

## **HYDROGEN**

### **TECHNOLOGY DESCRIPTION**

Hydrogen (H<sub>2</sub>) is a colourless and odourless combustible gas that is neither a greenhouse gas nor a local pollutant. It is a major component of water and many organic compounds such as natural gas, but it is not found freely on the Earth. It is, therefore, better described as an energy vector (a means of storing and transporting energy) rather than an energy source or energy conversion technology.

### **Environmental issues**

In end-use, hydrogen is the “cleanest” of fuels. Its combustion in stationary and mobile applications produces only very low oxide of nitrogen (NO<sub>x</sub>) emissions, plus pure water vapour. It is the ideal fuel for fuel cells, offering the potential for a high electrical conversion efficiency and zero exhaust emissions.

However, when considering the environmental advantages of hydrogen, it is important to consider the primary source of energy used in its manufacture. In fact, the environmental benefits and disbenefits of hydrogen should ultimately be evaluated over the complete fuel cycle, from extraction of the primary energy source to manufacture of the hydrogen, its distribution and end-use. The following examples serve to illustrate the issues:

- When hydrogen is manufactured using electricity generated from renewable energy sources, it can be regarded as a zero-emission and sustainable option (as long as any environmental impacts from manufacturing the renewable energy power plant are ignored).
- Manufacturing hydrogen from natural gas, through steam reforming, is a less sustainable option because of the associated carbon dioxide (CO<sub>2</sub>) emissions.
- If hydrogen is distributed by road for mobile applications, the environmental emissions of the road transport need to be included in the overall environmental assessment.
- The energy use (and environmental impact) associated with hydrogen compression/liquefaction and subsequent release from storage also need to be taken into account.

Most of the hydrogen produced today is used in situ for industrial and chemical process use, and only very small quantities are transported for use elsewhere.

### **Production and storage**

The most economic method of hydrogen production currently available involves the industrial-scale steam reforming of natural gas. This technology is both widely developed and commercially available.

A number of other production options also exist or are being developed:

- If produced from the electrolysis of water, hydrogen could be an effective means of “storing” the energy generated by intermittent renewable energy sources such as solar power or wind. This could be a significant advantage under the new electricity trading arrangements (NETA), which currently favour the more commercial, non-intermittent sources of energy. Furthermore, it would be possible to make use of renewable energy sources in the remoter parts of the UK: manufacturing the hydrogen close to the energy source and transporting it to areas of demand would minimise the amount of electrical infrastructure reinforcement needed.
- Hydrogen can be produced directly from sunlight and water using biological organisms and semiconductor-based systems.
- Hydrogen can also be produced indirectly, via the thermal processing of biomass or fossil fuels.

Hydrogen can be stored either at high pressures, as a gas, or at very low (cryogenic) temperatures, as a liquid. Weight-for-weight, liquefied hydrogen contains three times the energy of gasoline. However, on a volumetric basis, its energy density is much poorer than that of traditional fuels.

### **Competition and development potential**

As an energy vector, hydrogen is in competition with a range of other systems – electrochemical, electrostatic and even mechanical – that can often achieve much higher turn-round efficiencies. The production of hydrogen from electrolysis, followed by its storage, subsequent release and conversion back to electricity, has a typical overall efficiency of 20-35%, compared with efficiencies of 70-80% for some other systems.

Despite this, hydrogen is considered by many to be the “fuel” of the future. However, a sustainable hydrogen-based future will need to be able to rely on efficient and cost-effective methods of producing, storing, distributing and using hydrogen. The associated primary energy source(s) will also need to be sustainable.

There are currently two principal barriers to the development of a hydrogen economy:

- There is an economic barrier in that the costs of manufacture, distribution, storage and use make hydrogen substantially more expensive than traditional fuels such as gasoline. This is particularly true where schemes for hydrogen production are based on sources of electricity that are themselves uneconomic at the present time (PV, wave, tidal, biomass, offshore wind).
- The infrastructure barrier, ie the fact that a global fuel distribution infrastructure, based on oil for transport applications, is already in place. To replace this system with one based on hydrogen can only be a slow process: not only would it require massive investment, it would also, except in special cases, probably need to be undertaken globally. Furthermore, the assets already in place for the exploration, distribution and use of gasoline need to provide the expected investment return. If they fail in this respect, the financial and economic implications could be very serious.

