



THE HYDROGEN ECONOMY

A non-technical review

UNITED NATIONS ENVIRONMENT PROGRAMME



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Introduction

There is a growing belief among policy-makers, environmental organisations, energy analysts and industry leaders that hydrogen is the fuel of the future that will revolutionise the way we produce and use energy. In the long term, our reliance on finite fossil energy is clearly unsustainable, both environmentally and economically. Soaring prices of oil in recent years have drawn attention to the energy-security risks of relying on oil and gas, and have led to a growing perception that the world is starting to run out of cheap fuel, hastening the need to move to more secure and cleaner energy technologies. Hydrogen is widely held to be the most promising of a number of such technologies that could be deployed on a large scale in the foreseeable future. Replacing fossil fuels with hydrogen in final energy uses could bring major environmental benefits – as long as technical, environmental and cost challenges in the way hydrogen is produced, transported, stored and used are overcome.

UNEP is following developments in hydrogen-energy technology with great interest, as it holds out the prospect of providing the basis of a sustainable energy future – one in which the environmental effects of energy production and use are greatly reduced or eliminated. Indeed, the hydrogen economy will most likely never become a reality unless it brings major environmental benefits. But there are widespread misunderstandings about the role hydrogen could play in the global energy system, how quickly it could be introduced commercially on a large scale and its impact on the environment. UNEP believes that it is important to keep countries, especially those in the developing world, informed about the true potential, costs and benefits of hydrogen, and to counter popular misconceptions.

In keeping with its mission to encourage and facilitate the adoption of environmentally-friendly technologies, UNEP has decided to prepare this informative document on the hydrogen economy. It sets out in non-technical language the main issues surrounding the transition to a global energy system based on hydrogen. It provides a sober assessment of the current state of technology development, the technical and cost challenges that will need to be overcome, and the prospects for commercial deployment. It also considers what the emergence of hydrogen as a viable energy technology would mean for policy-making – particularly in developing economies.

The first part of this report briefly describes how the hydrogen economy would work and what it might mean for the environment. The following section reviews the cost and technical challenges that will need to be overcome for hydrogen to become commercially viable on a large scale. The next section discusses the potential barriers to development of a hydrogen system and the need for

government support, and describes long-term projections of hydrogen use. The report then considers the relevance of hydrogen for developing economies and what it could mean for national policy-making, and the role of international and non-governmental organisations. A concluding section summarises the key messages contained in this report.

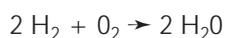
Annex A describes the activities of key players in hydrogen energy research and development. Annex B provides references to selected publications on hydrogen and the addresses of relevant websites for readers looking to find out more about hydrogen developments and programmes.

The Hydrogen Economy and Sustainable Development

Interest in hydrogen as a way of delivering energy services has been growing in recent years in response to heightening concerns about the environmental impact of energy use and worries about the security of fossil-fuel supplies. Hydrogen, as an energy carrier, can in principle replace all forms of final energy in use today and provide energy services to all sectors of the economy. The fundamental attraction of hydrogen is its potential environmental advantages over fossil fuels. At the point of use, hydrogen can be burned in such a way as to produce no harmful emissions. If hydrogen is produced without emitting any carbon dioxide or other climate-destabilising greenhouse gases, it could form the basis of a truly sustainable energy system – the hydrogen economy.

What is Hydrogen?

Hydrogen is the simplest, lightest and most abundant element in the universe, making up 90% of all matter. It is made up of just one electron and one proton and is, therefore, the first element in the periodic table. In its normal gaseous state, hydrogen is odourless, tasteless, colourless and non-toxic. Hydrogen burns readily with oxygen, releasing considerable amounts of energy as heat and producing only water as exhaust:



When hydrogen burns in air, which is made up mostly of nitrogen, some oxides of nitrogen – contributors to smog and acid rain – are formed. Hydrogen is highly flammable with a high flammability range, burning when it makes up 4% to 74% of air by volume. It has a high energy content by weight – nearly three times that of gasoline, for example. By contrast, hydrogen has a low energy density by volume at a standard temperature and atmospheric pressure. One gramme of hydrogen gas at room temperature occupies about 11 litres of space. Storing the gas under pressure or at temperatures below minus 253° C, at which point it turns into a liquid, raises its volumetric density.

Hydrogen is a carrier of energy, not a source (Box 1). It does not exist in a natural state on earth and must be manufactured using a hydrogen-rich compound as the raw material. Today, hydrogen is produced mainly through steam reforming of natural gas, but it can be extracted from other hydrocarbons by reforming or

partial oxidation. A major shortcoming of the processing of hydrocarbons is the resulting emissions of carbon dioxide and airborne pollutants. Most other production processes in use or under development involve the electrolysis of water by electricity. This method produces no emissions, but is typically more costly compared to hydrocarbon reforming or oxidation because it requires more energy and because electricity is, in most cases, more expensive than fossil fuels. Today, the commercial production of hydrogen worldwide amounts to about 40 million tonnes, corresponding to about 1% of the world's primary energy needs. This output is primarily used as a chemical feedstock in the petrochemical, food, electronics and metallurgical processing industries.

Box 1: Energy Sources and Carriers

Primary sources of energy such as coal, oil and natural gas store various forms of kinetic or potential energy. They occur in a natural state. They can be burned directly in final uses to provide an energy service, such as heating buildings, or they can be transformed into secondary energy sources for final consumption. Energy transformation allows energy to be transported or delivered in more convenient or useable form. Electricity is the most common secondary source of energy. Hydrogen is also a secondary source, as it must be produced using a hydrogen-rich source. It can be converted to energy (heat) either through combustion or through an electrochemical reaction to generate heat and electricity. Secondary sources are also known as energy carriers.

Hydrogen holds the potential to provide energy services to all sectors of the economy: transportation, buildings and industry. It can complement or replace network-based electricity – the other main energy carrier – in final energy uses. Hydrogen can provide storage options for intermittent renewables-based electricity technologies such as solar and wind. And, used as an input to a device known as a fuel cell, it can be converted back to electrical energy in an efficient way in stationary or mobile applications. For this reason, hydrogen-powered fuel cells could eventually replace conventional oil-based fuels in cars and trucks. Hydrogen may also be an attractive technology for remote communities which cannot economically be supplied with electricity via a grid. Because hydrogen can be produced from a variety of energy sources – fossil, nuclear or renewable – it can reduce dependence on imports and improve energy security.

The Environmental Implications of Hydrogen

The fundamental attraction of hydrogen – and the main driving force behind current research and development – is its environmental advantages over fossil fuels. But hydrogen is only as clean as the technologies used to produce and use it. Replacing fossil fuels with hydrogen in providing energy services could bring major environmental benefits, on condition that hydrogen is used in non-polluting fuel cells and that the carbon dioxide and noxious gases emitted in the hydrogen-production process are reduced or eliminated. At the point of use, burning hydrogen in the presence of oxygen in a fuel cell produces no harmful emissions, just electrical energy and water. The production of hydrogen can be emission-free if the energy used in the production process is derived from nuclear power or renewables, or, if based on fossil fuels, if the carbon dioxide emitted is captured at the point of production and stored permanently.

Replacing fossil fuels with hydrogen in providing energy services could bring major environmental benefits, on condition that hydrogen is used in fuel cells and that the carbon dioxide and noxious gases emitted in the hydrogen-production process are reduced.

Road transportation is an important and growing source of both air pollutants and climate-destabilising greenhouse gases. There is clear evidence of the harmful impact on human health of exposure to pollutants emitted by cars and trucks. As a result, local air quality has become a major policy issue in almost all countries. Air pollution in many major cities and towns in the developing world has reached unprecedented proportions. Most rich, industrialised countries have made substantial progress in reducing pollution caused by cars and trucks through improvements in fuel economy, fuel quality and the installation of emission-control equipment in vehicles. But rising road traffic has offset at least part of the improvements in emissions performance.

Because of increasing pollution from road traffic, road vehicles have been the focus of efforts to develop fuel cells. Replacing internal combustion engines fuelled by gasoline or diesel with hydrogen-powered fuel cells would, in principle, eliminate pollution from road vehicles. Fuel cells can also be used to provide electrical-energy services in industrial processes and buildings, replacing direct use of petroleum products, natural gas and coal.

Hydrogen could also contribute to reducing or eliminating emissions of carbon dioxide and other greenhouse gases. For this to happen, the process of manufacturing hydrogen would have to be carbon-free or at least less carbon-intensive than current energy systems based on fossil fuels. This could be achieved in one of three ways: through electrolysis using electricity derived solely from nuclear power or renewable energy sources; through steam reforming of fossil fuels combined with new carbon capture and storage technologies; or through thermochemical or biological techniques based on renewable biomass.

Despite the potential local and global environmental benefits of switching to hydrogen, there are a number of uncertainties about other environmental consequences of a large-scale shift towards a hydrogen economy. These concern mainly the potential effects of significant amounts of hydrogen being released into the atmosphere. The widespread use of hydrogen would make such releases inevitable, but the effects are very uncertain because scientists still have a limited understanding of the hydrogen cycle. Any build-up of hydrogen concentrations in the atmosphere could have several effects, the most serious of which would be increased water vapour concentrations in the upper atmosphere and, indirectly, destruction of the ozone layer. Increased hydrogen releases could also lower the oxidising capacity of the atmosphere, and so increase the lifetime of air pollutants and greenhouse gases such as methane, hydro-chlorofluorocarbons (HCFCs) and hydro-fluorocarbons (HFCs). More research is needed to obtain a better understanding of hydrogen sources and sinks.

Safety is a critical issue. Contrary to popular opinion, hydrogen is actually less flammable than light oil products, such as gasoline, and most other fossil fuels (Box 2). But the need to transport and store it under high pressure or at very low temperature brings other hazards. There is plenty of evidence that, with proper handling and controls, hydrogen can be as safe as the fuels in use today. Indeed, hydrogen has a long history of safe use in industry. But, for it to become widely accepted in other applications, it will become increasingly important to develop

and implement internationally agreed rules, regulations, codes and standards covering the construction, maintenance and operation of hydrogen facilities and equipment safely, along the entire fuel-supply chain. Uniformity of safety requirements and their strict enforcement will be essential to establishing consumer confidence.

