the world's first hydrogen economy, with hydrogen produced from renewable electricity sources (geothermal and hydroelectricity).

Issues

Visions and scenarios

There is an emerging consensus that hydrogen could have a key role in energy systems. The Government's *Powering Future Vehicles* strategy states that *"the ultimate low-carbon destination looks likely to be fuel cells using renewably produced hydrogen"*. A hydrogen economy would include generation of hydrogen from diverse and distributed sources, used to power transport, homes and industry. Generation would be possible at a range of scales, from large centralised plants using technologies such as steam reforming, to forecourt or even domestic electrolysis and reforming units. Hydrogen could be distributed from the larger sites by road, pipeline, or sold in solid storage units.

The large number of possible production routes gives several benefits. Numerous organisations and even individuals could become producers of hydrogen, forming a new and diverse economy. The security of supply of transport fuel would be enhanced, especially if hydrogen were produced from UK renewable electricity, biomass, waste or gas supplies.

Hydrogen safety

If a hydrogen vehicle were involved in a collision in an **open space**, there would be less risk than with a petrol vehicle. This is because hydrogen is very light, and so any leak would dissipate rapidly into the air, reducing the risk of fire or explosion. Hydrogen is not toxic, so a leak would not cause environmental damage. In addition to this, hydrogen storage tanks are significantly tougher than petrol tanks, and so are less likely to cause a large leak.
In a **confined space**, hydrogen could lead to fire or explosion if mixed with air. Any fire started would burn out quickly as the hydrogen dissipated. Some studies have suggested that hydrogen vehicles would have lower risks than petrol vehicles in confined spaces as petrol leaks would create a larger cloud of flammable gas. Hydrogen burns with little radiation of heat, so nothing would burn unless it were immediately next to the flame. Sensors would be needed to detect any slow leakage of hydrogen, e.g. in a garage, as hydrogen is a colourless, odourless gas.

Conditions for transition

A transition to a hydrogen economy is uncertain, and not inevitable. Transitions have been investigated using scenarios for future energy systems. Some scenario exercises, such as those prepared for the PIU Energy Review, assumed that use of hydrogen would require large scale infrastructure development. It was not clear how this would be developed, given that many national infrastructures were developed by monopolies or public bodies. This uncertainty resulted in infrastructure development being considered to be the primary barrier to use of hydrogen, and so widespread use projected only for the long term, after 2050.

However, several other studies (e.g. the Foresight *Fuelling the Future* exercise) consider that such a wholesale infrastructure change is not necessary. It is argued that development could start from niche markets and 'islands' of hydrogen availability and so would not, for example, involve switching all filling stations to hydrogen at the same time. Providing hydrogen at a local fleet vehicle depot or as part of CHP schemes could expand to supplying vehicles in a local area. Once several schemes had built up, networks could be formed.

A UK development path

Despite these differences of view, it is widely thought that hydrogen use in the UK may begin with transport, in particular for fuelling fleet vehicles and buses. Buses have fixed routes and can be refuelled and maintained at depots. Using hydrogen in stationary applications such as small CHP schemes is thought likely to develop at the same time, although there is some uncertainty as to the level of contribution in the next decade.

The next step would then expand transport use of hydrogen to cars and other light vehicles. The use of hybrid vehicles, which have a battery as well as a fuel cell or conventional engine may act as a stepping-stone to fuel cell commercialisation, as expertise and standardisation of components develops. Hybrid vehicles give a significant efficiency improvement over current technologies.

Strategic approach
Benefits of a hydrogen economy, and barriers to its development, cut across policy on energy, transport, air pollution, planning, agriculture and waste. Proponents of hydrogen (e.g. IPPR and the Carbon Trust[3]) have argued for a high-level long term strategic approach to developing a hydrogen economy, identifying key challenges, setting target dates for development and deployment, and coordinating UK and EU projects and targets. This has begun with the Greater London Authority's launch of the London Hydrogen Partnership in 2002, which will develop a plan for use of hydrogen in the city and may provide experience for a national plan.

Incentives
Transition to a hydrogen economy could be promoted using targets, regulations, standards, planning guidance, fiscal measures, grants and public procurement.

