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Article *in* Philosophical Transactions of The Royal Society A Mathematical Physical and Engineering Sciences · February 2007

DOI: 10.1098/rsta.2006.1965 · Source: PubMed

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PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A

Phil. Trans. R. Soc. A (2007) **365**, 1043–1056
doi:10.1098/rsta.2006.1965
Published online 1 February 2007

Hydrogen energy

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The problem of anthropogenically driven climate change and its inextricable link to our global society's present and future energy needs are arguably the greatest challenge facing our planet. Hydrogen is now widely regarded as one key element of a potential energy solution for the twenty-first century, capable of assisting in issues of environmental emissions, sustainability and energy security. Hydrogen has the potential to provide for energy in transportation, distributed heat and power generation and energy storage systems with little or no impact on the environment, both locally and globally. However, any transition from a carbon-based (fossil fuel) energy system to a hydrogen-based economy involves significant scientific, technological and socio-economic barriers. This brief report aims to outline the basis of the growing worldwide interest in hydrogen energy and examines some of the important issues relating to the future development of hydrogen as an energy vector.

Keywords: hydrogen; energy; production; storage; fuel cells; safety

1. Hydrogen: a versatile energy carrier

The principal drivers behind a sustainable energy vision of our future centre on the need to

- — reduce global carbon dioxide emissions and improve local (urban) air quality,
- — ensure security of energy supply and move towards the use of sustainable local energy resources, and
- — create a new industrial and technological energy base, crucial for future economic prosperity.

All modern-day assessments of global energy futures take the view that the growth in demand must be met increasingly by a diverse energy mix, including renewable or sustainable energy sources (Johnston *et al.* 2005; Dorian *et al.* 2006; Solomon & Banerjee, 2006). But it is the growth of tangible environmental concerns—now surely more evident than ever—which is providing one of the major driving forces towards sustainable energy development. Foremost among these concerns is the issue of the release and accumulation into the atmosphere of

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One contribution of 13 to a Discussion Meeting Issue 'Energy for the future'.

carbon dioxide (CO_2) and other climate-changing gases. These emissions are now unquestionably far above pre-industrial levels and are deemed to be responsible for raising the world's (average) temperature through the now-famous greenhouse effect. Unless there are drastic reductions in the amount of carbon dioxide that we release from our activities, there will be potentially disastrous consequences for our global climate. Such concerns are undoubtedly transforming the way we assess and use energy and its carriers, shifting the balance away from our traditional hydrocarbon base towards renewable or sustainable sources of energy.

Hydrogen is an attractive alternative fuel. However, unlike coal, gas or oil, hydrogen is not a primary energy source. Rather, its role mirrors more closely that of electricity as a secondary 'energy carrier', which must first be produced using energy from another source and then transported for future use where its latent chemical energy can be fully realized. Hydrogen can be obtained from diverse resources, both renewable (hydro, wind, wave, solar, biomass and geothermal) and non-renewable (coal, natural gas and nuclear). It can be stored as a fuel and used in transportation and distributed heat and power generation systems using fuel cells, internal combustion engines or turbines, with the only by-product at the point of use being water. The ability of hydrogen to replace fossil fuels in the transportation sector could address one of the world's major environmental problems (Jacobson *et al.* 2005). Automotive exhaust emissions are among the largest single sources of air pollution in the world today, especially in urban areas, and also contribute significantly to the world's carbon dioxide emission.

Hydrogen can also be used as a storage medium for electricity generated from intermittent, renewable resources, such as solar, wind, wave and tidal power; it thereby provides the solution to one of the major issues of sustainable energy, namely the vexing problem of intermittency of supply. As long as the hydrogen is produced from non-fossil fuel feedstock, it is a genuinely 'green' fuel. Moreover, locally produced hydrogen allows for the introduction of renewable energy to the transport sector, provides potentially large economic and energy security advantages and the benefits of a new infrastructure based on distributed generation. It is this key element of the energy storage capacity of hydrogen that provides the potent link between sustainable energy technologies and a sustainable energy economy, generally placed under the umbrella of 'hydrogen economy' (Muradov & Veziroglu 2005).