Box 2: Hydrogen Exonerated as the Cause of the Hindenburg Disaster

Televised images of the spectacular destruction of the Hindenburg airship affect people's perception of hydrogen and their acceptance of the gas as a safe energy carrier. The Hindenburg burst into flame in full view of a crowd of reporters and newsreel cameras while landing in New Jersey, in the United States, on 6 May 1937. The flammability of the hydrogen that fuelled the airship was blamed for the disaster, which effectively ended travel by airship. But a 1997 study by a retired National Aeronautics and Space Administration (NASA) engineer, Addison Bain, concludes that hydrogen played no part in starting the Hindenburg fire. According to the study, the paint used on the skin of the airship, which contained the same component found in rocket fuel, was the primary cause of the fire. As the Hindenburg docked, an electrical discharge ignited its skin, and a fire raced over the surface of the airship. Of the 37 people who died, 35 perished from jumping or falling to the ground. Only two of the victims died of burns, and these were caused by the burning coating and on-board diesel. The hydrogen burned quickly, upward and away from the people on board.

A Global Hydrogen Energy System

The transition to a hydrogen-energy system would represent the ultimate step on the path away from carbon-based fossil energy. The world's energy system has been becoming gradually less carbon-intensive as it has moved from coal to oil and then natural gas. The technology exists today to produce, store, transport and convert hydrogen to useable energy in end-use applications, such as fuel cells. Technologies to capture carbon dioxide and other gases released during the process of producing hydrogen from fossil fuels and store them have also been demonstrated. Almost every big car manufacturer plans to begin commercial production of fuel-cell cars within a few years, and small fuel cells to supply power to remote communities are already coming onto the market. Most of the major oil companies have active hydrogen and carbon capture and storage programmes. We can imagine today what the hydrogen economy might look like (Box 3).

Major technological and cost breakthroughs are needed before the hydrogen economy can become a reality. The cost of supplying hydrogen energy using current technologies, which have been developed over many decades, is still very high compared to conventional energy technologies. And some major technical problems need to be resolved. The main areas in which progress is needed are fuel cells; hydrogen production from renewables; distribution and storage infrastructure that meets environmental and safety criteria; and carbon capture and storage, without which hydrogen may never become a viable energy solution. Achieving this will require a lot more research and development.

The pace of technological progress and its impact on lowering the costs of hydrogen supply is inevitably extremely uncertain and hard to predict. Indeed, it is by no means certain that hydrogen will *ever* become cost-competitive. Rapid advances in carbon capture and storage technologies might allow us to continue using fossil fuels to generate electricity in an environmentally acceptable manner

Major technological and cost breakthroughs are needed before the hydrogen economy can become a reality.

Box 3: A Vision of the Hydrogen Economy

What might a hydrogen economy look like? Jump forward in time – perhaps 100 years, but possibly much less. The world has made the transition to a hydrogen economy. An efficient and competitive hydrogen production, storage and transport system has been built. Hydrogen has become widely accepted as a clean, safe and sustainable form of energy. Emissions are a fraction of what they once were, even though the world's population and economy are now much larger. Cities and towns are filled with highly efficient hydrogen-powered vehicles conveying people and goods, emitting only water vapour and driving along with only a gentle hum. Many of these vehicles refuel at public stations where hydrogen supplies are received by pipeline from centralised production facilities. Others fill their hydrogen tanks from home or at their workplace from either small-scale natural gas reformers or renewable energy powered electrolysis plants, some using photovoltaics.

In this future world, home owners have the choice of buying electricity from the grid or supplying their own energy needs with a dedicated fuel cell that provides electricity and thermal energy for heating and cooling. That fuel cell uses hydrogen produced by a small reformer, using natural gas supplied through the local pipeline distribution network. Electricity is produced in centralised power plants, using gasified coal or natural gas. The carbon emitted is captured and piped to a storage site or converted to useful and safe solid products. Some of the hydrogen produced is burnt in highly efficient gas turbines to provide electricity, and some is piped to customers for use in vehicles and distributed generation plants. Renewable energy sources also contribute to both power and hydrogen production. Hydrogen is used to store the intermittent energy generated from wind turbines and photovoltaics.

Source: Adapted from Commonwealth Government of Australia (2003).

and at an acceptable cost. The Earth's resources of oil, natural gas and coal are certainly large enough to meet our energy needs for many decades to come. Improved electric batteries in cars and trucks or improved emissions performance of technologies in use today could prove to be the preferred solution to urban pollution problems. Renewable energy sources or nuclear power may turn out to be a more cost-effective solution to the threat of global warming.

If hydrogen does emerge as a competitive energy carrier, it will not displace existing systems overnight because of the slow pace at which much of the capital stock that makes up the global energy system is replaced. And the widespread deployment of carbon capture and storage technology – most likely a key element of the hydrogen economy for as long as fossil fuels remain the world's main primary source of energy – will be a mammoth undertaking. The transition to a hydrogen economy would, therefore, be gradual, possibly taking several decades. The construction of entirely new supply infrastructure for hydrogen distribution would undoubtedly be costly and risky, which might be a major barrier to switching to hydrogen. And consumers must be convinced that hydrogen is economical, practical and safe. Strong government incentives will surely be needed to kick-start the transition process, in addition to continuing major investments in research, development and demonstration.

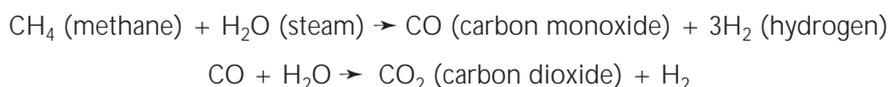
Technical and Cost Challenges

Formidable technical and cost challenges will need to be overcome for hydrogen to be able to compete with, and eventually replace, existing energy technologies. The biggest advances are needed in transportation and storage of the fuel, as well as in fuel cells in vehicles. And technologies that capture the carbon dioxide emitted when hydrogen is produced from fossil fuels and store it underground need to be adequately demonstrated on a large scale. Large cost reductions are needed – especially in the manufacture of fuel cells – for hydrogen to become competitive with existing fossil fuel- and renewables-based technologies. But recent advances in technology and a surge in public and private spending on research, development and demonstration suggest that the requisite technical and cost breakthroughs might be achievable within a generation.

Hydrogen Production, Distribution and Storage

A critical hurdle on the road to the hydrogen economy is the efficient and clean production of hydrogen. As an energy carrier, hydrogen has to be manufactured from a primary energy source. There are many industrial methods currently available for the production of hydrogen, but all of them are expensive compared with the cost of supplying the same amount of energy with conventional forms of energy (several times more expensive compared with fossil fuels). The distribution and storage systems that would be needed to supply hydrogen on a large scale are also much more expensive because of the low volumetric energy density of the fuel. Bringing production, distribution and storage costs down sufficiently to make hydrogen a viable competitor to existing fuels will require important technological advances.

Almost all the hydrogen produced in the world today involves the **steam reforming of fossil fuels** using a nickel catalyst. At present, this is a proven, commercial technology and is by far the cheapest way of making hydrogen on a large scale. In most cases, natural gas (methane) is the raw material. The methane first reacts with steam to produce carbon monoxide and hydrogen. The carbon monoxide, passed over a hot iron oxide or cobalt oxide catalyst, then reacts with the steam to produce carbon dioxide and additional amounts of hydrogen:



Steam reforming of fossil fuels – a proven, commercial technology – is by far the cheapest way of making hydrogen and is likely to remain so for the foreseeable future.

Natural gas is usually the cheapest feedstock for producing hydrogen in steam reforming. Even so, producing hydrogen from natural gas costs about two to three times more than producing gasoline from crude oil – not including the cost of capturing and storing the carbon dioxide produced in the process. A number of countries are conducting research into how to improve the efficiency of steam reforming of gas and other fossil fuels, and how to lower production costs.

Partial oxidation of methane is also used to produce hydrogen. The process involves reacting the methane with oxygen to produce hydrogen and carbon monoxide, which is then reacted with water to produce more hydrogen and carbon dioxide. Overall conversion efficiency is generally lower than for steam reforming, which is why the latter technique dominates commercial production today and is expected to continue to do so.

Gasification of coal is the oldest technique for making hydrogen, and is still used in some parts of the world. It was used to produce the “town gas” supplied to cities in Europe, Australia and elsewhere before natural gas became available. The coal is heated until it turns into a gaseous state, and is then mixed with steam in the presence of a catalyst to produce a mixture of hydrogen (around 60%), carbon monoxide, carbon dioxide and oxides of sulphur and nitrogen. This synthesis gas may then be steam-reformed to extract the hydrogen, or simply burned to generate electricity. Coal gasification for electricity production can be more thermally efficient than conventional coal-fired power stations and less polluting. Research into coal gasification is focused on handling the emissions of sulphur and nitrogen oxides – major pollutants – and carbon dioxide, with and without combustion of the synthesis gas in the plant.

Hydrogen can also be produced from **biomass**, such as crop residues, wood and dung, using pyrolysis and gasification (thermochemical) techniques. These processes produce a carbon-rich synthesis gas that can be reformed into hydrogen in the same way as natural gas or coal-based synthesis gas. The advantage of biomass over fossil fuels is that it produces no net emissions of carbon dioxide, since the carbon released into the atmosphere was previously absorbed by the plants through photosynthesis. But with the exception of remote locations where biomass supplies are ample and cheap, biomass-based hydrogen production costs are generally much higher than for fossil fuels. Purely biological routes to producing hydrogen from biomass involving fermentation, anaerobic digestion and metabolic processing techniques are also being investigated, but are currently far from competitive compared with conventional techniques based on fossil fuels.

Large reductions in the cost of renewables-based electricity and nuclear power are needed to enable hydrogen produced by electrolysis to compete with conventional sources of energy on a large scale.

Hydrogen production using **water electrolysis** is minimal today, because it requires large amounts of electricity, which is expensive. This technique is normally used only to produce hydrogen of very high purity, required in some industrial processes, or other products, such as chlor-alkali, with hydrogen as a by-product. But electrolysis could be used to produce small quantities of hydrogen close to the point of use; for example, at refuelling stations. To be economic, the electricity would need to be cheap. The environmental benefits of electrolysis-based hydrogen energy depend on how the electricity is produced. If it were generated from nuclear or renewable energy sources, such as wind,

solar and biomass, electrolysis would produce carbon-free hydrogen. But large reductions in the cost of renewables-based electricity and nuclear power are needed to enable hydrogen produced by electrolysis to compete with conventional sources of energy on a large scale.

There is some scope for reducing the cost of producing hydrogen. In 2005, the US Department of Energy set a new production-cost target of \$2–3 per gallon of gasoline equivalent (in 2005 prices) by 2015, regardless of the way the hydrogen is produced. Achieving the target would require a halving of the current cost. Steam reforming of natural gas or some other fossil-fuel feedstock is likely to remain the cheapest way of producing hydrogen for the foreseeable future, except where electricity is available at very low cost.