Targets for emissions reduction promote environmental improvement without being technology specific. *Powering Future Vehicles* calls for 600 new 'low-carbon' buses per year by 2012. The EST considers, however, that long term emissions targets will not be met unless hydrogen in particular is actively supported now; it recommends that Government should work with bus and fuel companies, so that by 2010, 5-10% of new buses use hydrogen fuel cells (about 150-300 buses). *Powering Future Vehicles* also sets out intentions for longer term targets for new vehicles to meet 'ultra-low' carbon standards. However, the term 'ultra-low' has not yet been defined and so it is unclear whether this will promote hydrogen technologies.

Other approaches include:
- enabling local authorities to adopt mandates requiring zero emissions from a proportion of their bus fleet, enabling them to meet local air quality objectives
- harmonisation of UK standards for storage and use of hydrogen with international standards being developed
- support for hydrogen infrastructure development through planning guidance (e.g. the ODPM's current revision of renewable energy planning)
- electricity market systems to allow generators to produce electricity for hydrogen production, grid export and local distributed generation
- widening of agricultural support schemes to include hydrogen production from biomass energy crops.

Fiscal incentives can also be used. It has been proposed that zero fuel excise duty on hydrogen would promote the early stages of market development and would reflect the lower environmental impacts of hydrogen use. Under the Government's *Green Fuel Challenge*, no fuel duty will be levied on a pilot project using hydrogen in fuel cell buses. Subject to the outcome of this project, the Government intends to exempt hydrogen from duty for a limited period to encourage development and early take-up. As hydrogen use expands, variable fuel excise duty could be used to differentiate between hydrogen derived from different sources depending on its environmental impact. Inclusion of hydrogen production in the Climate Change Levy could also achieve this aim.

Other fiscal incentives could include:
- variable vehicle excise duty (VED) for cars with very low emissions, or zero VED for zero emission vehicles
- variable company car tax for low emission vehicles.

Use of hydrogen in fleet vehicles could be promoted by use in public authority vehicles and schemes to support companies converting a proportion of their fleet, potentially with removal of night time delivery bans in urban areas for quiet vehicles. It has also been suggested that direct grants should be made available to support infrastructure changes. In the private vehicle market, uptake of new vehicles could be supported by direct grants, such as those administered under the *Powershift* programme for gas, hybrid and electric vehicles.

Technological development
The Engineering and Physical Sciences Research Council has funded the UK hydrogen energy network, to promote hydrogen research. Beyond a network, some have called for a dedicated programme to coordinate and fund UK research efforts and support demonstration projects as in the US, Germany and Japan. The programme could also include feasibility studies to identify the potential role for hydrogen in different sectors and areas and manage UK participation in EU and international projects.

Public acceptance
Public awareness of the benefits of using hydrogen and provision of information on hydrogen safety are likely to be key to acceptance of the technology. Demonstration projects involving hydrogen use in buses and public buildings have been well accepted elsewhere in the world and are considered to be one of the best ways to introduce the technology to a wide range of people.

Overview
Hydrogen is widely considered to have a strong potential for use in future energy systems, meeting climate change, air quality, noise and resource use goals. Hydrogen technology is well established in industry and further commercialisation for vehicles and stationary uses is expected in the next few years. However, the need for cost reduction, demonstration, and infrastructure development mean that mass markets are unlikely before 2015. Nevertheless, many have called for coordinated research and demonstration now and a clear strategy to enable future infrastructure and market development.

Endnotes
1 The Energy Saving Trust is a non-profit organisation aiming to reduce CO_2 emissions, funded by Government and the private sector
2 Hybrid vehicles (e.g. diesel/battery) can also reduce CO_2 emissions
3 The Institute for Public Policy Research (IPPR) is a UK think tank. The Carbon Trust is an independent non-profit company set up by the Government to take the lead on low carbon innovation in the UK

POST is an office of both Houses of Parliament, charged with providing independent and balanced analysis of public policy issues that have a basis in science and technology. POST is grateful to Jo Howes and Imperial College for Energy Policy and Technology for the research undertaken in the preparation of this briefing note. A longer report is available on the POST website.

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