It is clear from the above that the transition to a hydrogen economy could only happen over a very long time scale.

## **MARKET**

The principal market for hydrogen is as a commodity chemical for large-scale industrial and chemical processes such the production of ammonia, petrochemicals and methanol. It is also widely used in refinery operations. These markets are not expected to change substantially in the foreseeable future.

The global production of hydrogen currently stands at around 500 billion Nm<sup>3</sup>, predominantly from the industrial-scale steam reforming of natural gas. Most of this production is “captive”, ie hydrogen generation and use occur together at the same site, particularly where the hydrogen is required for petroleum refining and chemicals manufacturing. Hydrogen production under these circumstances is both reliable and cost-effective.

However, it is the potential of hydrogen as a future fuel and energy vector that is receiving much attention globally. The markets for hydrogen and its related technologies are potentially huge and hydrogen may, in the long-term, replace all other fuels.

Hydrogen has already been used as a fuel. Town gas, which was widely distributed during the first half of the 20th century before being replaced with natural gas, was 50% hydrogen. Hydrogen has powered space exploration for several decades, and vehicles fuelled by hydrogen were demonstrated in the early 1970s. It is also, currently, being considered as an aviation fuel.

Because of its potential significance in the future, several nations are already committed to establishing an energy economy based on hydrogen from fully sustainable/renewable sources. Iceland is foremost in adopting this approach: it has significant large-scale hydro power and few hydrocarbon resources, and hopes to achieve its hydrogen-based economy in about 30 years’ time. Elsewhere, the level of investment in hydrogen research and development has increased dramatically during recent years:

- The United States Department of Energy (USDoE) Hydrogen Program is currently spending ~US\$30M a year.
- Japan, which has very high energy costs and few indigenous energy sources, is committed to spending US\$2.5 billion over 28 years (from 1993) – its World Energy Network (WE-NET) programme.
- In Europe, the EC is supporting the European Integrated Hydrogen Project (EIHP): this is working towards a harmonised approach for the licensing and approval of hydrogen-related vehicles, infrastructural equipment and components, and other hydrogen vehicles and infrastructure equipment either in existence or being planned for the next few years.
- The International Energy Agency (IEA) is also expanding its hydrogen-related activities. Local infrastructures are already being developed and demonstrated by consortia of energy

companies, automotive manufacturers and fuel cell developers in initiatives such as the California Fuel Cell Partnership in the USA and the EIHP in Europe. In each of these initiatives, hydrogen supply is running hand in hand with the development and deployment of hydrogen-fuelled vehicles.

The early market for hydrogen as a fuel is likely to be depot-based road transport in urban areas (buses, delivery vans, taxis). This would reduce the need for novel, improved energy storage technologies and for a well developed (at least national, and perhaps global) fuel distribution infrastructure to be developed before the first vehicles become operational. The commercialisation of fuel cells will also create a steadily increasing demand for hydrogen, initially in transport and portable power applications.

The speed at which hydrogen is adopted as a fuel will depend on its availability and cost. Technically, if it were to be available now in significant quantities, it could be used to replace a proportion of domestic natural gas. However, the costs of producing, distributing and storing hydrogen are still far from commercial, as are the technologies for its use. Very substantial markets would exist for all such technologies, if delivered at a competitive price.