However hydrogen is produced, its widespread use will require large-scale infrastructure to transport, distribute, store and dispense it as a fuel for vehicles or for stationary uses. Because of its low volumetric energy density, hydrogen must be compressed and stored as a gas in a pressurised container or chilled and stored in a cryogenic liquid hydrogen tank for convenience. Both techniques have been demonstrated and are in commercial use today, but they use significant amounts of energy and the tanks are expensive to build and operate. The potential for storing hydrogen safely and efficiently in a solid state is being investigated.

Transportation and distribution are faced with similar problems. Compressed hydrogen can be transported by pipeline, but the energy-intensive nature of this technique means that it is only economic over short distances. There are some small hydrogen-pipeline systems in operation today, mostly in the United States

Box 4: Centralised versus Localised Hydrogen Production

Hydrogen can be produced in two ways: in large-scale centralised plants for bulk supply or in small, distributed facilities using local energy inputs. The choice of production has important implications for fuel and infrastructure needs. Centralised production would benefit from economies of scale. This would favour certain feedstocks or technologies, including steam reforming and coal gasification. The main drawback is the need to build the infrastructure to transport and distribute hydrogen, possibly over large distances. It may be possible to convert existing gas pipelines to hydrogen, though compressors and valves might have to be modified or replaced. Alternatively, mixing in small volumes of hydrogen – typically up to 15% by volume – with natural gas would avoid the need for modifications to the gas distribution network, but separating the two gases at the point of delivery would involve additional costs.

Distributed production – involving smaller plants sited close to centres of demand – may reduce delivery costs, but unit production costs would most likely be higher, except perhaps where there is a local supply of cheap feedstock. One benefit of decentralised production is that plants would require less investment and production could be scaled up to meet demand in the earlier stages of market development. Another advantage is that, if natural gas is the preferred feedstock, the existing natural gas distribution system could be used to supply hydrogen plants. The principal drawback is that carbon capture would probably be much more expensive than in centralised plants. Water electrolysis may be more suited to distributed than centralised production, depending on local availability of cheap electricity.

In practice, the choice between centralised and localised production will depend on cost and technological developments. Centralised production may prove most cost-effective in the long term, but localised production could still play an important role in some cases.

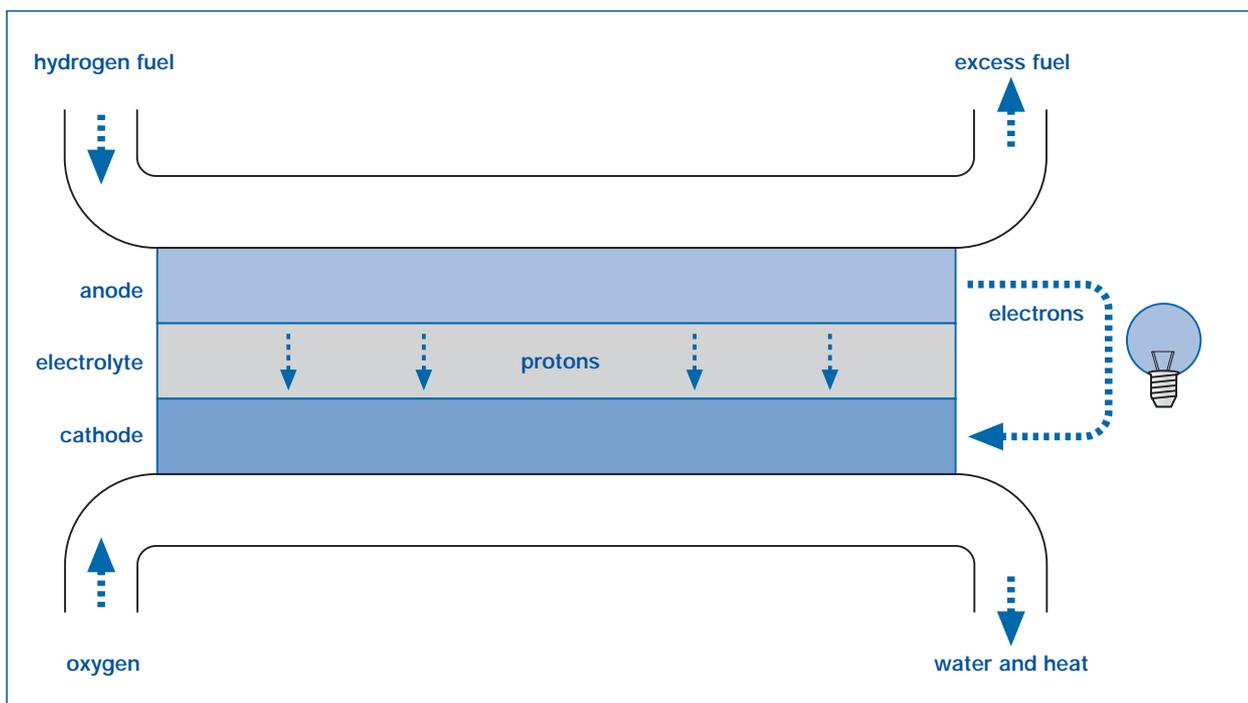
and Europe, but none exceed 200 kilometres in length. Over longer distances, it is cheaper to transport hydrogen by road, rail or barge in cryogenic tanks. It is then vaporised at the point of use. How successful research and development is in bringing down the cost of transportation and storage methods will affect both the viability of hydrogen as an energy carrier and whether centralised or localised production prevails (Box 4).

Fuel Cells for Mobile and Stationary Uses

The fuel cell has a long history. It was invented by an Englishman, William Grove, in 1839. The term “fuel cell” was coined later in 1889 by Ludwig Mond and Charles Langer, who attempted to build the first practical device using air and industrial coal gas. Fuel cells were used in the US and Soviet space programmes in the 1960s and 1970s. Although hydrogen can be burned in conventional devices such as boilers, turbines and internal combustion engines, fuel cells appear to be the best technology to exploit hydrogen because of their high efficiency.

A fuel cell is a device that uses a hydrogen-rich fuel and oxygen to produce electrical energy by means of an electrochemical reaction. The cell consists of two electrodes – an anode (negative) and a cathode (positive) – sandwiched around an electrolyte. Hydrogen is fed to the anode and oxygen to the cathode. The electrolyte causes the proton and electron in each hydrogen atom to separate and take different paths to the cathode. The electron goes through an external circuit, creating an electrical charge. The proton migrates directly through the electrolyte to the cathode, where it reunites with the electron and reacts with the oxygen to produce water and heat (Figure 1).

Figure 1: Fuel Cell Configuration



Because there is no combustion, fuel cells give off no emissions other than water vapour – for as long as the hydrogen is pure. Fuel cells are quiet and reliable as there are no moving parts, and can be small. These attributes make fuel cells a highly promising technology, especially for automotive vehicles. They can also be used in stationary applications, to provide electricity or heat for buildings.

A number of prototype fuel-cell cars, buses and trucks have been or are being demonstrated in various places around the world: the most recent models work well and prove popular with end users. Most use the proton exchange or polymer electrolyte membrane (PEM) technology. PEM fuel cells operate at relatively low temperatures of around 80° C, which allows a rapid start-up time and causes less wear on system components. They have a higher power-to-weight ratio than other types of fuel cell. However, they require a noble metal catalyst, which adds to the cost. Other technologies under development include the solid oxide fuel cell (SOFC), which uses a solid, non-porous ceramic compound as the electrolyte, and operates at high temperatures; and the alkaline fuel cell, which uses a potassium hydroxide solution as the electrolyte together with non-precious metals as the catalysts at the anode and cathode, operating at low to medium temperatures.

Several leading car manufacturers are working on demonstration fuel-cell cars, some of which can travel up to about 500 kilometres before they need refuelling. In June 2005, the American Honda Motor Company became the first automotive manufacturer to lease a fuel-cell vehicle to an individual customer. DaimlerChrysler has a fleet of around 100 small fuel-cell vehicles in operation in several countries, and aims to begin commercial production in 2012. BMW plans a production run of its new hydrogen-powered car in the hundreds by 2010, with sales aimed at fleet operators and individuals in Europe and the United States. The hydrogen fuels both an internal combustion engine for motive power and a separate fuel cell to supply electrical power. Ford, General Motors and Toyota also have major fuel cell development programmes. Most of the models currently being developed are fuelled directly with hydrogen, without on-board reforming of gasoline or methanol. The latter approach was originally the focus of fuel-cell vehicle development as car manufacturers believed that it would be easier to make use of the existing fuel-distribution infrastructure. Technical and environmental problems have led most of them to abandon on-board reforming.

Stationary fuel cells, for on-site production of heat and electricity, are also beginning to be commercialised. Their main use, at least in the near term, is expected to be for auxiliary and distributed power generation. Later, smaller units could be used to meet small-scale household needs for heat and electricity. SOFC devices currently under development reform natural gas internally, producing separate streams of hydrogen, which is supplied to the fuel cell, and carbon dioxide, which can be captured. They have an electrical efficiency of up to almost 56% and overall thermal efficiency of 88% (Larsen et al, 2004).

The essential drawback with fuel cells, whether used in vehicles, in building or for power generation, is cost. After decades of research and development, a hydrogen-powered fuel-cell vehicle still costs much more than an equivalent gasoline or diesel model because of the cost of the fuel cell itself. The current

production cost of a saloon car (sedan) fitted with a fuel-cell system is thought to be as much as \$1 million, though car makers and fuel-cell manufacturers are reluctant to reveal the true cost for commercial reasons. Fuel-cell buses cost closer to \$2 million. At present, the most competitive fuel cells cost up to fifty times more per kW of engine power than a standard gasoline-fuelled internal combustion engine, though fuel efficiency is twice as high.

Technical challenges also need to be addressed. There is a need to improve the durability and dependability of fuel cells. Currently, fuel cells – particularly those that operate at high temperatures – are prone to breaking down and have relatively short operating lives. More important, there is a need to design a practical system for on board storage of hydrogen. This is perhaps the biggest challenge facing developers of fuel-cell vehicles – the consequence of hydrogen's very low energy density at atmospheric temperature and pressure. To carry enough fuel to travel 400 kilometres, hydrogen would need to be compressed to extremely high pressures to fit into a standard-size car fuel tank. At present, it is possible to compress the gas to 700 bar. But even at that pressure, the tank has to be 4.6 times larger than a normal gasoline tank to contain enough fuel to travel as far as with gasoline. More research is needed to find affordable materials that are strong enough to withstand the pressure and resist the impact in an accident, yet light enough to carry in a normal car. Liquid storage for small vehicles faces practical problems, because large amounts of energy are needed to liquefy the hydrogen gas and maintain it at a temperature of minus 253° C. An alternative storage method currently being investigated is to store the gas in solid form as metal hydrides – alloys created through chemical processing – from which the hydrogen could be released as needed. But such a system is heavy, reducing vehicle fuel efficiency.