The importance of hydrogen as a potential energy carrier has increased significantly over the last decade, owing to rapid advances in fuel cell technology. Fuel cells, operating using hydrogen or hydrogen-rich fuels, have the potential to become major factors in catalysing the transition to a future sustainable energy system with low carbon dioxide emissions. The importance of such developments is rapidly increasing; many countries are now compiling roadmaps, in many cases with specific numerical targets for the advancement of fuel cell and hydrogen technologies. A main avenue of hydrogen R&D activity has been in the transportation sector, where most of the world's major vehicle manufacturers are investing heavily in fuel cell vehicle R&D programmes.

Figure 1 illustrates the central role of hydrogen as an energy carrier linking multiple hydrogen production methods and various end-user applications. One of the principal attractions of hydrogen as an energy carrier is obviously the diversity of production methods from a variety of resources. Hydrogen can

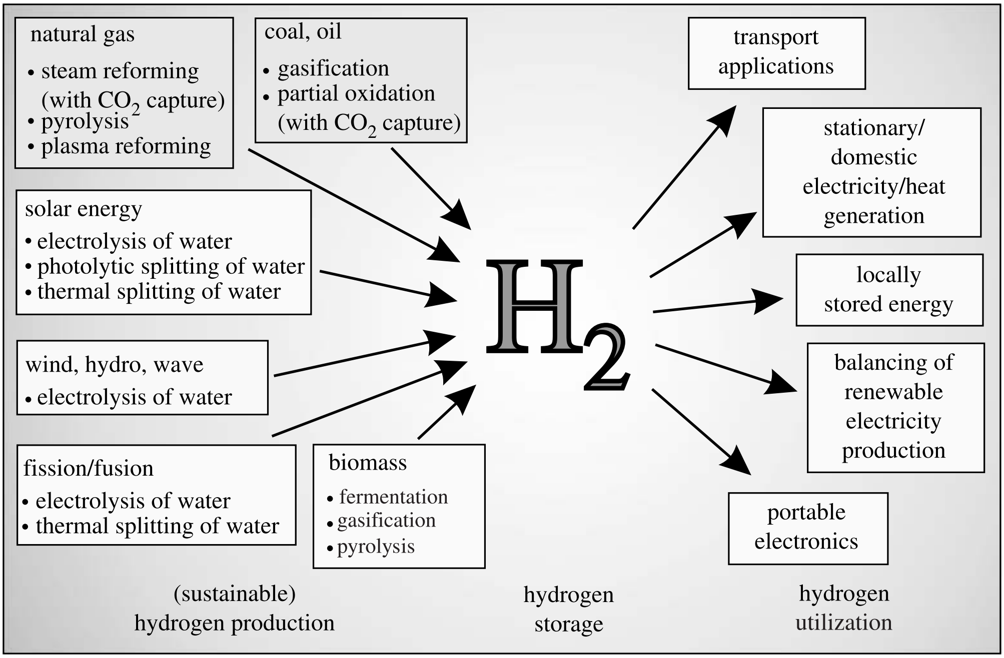

Figure 1. Hydrogen as an energy carrier linking multiple hydrogen production methods, through storage to various end-users. Shaded production routes can involve substantial carbon dioxide (by-product) generation.

be produced from coal, natural gas and other hydrocarbons by a variety of techniques, from water by electrolysis, photolytic splitting or high-temperature thermochemical cycles, from biomass and even municipal waste. Such a diversity of production sources contributes significantly to the security of energy supply.

A typical energy chain for hydrogen will comprise hydrogen production, distribution and delivery through hydrogen storage and ultimately its utilization. The energy chain for *sustainable hydrogen energy* would involve the harvesting of sunlight or other energy sources to yield hydrogen as the energy carrier, the storage and distribution of this energy carrier to its utilization at an end-device—centred on either fuel cells or combustion—where it is converted to power.

The ultimate realization of a hydrogen-based economy could potentially confer enormous environmental and economic benefits, together with enhanced security of energy supply. Perhaps, the most telling argument for a sustainable hydrogen economy is the potential (globally) to drastically reduce carbon emissions. However, the transition from a carbon-based (fossil fuel) energy system to a hydrogen-based economy involves significant scientific, technological and socio-economic barriers to the implementation of hydrogen as the clean energy source of the future.

In 2004, a report published by the United States National Research Council and National Academy of Engineering entitled 'The hydrogen economy: opportunities, costs, barriers, and R&D needs' (US National Research Council and National Academy of Engineering 2004) stated that four major hurdles to achieving the vision of the hydrogen economy are as follows.