## **BENEFITS**

Hydrogen offers a number of prospective benefits:

- a significant potential to contribute to diversity and security of fuel supply (as an energy vector that can be manufactured using a wide range of primary energy sources)
- cleaner energy for a wide variety of end-use applications (stationary and mobile)
- zero local emissions at point of use (when used in fuel cells)
- low NO<sub>x</sub> emissions when used to fuel internal combustion (ic) engines
- a means of stimulating the development of renewable energy sources by providing an effective means of energy storage and distribution
- a means of matching the timing of energy demand with the availability of intermittent renewable energy sources such as solar power and wind
- zero emissions when derived from renewable energy sources
- no (known) fuel-related health effects
- an opportunity to broaden the role of renewable energy in supplying clean fuels for transportation and heating
- the potential to reduce reliance on fossil fuels throughout the world, given that all countries possess some form of sustainable primary energy source

- an effective energy system where a conventional energy infrastructure either doesn't already or couldn't otherwise exist
- an opportunity to upgrade lower-quality solid and liquid fossil fuels such as coal and heavy oils, thereby reducing emissions and extending their range of applicability.
- an opportunity to upgrade biomass to common liquid or gaseous hydrocarbons??
- significant reductions in CO<sub>2</sub> and other emissions (carbon monoxide, NO<sub>x</sub>, oxides of sulphur (SO<sub>x</sub>), hydrocarbons and particulates), wherever it is used.

## TECHNOLOGY STATUS

When considering the development status of “hydrogen”, it is important to consider all the potential elements of its supply, distribution and conversion/use for the various applications.

### Transport applications

The range of technologies required (or as options) for a complete transport system are all at different stages of development.

### *Hydrogen production and storage*

There are several options for hydrogen production:

- The steam reforming of fossil fuels to produce hydrogen is well established, and systems operate with a very high thermodynamic efficiency and optimum economic yields. Although this method of production is less sustainable than production using renewable energy sources, it would be possible:
  - to provide hydrogen as a transport fuel from such a source using existing technology
  - to determine the costs of doing so – accurately.
- Combining fossil fuel power generation with electrolysis would be much less efficient overall than steam reforming of natural gas. The environmental performance would be poorer and, again, the option is not sustainable. Nevertheless, hydrogen could be provided in this way using existing technology, and the costs of so doing could be accurately determined. Electrolysis devices are already well established. While there are opportunities for improving their efficiency – the 450kW system at Munich airport is ~60-65% efficient – the scale of such improvements would be unlikely to generate a substantial increase in the adoption of hydrogen as a fuel.
- Combining nuclear power with electrolysis would eliminate CO<sub>2</sub> emissions but give rise to wider environmental concerns. If nuclear power were to feature strongly in future energy scenarios, it might be an option for generating hydrogen for transport use. However, the use of electrolysis would add to the system cost and reduce efficiency. Again, the cost of hydrogen from such a scheme could be accurately determined today.

- Combining electrolysis with power from renewable energy sources is also a possibility, with the combination of large-scale hydropower and electrolysis being the most commercially attractive option. It was this option that was studied initially by the EC's Euro Quebec Hydro Hydrogen Programme: the proposal was to use the Canadian surplus of large-scale hydropower to manufacture hydrogen by electrolysis, and then to transport the fuel to Europe by tanker.

In the UK, most large-scale hydropower has already been developed to meet electricity requirements, and there is little prospect of producing hydrogen using this approach. Furthermore, the electricity from other renewable energy sources currently costs more than large-scale hydropower, some of it, such as that from photovoltaic (PV) technologies, substantially more. Before any thought can be given to producing hydrogen from renewable energy sources such as tidal stream, wave power, PV and biomass, it is necessary to determine and, if appropriate, develop their potential for cost-effective electricity generation.

Furthermore, the current UK focus is to generate 10% of the country's electricity supply from renewable sources by 2010. This on its own is a demanding target, and it is hard to conceive of the additional use of renewable energy sources for transport fuel production within that time frame. Even beyond 2010, the production of hydrogen from renewable sources may need to be at the expense of electricity generation from renewables, and this may cause an element of conflict if more demanding targets for electricity production from renewable sources are eventually set.

- Methods for producing hydrogen, either directly from sunlight and water using biological organisms and semiconductor-based systems, or indirectly via the thermal processing of biomass, are still at an early stage of development. Considerable further work is needed to understand both the processes themselves and their prospects.