There have been major advances in fuel-cell technology over the last decade or so, and this gives hope that fuel cells may one day be able to compete with conventional vehicle technology on performance and cost (Box 5). This will require yet more research and development. Bringing fuel cells into

Box 5: Competing Options in the Transport Sector

Hydrogen as a transport fuel is just one of several options for enhancing energy security and reducing emissions of CO₂ and noxious gases. In practice, hydrogen might exist alongside other fuels, creating a system that is much more diverse than at present. The most promising options include the following:

- *Biofuels*: The United States and the European Union have ambitious plans to increase bio-ethanol, largely derived from corn, and bio-diesel, based on seed crops such as rape. Costs have fallen sharply in recent years but remain well above the cost of oil-based fuels – despite higher oil prices.
- *All-electric vehicles*: The efficiency of electric-battery vehicles, charged from the grid, can be higher than that of hydrogen fuel-cell vehicles. But the driving range and the time it takes to recharge the battery are still major hurdles to market deployment.
- *More efficient internal combustion engines*: These would reduce emissions from vehicles powered by petroleum-based fuels. Hybrid technologies, which combine an electric battery recharged by an on-board internal combustion engine, appear to have the greatest potential for raising efficiency in the near term.

commercial production will undoubtedly lower unit costs. In fact, car makers are confident of achieving large cost reductions in just a few years. Toyota aims to cut the cost of fuel-cell cars to \$50,000 by 2015. General Motors aims to have a car in full commercial production by 2010 with a fuel cell costing no more than \$5000. The US Department of Energy's Fuel Cell Program has a goal of lowering the cost of stationary fuel cells by a factor of ten to around \$400 per kW or less. This would be close to the current cost of a combined-cycle gas-turbine power plant.

Carbon Capture and Storage

The prospects for the hydrogen economy becoming a reality in the foreseeable future hinge on advances in carbon capture and storage (CCS) technology, and its integration into hydrogen production based on fossil fuels. This is a necessary, but not a sufficient, condition. Success in deploying CCS would also pave the way for environmentally acceptable production of electricity using fossil fuels; hydrogen would still have to compete against electricity in final energy uses, including transport.

There are three distinct steps involved in CCS associated with hydrogen production:

- Capturing CO₂ from the flue-gas streams emitted during the production process (pre-combustion capture).
- Transporting the captured CO₂ by pipeline or in tankers.
- Storing CO₂ underground in deep saline aquifers, depleted oil and gas reservoirs or unmineable coal seams.

CO₂ capture and transportation has been carried out for decades, albeit generally on a small scale and not with the purpose of ultimately storing it. There is a need to improve these technologies for them to be widely deployed on a large scale in association with hydrogen production, and to lower the cost. At present, most capture research and development is focused on post-combustion capture from burning fossil fuels in power plants. Much more work also needs to be done on carbon storage to demonstrate its viability and reduce the cost (Box 6).

Current carbon-capture technologies are capable of reducing emissions from hydrogen plants using steam reforming by about 85%, allowing for the additional emissions from the energy consumed in the capture process (IPCC, 2005). For every tonne of hydrogen produced today, 9 tonnes of carbon dioxide is vented into the atmosphere when natural gas is the feedstock and about 19 tonnes when coal is used. It is possible today to reduce those emissions to 1.5-3 tonnes (IEA, 2004b). Bigger reductions may be possible in the future, by improving the efficiency of both the hydrogen-production process and the capture technology. However, the cost per tonne of carbon dioxide captured increases sharply with each incremental improvement in the capture rate, so 100% capture is unlikely ever to be economic.

Box 6: Current Carbon Capture and Storage Demonstration Projects

A number of CCS demonstration projects have been launched in recent years. In most capture projects, existing technologies are applied at power plants. Various small-scale pilot plants based on new capture technologies are in operation around the world. Only one power plant demonstration project on a megatonne-scale has so far been announced: the *FutureGen* project in the US. This is a coal-fired advanced power plant for cogeneration of electricity and hydrogen. Its construction is planned to start in 2007. Other demonstration projects are planned in Canada, Europe, and Australia.

There are about a hundred ongoing and planned geologic storage projects. The two largest are in Norway and Canada. The first is at the offshore Sleipner oil and gas field, where CO₂ is stored in deep saline aquifers. About 1 million tonnes of the gas has been stored each year since 1996. No leakage has so far been detected. The second involves the use of CO₂ to enhance oil recovery and its subsequent storage underground at the Weyburn oilfield in Canada. About 2 million tonnes per year have been stored since 2001. The results of both projects suggest that the gas can be stored permanently without leakage or other major problems. Pilot projects suggest that CO₂-enhanced coalbed methane and enhanced gas recovery may also be viable storage methods.

Deep saline aquifers, depleted oil and gas reservoirs and unmineable coal seams are the most promising options for underground CO₂ storage. The capacity of saline aquifers – the single largest potential storage option – might be large enough to store decades-worth of global CO₂ emissions. Another option is storing the gas at the bottom of oceans, but the prospects are uncertain because of the unknown environmental effects. Transforming CO₂ into a solid and storing it underground is still at a conceptual stage. All three storage options need to be demonstrated on a large scale. A particular concern is whether the CO₂ can leak back into the atmosphere.

The future cost of CCS will depend on which technologies are used, how they are applied, how far costs fall as a result of research and development and market uptake, and fuel prices. Capturing CO₂ from plants which co-generate electricity and hydrogen might be more economical than stand-alone power or hydrogen production with CO₂ capture. Total CCS costs can be broken down into capture, transportation and storage:

- Current estimates for large-scale capture systems are of the order of \$25–50 per tonne of CO₂ (IEA, 2004b). Costs are expected to fall significantly as the technology is developed and deployed on a large scale, possibly to around \$10–25 for coal-fired plants and to \$25–30 for gas-fired plants over the next 25 years.
- With CO₂ transportation by pipeline, costs depend on the volumes being transported and on the distances involved. For a large-volume system, costs currently range from \$1–5 per tonne of CO₂ per 100 km.
- Storage costs depend on the type of site, its location and method of injection. They are low relative to capture and transportation costs, at about \$1–2 per tonne of CO₂. But in some parts of the world, storage sites are far from where hydrogen plants would be built, which would add to the cost.

At present, the total cost of CCS typically ranges from \$50 to \$100 per tonne of CO₂. This is equivalent to about 15–30 US cents per gallon of gasoline, \$20–40 per barrel of crude oil or 2–4 US cents per kWh – roughly equal to the current cost of gas-fired power generation. By comparison, the average price of a permit to emit one tonne of CO₂ under the European Emission Trading Scheme was around \$28 in September 2005. CCS costs could drop significantly in future – perhaps by half within the next 25 years – depending on funding for research and development and the success of demonstration projects. In this case, CCS would become competitive in Europe, even without any increase in carbon values.

CCS will not ensure a sustainable energy future, as fossil fuel resources are finite. But, if integrated into the production of hydrogen and/or electricity, it could provide the basis for a more sustainable energy system over a transitional period lasting at least several decades. The planet's fossil-fuel resources are far from being depleted. Proven reserves of oil are equal to 40 years of current production; natural gas reserves are equal to 67 years, and coal reserves, 164 years (BP, 2005). Exploration and improved production technologies that enhance recovery rates will undoubtedly increase these reserves. In the very long term, as fossil resources are eventually depleted, mankind will have no choice but to turn to renewable energy technologies – if they have not become competitive with fossil fuels associated with CCS before then.

The Transition to the Hydrogen Economy

The transition to a hydrogen economy would require trillions of dollars of investment in new infrastructure to produce, transport, store and deliver hydrogen to end users, as well as to manufacture fuel cells. The need to install carbon capture and storage systems will add to the cost. Continuing government support for research and development, and strong incentives to kick-start investment will be essential. The transition to the hydrogen-energy system could take several decades, because of the slow turnover of the existing stock of capital that either makes or uses energy and the sheer amount of capacity that would need to be built.

Investment in Hydrogen Infrastructure

The introduction of hydrogen on a large scale would require a radical transformation of the global energy-supply system. A vast infrastructure to produce, transport, store and deliver hydrogen, as well as to manufacture fuel cells, would need to be built. And consumers would need to invest in hydrogen fuel-cell vehicles and related equipment. The installation of facilities to capture the carbon emitted in the production process and store it underground would add to the cost, though this would be needed regardless of the choice of energy carrier for as long as fossil fuels remain the primary source of energy. New hydrogen and related infrastructure would be needed not just to replace existing energy facilities, but also to meet rising global energy needs. This presents both a challenge and an opportunity to introduce new hydrogen-energy infrastructure.

The total cost of building hydrogen infrastructure would depend on timing, the pace of unit-cost reductions and the extent to which hydrogen replaces existing energy systems. All these factors are very uncertain. Even if hydrogen were to replace only conventional automotive fuels, the eventual investment cost worldwide along the entire fuel-supply chain – over and above what would have been invested anyway – would certainly run to trillions of dollars, even on optimistic cost assumptions. Fuel-cell vehicles would probably account for a large part of the cost. If all of the estimated 800 million vehicles on the world's roads today were eventually replaced with fuel-cell models, the incremental production cost alone would be \$2 trillion, on the hypothetical assumption that each fuel-cell vehicle costs on average \$2 500 more than a conventional vehicle. The cost of building pipelines to supply hydrogen refuelling stations and hydrogen plants would also be very large. For example, on current costs, building

Building enough centralised hydrogen plants to supply the fuel needed to run all the cars, trucks and buses in use in the world today would require a staggering \$8 trillion of investment at current costs.

enough centralised hydrogen plants to supply the fuel needed to run all the cars, trucks and buses in use in the world today would require a staggering \$8 trillion in investment – not including the cost of carbon capture. This sum is equal to almost half the total cumulative investment in the entire energy sector that the International Energy Agency estimates will be needed worldwide over the next quarter of a century (IEA, 2005a).

Cost is the principal barrier to investment in hydrogen. No private firm will invest in a commercial hydrogen venture unless it believes that it will be able to compete against existing fuels and turn a profit. Hydrogen is still far from being competitive in most applications, but that could change with technological breakthroughs and government incentives or mandates. If that is the case, the opportunities for profitable development of hydrogen facilities would expand over time. Initially, investment may be limited to a few remote locations, where the costs of fuel distribution and electricity infrastructure are relatively high, where public concern about environmental sustainability is especially strong and where governments provide large incentives. As the market develops mass production of supply equipment and fuel cells will bring economies of scale, advance the learning process and further lower costs.