— To develop and introduce cost-effective, durable, safe and environmentally desirable fuel cell systems and hydrogen storage systems.
— To develop the infrastructure to provide hydrogen for the light-duty-vehicle user.
— To reduce sharply the costs of hydrogen production from renewable energy sources over a time frame of decades.
— To capture and store ('sequester') the CO_2 by-product of hydrogen production from coal and natural gas.

The vision of such an integrated energy system for the future would combine large and small fuel cells for domestic and decentralized heat and electricity power generation with local (or more extended) hydrogen supply networks, which would also be used to fuel hydrogen fuel cell or internal combustion vehicles. In the following sections we outline just some of the challenges facing the transition to the hydrogen economy.

2. Hydrogen production and distribution

Hydrogen is the third most abundant chemical element in the Earth's crust, but it is invariably bound up in chemical compounds with other elements. It must, therefore, be produced from other hydrogen-containing sources using energy, such as electricity or heat.

At present, hydrogen is produced in large quantities from fossil fuels by steam reforming of natural gas and partial oxidation of coal or heavy hydrocarbons (see also the article by Sigfusson 2007). These methods can take advantage of economies of scale and are currently the cheapest and most established techniques for the large-scale production of hydrogen. They can be used in the short to middle term to meet hydrogen fuel demand and enable the proving and testing of technologies related to hydrogen production, storage, distribution, safety and use. However, in the long term, it is clearly unsustainable that the hydrogen economy is driven by hydrogen derived from hydrocarbons.

The manufacture of hydrogen from fossil fuels using reformation and gasification processes always yields carbon dioxide as a by-product. Carbon dioxide emissions, the principal cause of global climate change, can be efficiently managed at large-scale facilities through the so-called carbon dioxide sequestration, which involves the capture, liquefaction, transportation and storage of carbon dioxide underground (e.g. in depleted natural gas and oil wells or geological formations). However, all the operations associated with sequestration are energy intensive, costly and potentially damaging to our environment. The key risk results from the uncertain long-term ecological consequences of carbon dioxide sequestration. A more promising route of hydrogen production without carbon dioxide release is the high-temperature pyrolysis (decomposition in the absence of oxygen) of hydrocarbons, biomass and municipal solid waste into hydrogen and (solid) carbon black accompanied by its industrial use and/or easy sequestration. At present, the cost of this process is significantly higher than that of steam reforming of natural gas.

However, to achieve the benefits of a truly sustainable hydrogen energy economy, we must clearly move to a situation where hydrogen is produced from non-fossil resources, principal among these being water (Turner 2004;

Sherif *et al.* 2005; Penner 2006). Hydrogen can be produced by splitting water through various processes, including electrolysis, photo-electrolysis, high-temperature decomposition and photo-biological water splitting. The commercial production of hydrogen by electrolysis of water achieves an efficiency of 75%; however, the cost of hydrogen is currently several times higher than that produced from fossil fuels (Dutton 2002; Ewan & Allen 2005; International Energy Agency 2006). Electricity derived from renewable energy resources (e.g. wind, wave, tidal) might provide local hydrogen needs, but certainly will not meet the volumes of hydrogen required globally for its widespread use as the new energy source.

Production of hydrogen via biological reformation of biomass using micro-organisms and fermentation is clearly attractive if one could indeed demonstrate that such an approach could be used to produce the necessary huge volumes of hydrogen. This method releases carbon dioxide, but this can be recycled by the growth of more biomass (thereby counted as a carbon dioxide neutral activity). However, a cautionary point must be made; if fertilizers are used to grow crops/biomass, this will of necessity incur a 'CO_2 cost' since ammonia is used to synthesize fertilizers, and this ammonia is synthesized from hydrogen and nitrogen, the former currently produced from hydrocarbons.

The holy grail of hydrogen production will be the efficient, direct conversion of sunlight through a photocatalytic process that uses solar energy to split water directly into its constituents, hydrogen and oxygen, without the use of electricity. This ideal production route therefore harvests 'solar hydrogen', the power of the Sun, to split water from our oceans. A recent US Department of Energy (DoE) report suggests that the solar photodecomposition of water is probably the only major—but long-term—solution to a CO_2-free route for the mass production of the huge volumes of H_2 needed if the hydrogen economy is to emerge (US Department of Energy, Office of Science 2003). Achieving low-cost and efficient solar energy production of hydrogen requires development of innovative materials, emerging physical phenomena, novel synthetic techniques and entirely new design concepts.