Irrespective of production technology issues, there are a number of major barriers to the implementation of a hydrogen transport economy:

- the lack of suitable energy storage options
- the lack of any current demand for hydrogen fuel
- the scale of investment that is already in place for the manufacture of gasoline from oil
- the scale and investment required to convert to a widespread hydrogen-based system.

The lack of suitable hydrogen storage options is the main technical barrier. The volumetric energy density of hydrogen is significantly poorer than that of gasoline, and this results in compromises, either in the vehicle's range or in its passenger- or freight-carrying capacity. However, the energy density of liquid hydrogen (LH<sub>2</sub>) is much better than that of compressed hydrogen (CH<sub>2</sub>) and is also better than gasoline on a weight basis.

A number of novel hydrogen storage technologies are under development, particularly in the USA and Japan: these include carbon nanofibres, glass micro-spheres and metal hydrides. The future of these novel technologies is still uncertain and the technologies themselves are some way from meeting the required commercial targets for energy density

and cost. Nevertheless, they do offer the prospect of lighter and more compact forms of hydrogen storage that are more appropriate to road transport.

### ***Energy conversion technologies***

Of the energy conversion technologies available, fuel cells are clearly potentially significant in the development of a future hydrogen economy. Fuel cells operate most effectively on hydrogen, achieving excellent efficiency and zero tail-pipe emissions. Furthermore, the successful development of an appropriate hydrogen storage technology may facilitate the more widespread use of hydrogen in fuel cells, as the power plant would be simpler and cheaper, have a better dynamic response and be easier to control without an on-board fuel reformer. Emissions would also be lower, depending on the primary energy used to manufacture the hydrogen.

There is a huge global effort already in place to develop fuel cells for automotive applications, and several fuel cell buses and other vehicles are being demonstrated in various locations around the world.

Hydrogen can also be used to fuel ic engines. The fuel economy would be lower than with fuel cells (and the hydrogen storage requirements consequently greater), and there would be some emissions (eg NO<sub>x</sub>). Despite this, the use of hydrogen in ic engines could be an important stepping stone to the eventual use of hydrogen in fuel cells because of the massive, global infrastructure already in place for manufacturing and servicing ic engines. A major vehicle manufacturer is already operating a fleet of 15 hydrogen-fuelled ic engine vehicles in Germany.

### ***Hydrogen distribution***

Projects are currently under way to assess the costs of the required fuel distribution infrastructure and to identify preferred hydrogen supply routes. If existing gas supply networks were to be used for distribution, these would need considerable upgrading. A small number of refuelling stations are also being evaluated.

### ***Safety***

Work has recently started on safety issues associated with the widespread distribution and public use of hydrogen, including refuelling at retail sites. Hydrogen raises concerns about safety because of its flammability. However, hydrogen burns with a low radiative energy and a high convectivity: its buoyancy means that most of the combustion energy is directed upwards, rapidly. As a result, hydrogen is not necessarily any less safe than gasoline or natural gas. However, the issues involved are different and perceptions have an important effect on the acceptability of this fuel. It is already clear that considerable research and investment will be needed over many years:

- to establish and demonstrate a hydrogen infrastructure that is substantial, safe and reliable
- to tackle safety perception issues.

Demonstration projects would be an important element of any future programme to allay fears relating to hydrogen safety.

## ***Conclusion***

It is clear that, for the traditional sources of energy (gas, coal and nuclear), the processes for manufacturing and distributing hydrogen are well characterised, and the economics can be accurately determined. Analyses show that hydrogen would not be competitive as a fuel today. If a suitable hydrogen storage technology were available, the cost of the fuel would still be a major barrier to its deployment.

## **Stationary applications**

Hydrogen could be used in conjunction with intermittent renewable energy technologies, to increase their commercial attractiveness under NETA. Where such technologies are already deployed commercially, as in the case of wind power, schemes such as this could be accurately evaluated now, with a high degree of certainty. They would not require novel hydrogen storage technologies, and the basic question is a commercial one: does the cost of introducing electrolysis, storage and subsequent conversion back to electricity justify the extra return associated with increasing the predictability of the power eventually supplied?