Hydrogen could become competitive with technological breakthroughs and government incentives or mandates.

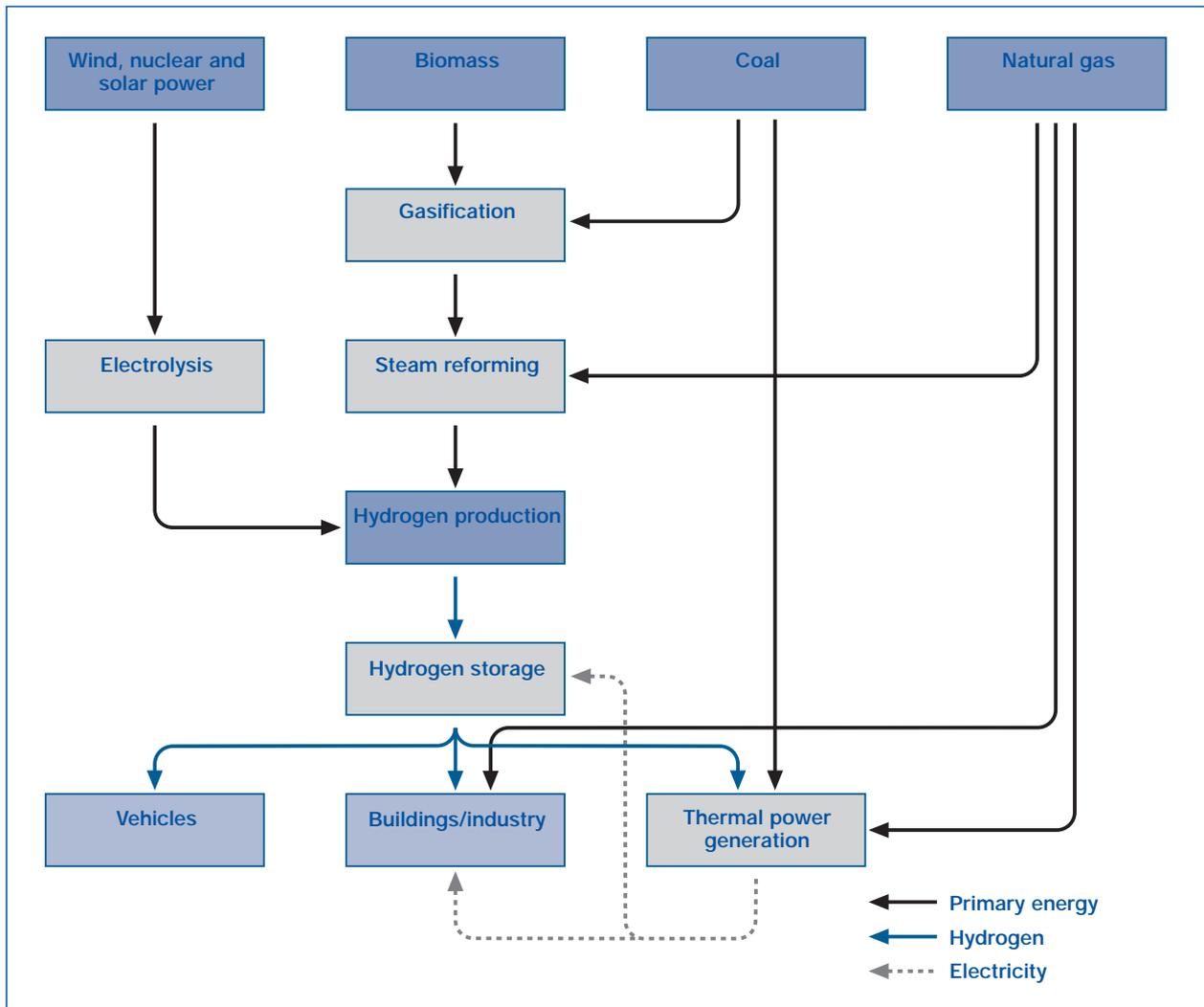
But cost is not the only barrier to investment. As with any radically new technology, hydrogen could face the classic chicken-and-egg conundrum: the lack of a market in the first place deters investment, preventing the market from developing. Put another way, why develop hydrogen cars when there is no distribution network, and why develop a distribution network if there are no hydrogen cars? Hydrogen use will not take off until critical market mass is achieved. The market needs to be large enough to demonstrate to potential users and fuel providers that hydrogen is a safe, reliable and cost-effective alternative to conventional fuels. The more fuel-cell vehicles there are on the road, the more confidence other vehicle owners will have to switch fuels. And the hydrogen refuelling network would have to be developed quickly: a lack of refuelling stations would be a major impediment to persuading vehicle owners to switch to hydrogen, even if there were a financial incentive to do so.

The sheer scale of investment in a hydrogen project, together with inherent technical and financial risks, could also discourage private companies. Government intervention in the form of financial incentives and regulatory measures that tilt the playing field in favour of hydrogen will almost certainly be necessary to get around this problem, especially where the economic case for hydrogen is marginal (see below). A strong, long-term commitment by government to the development of hydrogen infrastructure will be essential in giving fuel suppliers, equipment manufacturers and consumers confidence that they will be able to make a reasonable return on the investments required to switch fuels.

In the early stages of the transition – or more accurately, series of transitions – to hydrogen, the fuel would both complement existing energy systems and compete against them (Figure 2). The inter-linkages that could emerge could make the energy system more flexible, more diversified and more secure. Natural gas and coal would probably provide the main inputs to hydrogen production, while also remaining important inputs to electricity-generating plants. Gas would

also continue to play a role in meeting energy needs in stationary uses in industry and in buildings, and possibly in the transport sector as well (in the form of compressed natural gas). It might also prove economic to mix hydrogen with natural gas for distribution through the existing gas-pipeline system.

Figure 2: Linkages between Hydrogen and the Rest of the Energy System



Source: Menecon Consulting analysis.

Hydrogen would compete against electricity and gas, as well as oil, in all final energy uses, but might also complement electricity by providing a means of storing it. This could be a particularly attractive solution for handling unpredictable fluctuations in outputs from intermittent sources of power generation, such as wind power, and for managing diurnal or seasonal load variations. Local hydrogen-storage facilities would reduce the need for expensive investments in transmission capacity connecting centralised power stations to where electricity service is needed. They would enhance the security of electricity supply, by providing back-up in the event of a failure at a power station or in the transmission system.

Government Support

For the transition to the hydrogen economy to begin, there will most likely be a need for decisive government action in two areas:

- Research, development and demonstration of hydrogen technologies. This effort could be vital to achieving the necessary technological breakthroughs.
- Incentives to encourage investment in hydrogen infrastructure and switching to the fuel once technologies are deemed to be economic.

Because hydrogen is a long way from becoming competitive, the focus of government action today in the field of hydrogen is in research and development (R&D). Research into the use of hydrogen for energy purposes goes back many decades, but the scale of public (and private) funding for hydrogen and fuel cell R&D and demonstration activities has increased enormously in the last few years. This reflects significant technological advances that make it more likely that the fuel will become a viable energy solution in the not too distant future, as well as a growing urgency on the part of policy-makers to seek out sustainable energy solutions that address environmental and energy-security concerns. Many governments now expect the transition to the hydrogen economy to begin within the next two decades and are looking to speed up the process, often through collaborative international and joint private-public sector programmes.

Research into the use of hydrogen for energy purposes goes back many decades, but funding has increased enormously in the last few years.

The International Energy Agency (IEA) estimates that current public hydrogen R&D spending worldwide amounts to about \$1 billion per year (IEA, 2004a). This spending might seem impressive, but is actually modest compared to the sums governments are spending on other forms of energy R&D. In member countries of the Organization for Economic Cooperation and Development (OECD), hydrogen accounts for only about 15% of total energy R&D budgets. R&D spending on hydrogen is thought to exceed that on fossil fuels and renewables, but is still much lower than that on nuclear energy. In 2001 – the latest year for which comprehensive data is available – OECD countries spent \$3.8 billion on nuclear energy, \$700 million on fossil fuels and \$760 million on renewables (IEA, 2004d). Total OECD R&D spending in that year was \$8.9 billion. Official data may underestimate the importance of hydrogen R&D, as some activities related to hydrogen are covered by fossil-fuel, nuclear energy and end-use technology programmes.

By far the largest hydrogen programmes are in the United States, Japan and the European Union (Table 1). Between them, these countries account for about two-thirds of total public hydrogen R&D spending. The US administration sharply increased funding, with the launch in late 2003 of a five-year \$1.7 billion hydrogen programme. This includes \$1.2 billion for the Hydrogen Fuel Initiative and \$0.5 billion for the *FreedomCAR* programme, a joint initiative between the US Department of Energy, General Motors, Ford and DaimlerChrysler to develop a commercially viable fuel-cell vehicle. Japan – the first country to undertake a large-scale hydrogen fuel-cell R&D programme – has allocated ¥35 billion (\$320 million) to its hydrogen-research activities in the financial year 2005. Total EU funding – not including national budgets – is expected to reach €2.8 billion over the ten years to 2011, half of which will be provided by the private sector. Of this amount,

production-related projects will account for €1.3 billion and end-use projects for €1.5 billion. Other industrialised countries account for almost all the rest, though some developing economies – notably China, Brazil and India – have launched their own programmes. Details of national and collaborative international programmes, as well as private-sector activities, can be found in Annex A.

Table 1: Public Research and Development Spending on Hydrogen and Other Energy Technologies in the Largest OECD Countries, 2003 (\$ million)						
	Hydrogen	Fossil fuels	Renewables	Nuclear	Other	Total
Canada*	24	47	30	47	92	240
Japan	270	n.a.	n.a.	n.a.	n.a.	n.a.
Germany*	34	14	74	154	25	301
France**	45	33	27	359	0	463
Italy	34	15	61	107	124	341
United Kingdom	3	5	20	n.a.	n.a.	n.a.
United States*	97	416	243	371	1623	2750
<i>* Federal spending only. ** 2002 data.</i>						

Source: International Energy Agency (2004d).

Despite recent increases in public spending on hydrogen R&D, it is still dwarfed by that of private companies and organisations, including energy companies, car makers, chemical producers, power utilities and fuel-cell manufacturers. The total amount of private hydrogen-related R&D spending is not known precisely, but it is thought to total about \$3-4 billion per year. This gives an indication of how optimistic the private sector is about the prospects for hydrogen. However, much of this spending would probably not occur without matching commitments from the public sector. Many private research bodies work in partnership with publicly-funded programmes. A continued strong government commitment to R&D will remain a key determinant of the success of long-term efforts to bring hydrogen energy into commercial use.

Government incentives will almost certainly be needed to encourage the development of the hydrogen market as the technology approaches the threshold of competitiveness. Such incentives could be justified by the long-term social, economic and environmental benefits that a shift to hydrogen would bring. They could take the form of favourable taxation vis-à-vis conventional forms of energy, other economic incentives or regulatory measures aimed at speeding up the switch to hydrogen. They might come on top of carbon penalties, in the form of carbon taxes or emission caps, which would most likely favour hydrogen. These subsidies would normally be removed once scale economies have been achieved, the technology is well proven and critical market mass has been reached. There are plenty of precedents for proactive government action to effect a shift in the pattern of energy use through the use of market instruments. For example, governments in continental Europe used preferential

taxes to encourage the development of the natural gas transmission and distribution network.

Governments will also need to work with fuel providers, equipment manufacturers, car makers and standard-setting bodies to establish appropriate standards and codes for designing, building, testing and ultimately marketing hydrogen-related equipment. They will be crucial to ensuring safety and lowering costs. International harmonisation of standards would encourage trade and avoid parallel development of incompatible equipment and technology lock-in with different standards, further driving down costs. Governments will also be called upon to assist in promoting public awareness about the benefits of hydrogen, as well as the training and education of industry personnel.

Long-Term Projections of Hydrogen Use

It is extremely hard to predict how soon the transition to hydrogen as an energy carrier might begin and how long it might take, as it depends critically on technology breakthroughs in a number of different areas. It is impossible to know when these might occur and the extent to which they will lower costs and enhance the competitiveness of hydrogen vis-à-vis conventional forms of energy. As a result, all long-term projections of hydrogen use are based on assumptions about supply costs.

However successful current hydrogen R&D efforts are in bringing down costs and improving performance, the transition process to a hydrogen economy would undoubtedly be gradual, probably lasting several decades. The planning, construction, operation and decommissioning of energy infrastructure stretch over very long timeframes. Cars and trucks typically last a decade or two, but power stations, oil refineries and pipelines are built to last for decades. Retiring them early would be very expensive. And the widespread deployment of carbon capture and storage technology will be a mammoth undertaking. Mobilising all the investment needed to completely overhaul the entire existing energy system within a decade or two would simply not be practical, even if we were prepared to pay the enormous cost of phasing out existing energy facilities early. So, even if competitive hydrogen technologies were to emerge within the next 20 years, it would probably take most of the rest of this century to complete the transition to the hydrogen economy – a stage at which only hydrogen and electricity are used to deliver energy services.

If competitive hydrogen technologies were to emerge within the next twenty years, it would probably take most of the rest of this century to complete the transition to a hydrogen economy.

The leading sources of long-term global energy projections, including the US Energy Information Administrations' *International Energy Outlook 2005* and the IEA's *World Energy Outlook 2005*, project hydrogen to play only a marginal role in meeting final energy needs in the next 20-25 years. However, both reports acknowledge that major technological breakthroughs could result in earlier and faster market penetration. Longer-term scenarios developed by the IEA paint a slightly more optimistic outlook for hydrogen use: in a scenario that assumes a \$50 per tonne carbon-dioxide penalty, hydrogen use, mostly for transport, reaches almost 300 million tonnes of oil equivalent – enough to fuel over a quarter of all passenger cars in the world. Fuel cells also play a significant role in

industry, power generation and the residential and commercial sectors.

All projections of hydrogen use are, of course, highly sensitive to assumptions about the rate at which the unit costs of different components of a hydrogen-energy system decline over time. The technology-learning curves observed for technologies in the past vary considerably, so it is hard to be sure about what might reasonably be expected in the way of cost improvement for hydrogen technologies. How many resources are devoted to research and development will be vitally important, as will the commitment of energy providers and vehicle manufacturers to large-scale commercial production. Government incentives and regulations, including carbon penalties, to encourage investment in hydrogen infrastructure will also play a key role.

Hydrogen and the Developing World

Developing economies have at least as much to gain from a move towards the hydrogen economy as industrialised ones, since they generally suffer more from urban pollution and their economies tend to be more energy intensive. Yet the transition will probably start later in most developing nations, as they are less able to afford to participate in R&D and the financial incentives needed to kick-start the process. The rich world must be ready to support developing economies in making this happen, as and when it becomes a viable energy solution, to the benefit of the overall push for hydrogen. International and non-governmental organisations have an important role to play in assisting countries in creating a market-based policy environment within which hydrogen and other emerging energy technologies are able to compete against existing, conventional energy systems.

Relevance of Hydrogen to Developing Economies

Although most current hydrogen R&D is taking place in the industrialised countries, developing economies have as much – if not more – to gain from moving to the hydrogen economy. Their towns and cities generally suffer far more from the pollution caused by road traffic, coal-fired power stations and industrial boilers. Many developing economies are more economically vulnerable to fluctuations in international energy prices, as their economies are more energy-intensive. The poorest countries lacking appreciable resources of fossil fuels may be able to exploit their biomass and other renewable energy potential to produce hydrogen. The entire world stands to benefit from the deployment of hydrogen in developing economies, if it leads to fewer emissions of greenhouse gases and less regional pollution, and if it stimulates economic development.

The transition to hydrogen is likely to begin later in most developing economies than in the industrialised countries, as they will be less able to afford the cost of participating in R&D. But engaging developing economies early in the process of developing and commercialising hydrogen technologies could speed up the transition to hydrogen in the developing world. This could allow the poorest countries, which today have only limited energy-distribution networks, to leapfrog conventional fossil-fuel technologies. The developing economies as a whole are expected to account for the bulk of the increase in global energy use

Developing economies have as much – if not more – to gain from moving towards a hydrogen economy than industrialised ones.

The earlier developing economies begin the transition to hydrogen, the less their energy use would be tied to fossil-energy systems.

in the coming decades. Most of that increase will take the form of oil, natural gas and coal – unless there are breakthroughs in technology or radical shifts in energy policy that allow renewables and/or nuclear energy to play a much bigger role than currently appears likely. The earlier these countries begin the transition to hydrogen, the less their energy use would be tied to fossil-energy systems and the quicker they could achieve energy sustainability.

The initial focus of efforts to establish hydrogen systems in developing economies will most likely be on transport and possibly on stationary uses in remote, rural settings where the cost of connecting communities to the electricity grid is highest. The local environmental gains from switching from conventional automotive fuels to hydrogen would generally be much greater in developing than in industrialised countries, where automotive-fuel quality and vehicle-emission control technology is already much more advanced and air pollution is consequently less of a problem. In most cities in the developing world, road traffic is the primary source of air pollution – a problem that has reached catastrophic proportions in many cases. Demonstration projects of fuel-cell vehicles and refuelling systems are already underway in parts of the developing world. The joint Global Environment Facility / United Nations Development Programme *Fuel Cell Bus Programme*, for example, involves commercial demonstrations in Beijing, Cairo, Mexico City, New Delhi, Sao Paulo and Shanghai. China has also set up its own fuel-cell bus demonstration scheme, with the aim of putting 200 buses into commercial operation in time for the 2008 Olympic Games in Beijing.

The local availability of biomass, solar energy and wind resources could provide the basis for the production of hydrogen in those countries where fossil fuel resources are scarce. This would preclude the need to capture and store carbon dioxide. Biomass, in particular, could be a low-cost option for some countries. The modular nature of fuel cells makes them an attractive option for supplying power to remote, off-grid communities. Hydrogen could provide a means of storing electrical energy generated from intermittent solar or wind energy.

Implications for National Energy Policy-making

What should the governments of developing economies be doing today in anticipation of an eventual transition to a hydrogen economy? For the largest and richest countries, active involvement in hydrogen research and development, especially through collaborative international programmes, could facilitate the introduction of new hydrogen technologies as they become competitive. Brazil, China and India have launched their own hydrogen programmes and are members of the International Partnership for the Hydrogen Economy (see Annex A for details). But, with the exception of China, the resources that they will be able to devote to these activities will inevitably remain modest compared to those of the biggest industrialised countries. For the poorest developing economies, a strong commitment to research and development is simply beyond their means. Most developing economies will probably be buyers rather than developers of cutting-edge technologies.

As hydrogen technologies approach the stage at which they are ready to be commercialised, policy-makers will need to pay more attention to the implications for the transition to hydrogen of immediate decisions about investment in large-scale conventional energy infrastructure. As developing economies grow richer, they will build thousands of power plants, as well as new refineries and pipeline systems. These facilities will be intended to last many decades. Replacing them before the end of their economic lifetimes would be very expensive. There is a risk that a decision taken today to pursue a conventional energy project will hinder the introduction of hydrogen technologies at some point in the future, by anchoring the energy system to fossil fuels. There is inevitably a trade-off between the benefits of providing modern energy services today and developing a sustainable energy system in the longer term. There is an urgent need to make available those services to the two billion people in the developing world that do not yet have them. Waiting for affordable clean energy solutions to emerge is neither a practical nor a morally acceptable option.

The best way to ensure that energy investment is undertaken in the most economically efficient manner is to establish a market-based policy framework. The aim should be to establish competitive markets and effective mechanisms for regulating natural monopolies, and to make sure that energy is priced correctly. In properly regulated, well-functioning markets, competition ensures that the full costs of supplying energy are reflected in the price the consumer pays. In practice, this is often far from the case. In many developing economies, energy is heavily subsidised, leading to excessive consumption and waste, and exacerbating the harmful effects of energy use on the environment. Subsidies can also place a heavy burden on government finances and undermine private and public investment in the energy sector, impeding the expansion of distribution networks and the development of more environmentally benign energy technologies.

The best way to ensure that energy investment is undertaken in the most economically efficient manner is to make sure that energy is priced and taxed correctly.

Getting energy prices right does not stop there. The environmental and health costs of harmful emissions from burning fossil fuels are rarely reflected in the prices of those fuels, especially coal, in most countries – developing and industrialised alike. There is no perfect way to do this, but one sensible approach is for governments to tax the consumption of each form of energy according to how much carbon dioxide and/or noxious gases it emits. At a minimum, the dirtiest fuels should be taxed more. In that way, the external environmental costs are reflected, or internalised, in the final prices for energy, and the polluter pays proportionately for the damage he causes. Alternatively, the authorities can impose emission limits on each power plant or industrial facility and allow the owners to trade emission allowances – the approach adopted by the European Union to reduce carbon dioxide emissions. Both approaches provide an incentive for power generators and end users to reduce their use of dirty fuels such as coal in conventional plants and to invest in clean technologies, including CCS, renewables and hydrogen.