Hydrogen could also facilitate the use of renewable energy resources that are remote from the main areas of electricity demand (and hence the electricity grid). In the UK, this approach would be particularly relevant for wave power or tidal stream generation. Much of the exploitable wave power resource, for instance, is off the north west of Scotland, well away from the demand for power. However, it might be possible to link wave power schemes to electrolysis, with subsequent hydrogen distribution.

For both wave power and tidal stream generators, the cost of the energy produced is a major uncertainty when assessing the commercial prospects for such linked schemes. For these, and for other renewable energy technologies that are still some way from being a commercial option, the main focus needs to be on improving the core electricity-generating technology.

Hydrogen could also be used to generate electricity (and heat) from fuel cells, either connected to the grid, embedded within the distribution system or at individual sites. The major technical issue here is the availability of economic and proven fuel cell technology.

## **TARGETS FOR COMMERCIAL COMPETITIVENESS**

Using hydrogen as an energy vector adds elements to the normal power generating system: the hydrogen has to be manufactured, distributed and then used to generate electricity. All these additional steps add to the cost, and present-day analysis shows that, except perhaps in special cases, the additional cost cannot be justified.

However, hydrogen can be considered as a long-term option. This involves looking ahead to a time when the world energy economy is very different from today – when oil and gas reserves are significantly lower and their prices substantially higher, and when there is pressure to improve the sustainability of energy use and minimise its environmental impact. It is therefore considered inappropriate to consider targets for commercial competitiveness.

## RESEARCH AND DEVELOPMENT ISSUES

### R&D

The R&D focus for hydrogen is those technology areas that:

- are not being addressed by other elements of the DTI's Sustainable Energy Technology Programme
- may be being addressed elsewhere but are perhaps better placed within a hydrogen R&D programme.

The topics indicated below are not of equal priority, and work on many of them could, and perhaps should, be delayed until greater progress is seen in key development areas, particularly hydrogen storage.

#### *Hydrogen production*

- better and cheaper production methods
- electrolyser development (greater efficiency, reduced cost, high pressure).

#### *Hydrogen storage*

Hydrogen storage is the fundamental technical barrier to the more widespread use of hydrogen. It is therefore an area in which significant additional R&D may be justified. The United States Department of Energy has set targets for hydrogen storage, and these are summarised below.

	<b>Units</b>	<b>Physical storage</b>	<b>Chemical storage</b>
Storage weight	%	6	6
Storage efficiency	%	95	90
Energy density (gas at 510 bar)	Wh/litre	1050	1500
Specific energy	Wh/kg	2000	2000
Cost of storage	\$/kWh	5	5
Cycle life	Cycles	500	500
Operating pressure (gas)	Psig	7500	N/A
Refuelling time	Minutes	<5	<5

Possible areas for UK R&D include:

- low-cost composite cylinders capable of storing compressed hydrogen at >750 bar
- low-cost high-density solid storage systems
- viable metal hydride systems that do not require high temperatures or long cycle times
- the development and evaluation of other novel systems.

### ***Transportation/handling***

- low-cost liquefaction systems
- efficient, low-cost, compact compressors for hydrogen and air
- fast, safe refuelling technologies
- thorough analysis of the safety issues associated with hydrogen production, distribution and use (including refuelling)
- safety issues associated with compressed storage in high-pressure cylinders
- codes and standards for vehicle and refuelling infrastructure.

### **Demonstration**

Field trials will be needed to evaluate and verify complete system performance, and to demonstrate safety, once the R&D has been successfully completed. Successful field trials will need to be followed by potentially significant promotional programmes to encourage the transition to a hydrogen economy.

### **Studies**

A number of studies could usefully be undertaken:

- to provide information on the status of key technologies
- to evaluate market opportunities
- to establish fully the UK's capabilities
- to evaluate first-of-a-kind installations in the utility, residential and transport sectors
- to provide economic and environmental analyses of, for example, infrastructure and fuel handling.