The prospects for the commercial introduction of hydrogen in developing economies would be much brighter were governments to pursue market, pricing and tax reforms along these lines. There may be a case for more targeted action to spur the take-up of hydrogen – especially in the transport sector and

in rural communities that lack access to modern energy. Rural energy development plans could be modified to support the building of physical linkages between hydrogen, renewable technologies and off-grid systems to supply electricity and other forms of commercial energy to rural areas not yet served by existing distribution networks. This could be justified by the market barriers to the deployment of hydrogen and its long-term social, environmental and economic benefits.

Role of International and Non-Governmental Organisations

The rich world will need to help poorer countries to switch to cleaner energy. The G8 leaders attending the Gleneagles summit in July 2005 acknowledged that it is in their interests to work together with developing economies to find ways to achieve substantial reductions in greenhouse gas emissions and to enhance private investment in more sustainable energy technologies – including hydrogen – and their transfer to those countries. The rich world must be ready to help pay for the poor to switch to low-carbon energy. This should not be seen as charity, but rather as part of a cost-effective strategy to address the threat of global warming.

International and non-governmental organisations – including UNEP – have an important role to play in this process. It is not for any organisation to try to pick winners among the various energy technologies that could emerge in the coming years. The aim should rather be to assist developing economies in creating an energy-policy landscape that promotes efficient, competitive markets, and in facilitating the rapid introduction of hydrogen energy as and when it reaches competitiveness. This will require energy to be priced and taxed so as to reflect the full account of the environmental costs and benefits of different technologies. The scale of the challenge should not be underestimated: the energy-market and pricing reforms that are necessary to make this happen are thorny issues in many developing economies. Development aid, multilateral lending institutions and export-credit agencies will need to play a central role in providing technical assistance to help developing economies along this path, as well as to supply the capital needed to bring hydrogen projects to fruition.

UNEP will play its part in encouraging and facilitating the adoption of hydrogen and other emerging technologies where they are economic and where they bring clear environmental benefits – especially in developing economies. This will involve informing and educating stakeholders, including policy-makers and national and multilateral development-aid funds about the environmental implications of hydrogen. To this end, UNEP is investigating various platforms for disseminating information and advice about hydrogen and fuel-cell developments. Later, UNEP will be on hand to assist countries in preparing for the introduction of hydrogen on a commercial scale.

Key Messages

Hydrogen holds out the promise of a truly sustainable global energy future. As a clean energy carrier that can be produced from any primary energy source, hydrogen used in highly efficient fuel cells could prove to be the answer to our growing concerns about energy security, urban pollution and climate change. This prize surely warrants the attention and resources currently being directed at hydrogen – even if the prospects for widespread commercialisation of hydrogen in the foreseeable future are uncertain.

Considerably more research and development will be needed to overcome the formidable technical and cost hurdles that currently stand in the way of hydrogen. Large reductions in unit costs, notably in bulk transportation and storage, and in fuel cells, are needed for hydrogen to become competitive with existing energy systems. Finding a practical solution to the problem of storing hydrogen on board vehicles is a critical challenge. Governments, energy companies, car makers and equipment manufacturers, who between them are investing billions of dollars in hydrogen-supply and fuel cell R&D and demonstration, are confident that these challenges can be overcome. Unexpected technological breakthroughs stemming from advances in basic sciences, which could have a revolutionary impact on hydrogen supply and fuel cells, cannot be ruled out.

If technological and cost breakthroughs were to be achieved in the near future, the transition to a hydrogen energy system would still take several decades. The slow turnover of the existing stock of capital that either makes or uses energy and the sheer amount of capacity that would need to be built to replace existing systems and to meet rising demand will mean that fossil fuels will most likely remain the backbone of the global energy system until at least the middle of the century.

It seems likely that, in the initial stages of any transition to the hydrogen economy, the fuel would be produced in large part from fossil fuels using existing energy systems. Natural gas, in particular, could provide a “bridge” between the existing fossil fuel economy and the future hydrogen economy. If integrated with carbon capture and storage, hydrogen could be produced from gas or coal with minimal emissions of greenhouse gases. In the longer term, as fossil fuel resources are depleted, renewable energy sources or nuclear energy would increasingly need to take over as primary energy sources for the production of hydrogen and electricity.

Developing economies have at least as much as industrialised countries to gain from an eventual shift to the hydrogen economy, since they generally suffer more from urban pollution and their economies tend to be more energy intensive. But

that process may start later in most developing economies, as they are less able to afford to participate in hydrogen R&D. They could speed up the commercial introduction of hydrogen by establishing a market-based policy framework that ensures that energy is priced and taxed efficiently. In any event, the rich world must be ready to support developing economies in moving onto more sustainable energy paths. International and non-governmental organisations have an important role to play in assisting countries in creating a policy environment within which hydrogen – and other emerging energy technologies – can penetrate the market, as and when it becomes a viable energy solution.

Annex A: Key Players in Hydrogen Research and Development

National and Regional Programmes

Most OECD countries and a growing number of developing economies have active hydrogen and fuel-cell R&D programmes, with aggregate public funding worldwide now running at about \$1 billion per year. Fuel cells account for about half of this spending. Most of the rest is devoted to production, transportation and storage, with small amounts going to end-use technologies not based on fuel cells, such as gas turbines and internal combustion engines. Total spending has increased sharply in the last few years. The biggest increases in funding in dollar terms have occurred in the United States and the European Union. Almost all other countries that undertake hydrogen R&D have also stepped up their activities.

Some countries have integrated R&D programmes that cover all elements of hydrogen supply and end uses. Others focus on specific aspects. In each case, the balance of funding between different research areas reflects a mixture of national policy priorities, indigenous resource endowment, and research traditions and strengths. For example, the COAL21 programme in Australia, a country with very large coal reserves, covers hydrogen production from coal integrated with CCS. Germany places heavy emphasis on fuel cells for vehicles, reflecting the country's traditional strength in vehicle manufacturing.

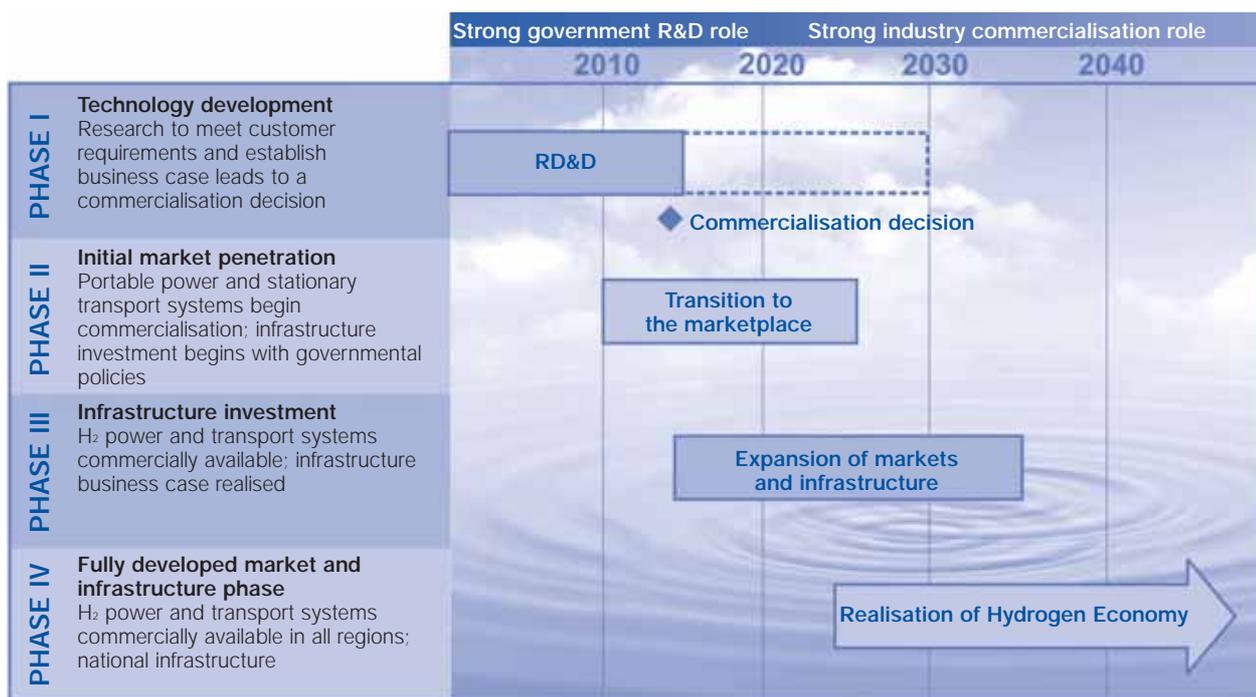
United States

The US government carries out most of its hydrogen and fuel-cell R&D under the Hydrogen, Fuel Cells and Infrastructure Technologies Program, run by the Department of Energy. The government's strategy is to concentrate funding on high-risk applied research on technologies in the early stages of development, and leverage private-sector funding through partnerships. The administration sharply increased funding in 2003, with the launch of a five-year \$1.2 billion hydrogen development programme, known as the Hydrogen Fuel Initiative. An additional \$500 million has been earmarked for the *FreedomCAR and Fuel Program*, a joint private/public initiative to develop a fuel-cell vehicle (see below).

The Department of Energy has identified four phases in the transition to the hydrogen economy (Figure 3). In phase 1, government and private organisations will conduct R&D, implement technology-demonstration projects, carry out public education and develop codes and standards. In 2015, the administration will determine whether or not hydrogen technologies can be commercialised in the near term and whether R&D should be continued. The second initial market penetration phase is expected to begin as early as 2010. The government will subsidise the modification of existing infrastructure to support stationary and transport hydrogen applications. If the commercialisation decision is positive,

the federal government will continue with phase 2 and launch phase 3, which will involve building large-scale infrastructure for manufacturing fuel cells and distributing hydrogen. Subsidies are expected to remain in place to maintain the momentum. The final phase 4, the realisation of the hydrogen economy, is expected to begin in 2025.

Figure 3: Transition to the Hydrogen Economy Envisaged by the US Hydrogen Programme



Source: www.hydrogen.gov/president.html

Japan

Japan was the first country to undertake a large-scale hydrogen fuel cell R&D programme – a ten-year, ¥18 billion (\$165 million) effort that was completed in 2002. The New Hydrogen Project (NEP), which started up in 2003, focuses on commercialisation. Funding has been raised each year since the project began, reaching ¥35 billion (\$320 million) in the financial year 2005. The Japanese government is confident that, with continuing strong financial support, hydrogen fuel cells can become competitive within the next two decades.

The NEP sets ambitious targets for the introduction of fuel-cell vehicles, refuelling stations and stationary fuel-cell capacity for 2010 and 2020 (Table 2). Implementation is due to occur in three stages. The initial stage, which ran through to 2005, focused on continued technology development, fuel cell demonstrations and the development of codes and standards. The induction stage, which will run to 2010, involves the acceleration of vehicle sales in parallel with the construction of refuelling infrastructure. The diffusion stage, which will run from 2011 to 2020, will step up initiatives to build infrastructure started in the second stage.

Table 2: Hydrogen Commercialisation Targets in Japan

	2010	2020
Fuel-cell vehicles on the road (number)	50,000	5,000,000
Hydrogen refuelling stations (number)	-	4000
Stationary fuel-cell co-generation systems (MW)	2200	10,000

Source: International Energy Agency (2004a).

European Union

Most EU funding for hydrogen-related activities is provided under the Renewable Energy Sixth Framework Programme, which runs from 2002 to 2006. Some €100 million (\$120 million) of EU funds, matched by an equivalent amount of private investment, has been awarded to R&D and demonstration projects for hydrogen and fuel cells after the first call for proposals in 2003. Further calls for R&D proposals, worth a public and private investment of €300 million (of which EU funding will amount to €150 million), are planned. Total public and private funding is expected to reach €2.8 billion over the ten years to 2011. Of this amount, production-related projects will account for €1.3 billion and end-use projects in communities, €1.5 billion. Some other EU programmes also include some activities related to hydrogen.

All the hydrogen projects that are being funded by the European Union are intended to support the large-scale *Quick Start* initiative, which aims to attract private investment in infrastructure projects in partnership with national public institutions and the European Investment Bank. The ultimate goal is to accelerate the commercialisation of hydrogen-related technologies during the coming decades. Production-related projects aim to advance cutting-edge research to build a large-scale demonstration plant that is able to produce hydrogen and electricity on an industrial scale and to separate and store safely the CO₂ generated in the process. End-use projects are intended to explore the economic and technical feasibility of managing hydrogen-energy communities, known as the "hydrogen village". This will involve establishing centralised and decentralised hydrogen production and distribution infrastructure, autonomous and grid-connected hydrogen/power systems, a substantial number of hydrogen-powered vehicles and refuelling infrastructure. Research will also be conducted into different production pathways including renewable energy sources, notably wind and biomass, culminating in demonstrations of leading-edge technologies.

Other Programmes

There are sizeable hydrogen programmes in a number of other OECD countries, including Australia, Canada, France, Germany, Italy and Korea. In most cases, projects are carried out in collaboration with private organisations:

- *Australia's* hydrogen programme is aimed at reducing the carbon/greenhouse-gas intensity of energy supply and use, to allow the continued exploitation of

its large fossil-fuel reserves. One focus of R&D is the production of hydrogen through the gasification of coal under the COAL21 programme.

- *Canada's* hydrogen R&D focuses on production from renewable energy and fuel cells. Notable successes include the development of the Ballard PEM fuel cell, which led to the world's first demonstration of a fuel-cell bus in 1993, and the Hydrogenics alkaline water electrolyser. Public funding has been running at over C\$30 million (US\$25 million) per year and cumulative spending since the early 1980s exceeds C\$200 million.
- In *France*, hydrogen activities cover PEM and solid-oxide fuel cells; production technologies based on coal-gasification with carbon capture, high-temperature solar and nuclear energy, and small biomass and fossil-fuel reforming; and storage devices. Total annual government spending, including EU contributions, is estimated at about €40 million (\$48 million).
- *Germany* is a world leader in hydrogen and fuel cell development. Fuel cells have become the main focus of public and private R&D and demonstration, reflecting in large part the country's traditional strength in car manufacturing. There are a number of demonstration projects under way, including two hydrogen-refuelling stations at Munich Airport to support three buses and a fleet of hydrogen-powered BMWs, and the Clean Energy Partnership initiative in Berlin, which involves the installation of a refuelling station for up to 30 fuel-cell cars. In fact, nearly three-quarters of the fuel cells being demonstrated in Europe are in Germany. In total, the country's fuel-cell industry employs an estimated 3000 people. Total public funding for hydrogen-related activities is estimated at €34 million (\$41 million) per year.
- In *Italy*, public funding has averaged about €30 million per year since the start of the decade, with about 60% going to hydrogen production and the rest to fuel cells. Several demonstration projects are under way. One notable achievement is the construction of a plant producing hydrogen through electrolysis integrated with photovoltaics. Another initiative, the Biocca Project, aims to demonstrate urban hydrogen infrastructure in Milan and in the Lombardy region.
- The government of *Korea* only started funding hydrogen-related R&D in 1998, but is emerging as a major player. A new programme was launched in 2004 with a budget of \$586 million through to 2011. The programme targets for 2012 the development of hydrogen-production systems using renewables-based electrolysis, the commercialisation of a stationary 370 MW fuel cell and the introduction of 10,000 fuel-cell vehicles. The government also makes available large subsidies for hydrogen and fuel-cell investments.

Outside the OECD, the leading countries in hydrogen R&D are China, India, Russia and Brazil. *China's* hydrogen R&D and demonstration efforts are motivated largely by severe pollution in many of its cities, as well as by worries about energy security. Annual public funding is thought to be in the tens of millions of dollars, with even larger sums being spent by private organisations. A fuel-cell bus demonstration scheme in Beijing aims to put 200 buses into

commercial operation in time for the 2008 Olympic Games. The first hydrogen-powered buses have already begun operation in the city under the UNDP/GEF demonstration project. The Shanghai government also plans to introduce 1000 fuel-cell vehicles by 2010.

India has budgeted 2.5 billion rupees (\$58 million) to fund hydrogen and fuel cell projects in universities and government-run research laboratories over the three years to 2007. A planned pilot project involves blending small amounts of hydrogen into diesel fuel for use in about 50 buses in New Delhi. Nationally, there are plans to introduce by the end of the decade 1000 hydrogen-powered vehicles, of which 800 will be three-wheelers, and 200 buses. Car makers are expected to contribute at least 5 billion rupees (\$116 million) to the development and demonstration of fuel-cell vehicles over the next five years.

Russia has a long history of hydrogen production and R&D. A national hydrogen development programme, financed by the federal budget and private investors, is under discussion, aimed at developing a market for hydrogen-powered vehicles. Hydrogen-related activities were stepped up in 2003 with an agreement between the Russian Academy of Science and the Norilsk Nickel Company on a fuel cell development programme. Total joint funding will be \$120 million, of which \$30 million was budgeted in 2005.

Brazil has devised a Hydrogen Roadmap, which aims to commercialise fuel cells for transport and off-grid energy systems. The focus of Brazilian hydrogen R&D is on production from water electrolysis; reforming of natural gas and reforming or gasification of ethanol and other biofuels; storage technologies, including metal hydrides; and fuel cells.

Private Industry

Private-sector spending on R&D and demonstration of hydrogen, fuel cells and related technologies is thought to be considerably larger than public budgets. Precise budgets are not available. The International Energy Agency estimates that private-sector spending currently amounts to between \$3 billion and \$4 billion per year – up to four times the amount being spent by public bodies. The main players are oil and gas companies, car manufacturers, electricity and gas utilities and power-plant construction companies. A growing number of firms that manufacture fuel cells and other hydrogen-related equipment supplied to private- and public-sector organisations also fund their own R&D.

One of the largest projects in which private firms are involved is the *FreedomCAR and Fuel Partnership*, a joint initiative originally set up in 2002 by the US Department of Energy with General Motors, Ford and DaimlerChrysler to develop non-oil fuelled vehicles. It was expanded to include five energy companies – BP America, ChevronTexaco Corporation, ConocoPhillips, Exxon Mobil Corporation and Shell Hydrogen (US) – in 2003. Hydrogen fuel cells are a central element of the project. US government funding is \$500 million.

The US government is also seeking private funding for *FutureGen* – an initiative to build the world's first zero-emission hydrogen production and power plant

integrated with CCS. The Department of Energy is negotiating a cooperative agreement with a consortium led by the coal-fired electric power industry and the coal-mining industry. The consortium will be responsible for the design, construction and operation of the plant, and for the monitoring, measurement and verification of carbon dioxide capture at the plant. The consortium is expected to contribute approximately \$250 million towards the total cost of the project, which is estimated at \$950 million (in year-2004 dollars).

The California Fuel Cell Partnership is another example of a collaborative private-public initiative, involving car manufacturers, energy companies, fuel-cell developers and government agencies. It aims to develop and demonstrate fuel-cell vehicles under real day-to-day driving conditions, and promote the development of refuelling infrastructure.

International Cooperation

Government and private R&D efforts are complemented by three major multilateral international collaborative initiatives, all of which were launched in 2003:

- The International Partnership for the Hydrogen Economy (IPHE) was set up to serve as a mechanism for international collaboration on all aspects of hydrogen and fuel cell R&D and commercialisation. It provides a forum for advancing policies, and developing common technical codes and standards to accelerate the cost-effective transition to a hydrogen economy. It also educates and informs stakeholders and the general public on the benefits of, and challenges involved in, establishing the hydrogen economy. IPHE members include 12 OECD countries, the European Commission and four non-OECD countries: Brazil, China, India and Russia.
- The Hydrogen and Fuel Cell Technology Platform, set up by the European Commission, brings together all EU-funded public/private R&D activities being undertaken within the Commission's Framework Programmes. It helps to develop awareness of market opportunities for fuel cell and hydrogen technologies, to elaborate energy scenarios, and to foster co-operation between stakeholders within and outside the European Union.
- The International Energy Agency Hydrogen Coordination Group aims to enhance coordination of the public R&D programmes and policies of member countries. It builds on existing IEA implementing agreements on technology collaboration covering, among other activities, hydrogen, advanced fuel cells, greenhouse gas R&D, bio-energy, advanced motor fuels and clean coal.

There is some overlap in the membership of these collaborative groups and in their activities, which promotes a degree of cross-fertilisation and transfer of knowledge.

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The UNEP Division of Technology, Industry and Economics (DTIE) helps governments, local authorities and decision-makers in business and industry to develop and implement policies and practices focusing on sustainable development.

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UNEP DTIE activities focus on raising awareness, improving the transfer of knowledge and information, fostering technological cooperation and partnerships, and implementing international conventions and agreements.

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Hydrogen holds out the promise of a truly sustainable global energy future. As a clean energy carrier that can be produced from any primary energy source, hydrogen used in highly efficient fuel cells could prove to be the answer to our growing concerns about energy security, urban pollution and climate change. This prize surely warrants the attention and resources currently being directed at hydrogen – even if the prospects for widespread commercialisation of hydrogen in the foreseeable future are uncertain.

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