### **NON-TECHNICAL ISSUES**

Substantial barriers to the development of a hydrogen economy would still remain, even after successful resolution of the hydrogen storage issue and a significant improvement in the overall economics of a hydrogen energy system:

- The hydrogen economy is a global issue. Only in special cases (eg Iceland) could a single country, or certain regions of a country, make this transition unilaterally. Energy is a global business, and fuel suppliers are global companies operating in global markets. It is by no means certain that a global hydrogen economy would, in fact, come about.

- The investment required for transition to a hydrogen economy is huge and the change could only happen very slowly. Hydrogen has a production capacity that is currently way below that required for its widespread application as a fuel, and the hydrogen that is available is expensive (particularly delivered) when compared with other fuels.
- The demand for hydrogen fuel is currently very low. The expected introduction of fuel cells for both transport (initially fleet vehicles operated from central depots) and stationary applications during next few years is likely to increase this demand as hydrogen is the perfect fuel for fuel cell operation. The fleet vehicle demand may initially be met using local steam reformers fuelled by natural gas.

The introduction of fuel-cell-powered cars would seem to be an important step towards the more widespread development of a hydrogen infrastructure and economy. Fuel cell car users will expect to maintain the range they currently have and to be able to refuel with the convenience that exists today – unless fuel cell cars are to be restricted to urban environments. The transition from local/urban/fleet applications to widespread availability and use is one that will require close co-operation between the fuel supply and automotive industries.

Hydrogen is already receiving significant attention from the automotive and fuel supply industries. It features strongly in the strategies of many global energy companies, and all of the world's major car manufacturers have significant fuel cell development programmes.

## **UK INDUSTRY STRENGTHS**

UK industry has many strengths that are relevant to the possible future development of a hydrogen economy. Those that relate to individual renewable energy technologies are being assessed by other components of the Sustainable Energy Technology Programme. Those that are more generally applicable to the hydrogen economy are summarised below:

- There are world-class fuel suppliers with significant activity and manufacturing in the UK, and there are likely to be significant opportunities for UK industry in the design, manufacture, installation and maintenance of hydrogen production, refuelling and storage systems.
- UK universities offer a flexible and highly capable science and technology research and development base, with world-class expertise in key areas such as materials, catalysis and bio-engineering. At least 22 UK universities are already involved in researching issues associated with hydrogen. A large number of these have ongoing research into hydrogen storage.

## **RATIONALE FOR A DTI PROGRAMME**

Whether or not hydrogen will contribute significantly to our future energy needs (and in what ways) is still a matter of great uncertainty. Hydrogen represents an alternative option to the range of “fuels” currently deployed, and its use can be expected to increase to some degree.

The expected increase in demand will be met, for the foreseeable future, from the conversion of fossil fuels, and there will be no particular environmental benefit. The linking of hydrogen and renewable energy sources is of key importance, but the time scales are still considered to be very long-term. Even here, hydrogen faces tough competition from other, often more efficient, energy storage/conversion schemes that are currently under development, eg redox cells.

Major barriers to development include the economics of the technology, together with the huge investment costs required to bring a hydrogen economy into being. Furthermore, hydrogen does not (yet) provide a better solution to the world's energy and environmental needs. As a result, the markets for hydrogen are unlikely to emerge (or, at least, to emerge with any speed) without significant political intervention.

Despite this (or perhaps even because of it), there are strong reasons for the DTI to establish a hydrogen R&D programme:

- Hydrogen is, potentially, a very significant component of any policy that seeks to achieve sustainability, improved future fuel security, increased diversity and flexibility of energy supply, and a long-term reduction in the environmental impact of energy consumption. Its increased use in urban areas would make a major contribution to the improvement of urban air quality.
- If hydrogen is to become an important fuel (and an important energy vector), whether or not it becomes the world's future fuel of choice, it is crucial for the UK to play a full and active part both in the deliberations and in developing the outcome. To ignore this could be to deny UK industry significant opportunities. As a result, any hydrogen economy could evolve in a way that is not best suited to UK interests.
- There could be significant future market opportunities for UK companies in hydrogen and its related technologies. Companies are unlikely to pursue these opportunities at present as they lie well outside their normal commercial activities. Furthermore, the time scales are too long and the commercial risks too great. A DTI programme would help reduce the significant technical and market uncertainties relating to hydrogen. It could also help to establish clear frameworks for planning and safety.
- No one company or country is likely to have the resources and/or commitment to pursue a hydrogen development programme in isolation, and international collaboration is seen to be the key. A DTI programme could act as a focus for collaboration and information exchange both within the UK and at the international level. It would help UK companies to initiate key international relationships; it would co-ordinate the UK's involvement in international programmes managed by, for example, the EU and the IEA; and it would help to establish a clear view of international technical progress in the production, storage and use of hydrogen that could guide hydrogen research decisions in the UK.

## **TECHNOLOGY ROUTE MAP FOR THE DTI PROGRAMME**

As already indicated, many hydrogen issues are already being addressed by other elements of the DTI's Sustainable Energy Technology Programme. For example, natural gas reforming is

dealt with under Fuel Cells, hydrogen production from biomass under Biofuels, and the evaluation of regenerative technologies under Embedded Generation. Those priority R&D topics that are not covered effectively elsewhere are hydrogen storage, particularly for vehicle applications, and electrolysis. A new hydrogen programme is proposed that addresses these two topics while keeping a “watching brief” on the wider scene.

Activity	Target date
Establish a “hydrogen discussion group” that would bring together key UK players representing all aspects of hydrogen. The group would meet every 6-12 months. The aim would be to encourage discussion, informing both members and UK Government. The group would identify and prioritise the studies to be commissioned.	
<p>Initiate a major, properly resourced, long-term research programme to develop:</p> <ul style="list-style-type: none"> <li>• improved hydrogen storage technologies, particularly for vehicle applications</li> <li>• the low-cost and efficient production of hydrogen from electricity (electrolysis).</li> </ul> <p>The programme should:</p> <ul style="list-style-type: none"> <li>• build on international work already under way or completed</li> <li>• address the full range of existing options and seek new ones</li> <li>• involve collaboration between universities</li> <li>• work in co-operation with the Engineering and Physical Sciences Research Council</li> <li>• play a full and active part in the wider international effort</li> <li>• establish its own Route Map to measure progress and to make sure it focuses on attractive options.</li> </ul>	2003
Review existing studies and/or commission new ones that will produce a definitive assessment of the current economics of every option for producing, distributing, storing and using hydrogen as the principal fuel. The studies should be based on existing technology and should, ideally, be part of a wider international effort.	2003
Build, in co-operation with the Embedded Generation programme component, an onshore wind energy/hydrogen storage scheme. Evaluate the commercial attractiveness of this approach as a means of achieving greater predictability of power generation under NETA.	2003
Commission work that evaluates the costs and benefits of using hydrogen as an energy vector in conjunction with wave and tidal energy schemes that are remote from the electricity grid and the demand for power. Exact timing will depend on progress in the development of wave and tidal power and should, at least, await the completion and economic evaluation of significant field trials of wave and tidal devices.	2003
In co-operation with international initiatives, generate codes and standards for hydrogen handling and safety.	2005
Develop a clearer understanding of routes to the global development of a hydrogen economy.	2010
Subject to R&D progress on hydrogen storage, undertake field trials designed for the complete evaluation of hydrogen energy schemes, and verify their technical, economic and environmental performance. Trials	Beyond 2010

could be based on renewable energy sources.	
Begin to tackle other R&D issues that are currently of low priority but that will have increased priority once the storage issue is resolved (or on the way to being resolved) and the cost of electricity from renewable sources has become more competitive.	Beyond 2010
Undertake demonstrations of hydrogen-fuelled systems in commercial, residential and transport applications that will enhance public awareness, improve perceptions of safety and promote the development of a sustainable hydrogen economy.	Beyond 2010