Current nuclear (fission) technology generates electricity that can be used to produce hydrogen by the electrolysis of water. Advanced nuclear reactors are also being developed that will enable high-temperature water electrolysis (with less electrical energy needed) or thermochemical cycles that will use heat and a chemical process to dissociate water. Fusion power, if successfully developed, could be a good source of a clean, abundant and carbon-free resource for hydrogen production.

The current transportation system for delivering conventional fuels to consumers cannot be easily transformed for use with hydrogen. The present options for transporting hydrogen include compressed gas (200 bar) in steel tube cylinders, liquid hydrogen tanks and a few examples of local networks of hydrogen pipelines. All these options are expensive and contribute significantly to the cost of hydrogen for end-users. New concepts will be needed to reduce delivery costs while retaining high safety standards from the point of production through to refuelling end-users.

The basic components of a hydrogen delivery infrastructure therefore need to be developed, initially to supply local hydrogen refilling stations for transportation use—widely regarded as the first major inroad into the hydrogen economy. Subsequently, the components of a national hydrogen delivery and distribution network should be constructed, providing a reliable supply of low-cost hydrogen. The construction of a new hydrogen network would require significant investment accompanied by research and development of new materials, low-cost compressor technology, seals, sensors and controls, as well as refilling stations' infrastructure required to ensure the safety of any hydrogen delivery system.

A model of decentralized (i.e. localized) hydrogen production for local power generation and hydrogen fuelling stations would centre on small-scale plants with entirely new requirements for size, production cost, etc. In those areas where natural gas is not available, hydrogen could be best produced on-site from water, methanol or ammonia, via electricity—ideally from renewable energy sources, e.g. wind or solar, or from biofuels. Localized hydrogen production might fit better with accessible fuel distribution, but CO_2 sequestration might not be as effective as for large-scale centralized production.

When high penetration rates of hydrogen in energy sector are reached, the ideal long-term option for hydrogen distribution will be a grid of hydrogen pipelines connecting centralized hydrogen production facilities with stationary users and mobile filling stations. However, in some areas, it might still be cheaper to produce hydrogen locally, for example, at remote refilling stations or households using electrolysis of water, effective (small-scale) reformation units or other advanced hydrogen production methods.

3. Hydrogen storage

Viable hydrogen storage is considered by many as one of the crucial and the most technically challenging barrier to the widespread use of hydrogen as an effective energy carrier (Crabtree *et al.* 2004; Harris *et al.* 2004). Hydrogen contains more energy on a weight-for-weight basis than any other substance. Unfortunately, since it is the lightest chemical element of the periodic table, it also has a very low energy density per unit volume (table 1).

The hydrogen economy will require two types of hydrogen storage systems; one for transportation and another for stationary applications. Both have different requirements and constrains. The transportation sector is believed to be the first high-volume user of hydrogen in the future hydrogen economy. The hydrogen storage requirements for transportation applications are far more stringent than those for stationary applications. These operating requirements for the 'ideal' hydrogen storage system for transportation applications include the following:

— multicycle reversibility of hydrogen uptake/release (not less than 500 cycles),
— low-operating pressure (less that 4 bar),
— operating temperature in the range from -50 to 150°C,
— fast kinetics of hydrogen uptake/release,
— high gravimetric and volumetric hydrogen densities (greater than or equal to 9 wt% and greater than or equal to 70 g of H_2 per litre of storage system),
— safety under operating conditions and public acceptance, and
— cost of hydrogen storage system of less than £15/kg.

Table 1. Gravimetric (specific) and volumetric energy content of fuels, hydrogen storage options and energy sources (note: weight and volume of the container are excluded).

fuel	specific energy ($kWh\,kg^{-1}$)	energy density ($kWh\,dm^{-3}$)
liquid hydrogen	33.3	2.37
hydrogen (200 bar)	33.3	0.53
liquid natural gas	13.9	5.6
natural gas (200 bar)	13.9	2.3
petrol	12.8	9.5
diesel	12.6	10.6
coal	8.2	7.6
$LiBH_4$	6.16	4.0
methanol	5.5	4.4
wood	4.2	3.0
electricity (Li-ion battery)	0.55	1.69

This set of stringent (and coupled) requirements represents a major scientific challenge for the development of a viable hydrogen storage for transportation use; at the moment, there are simply no hydrogen storage systems that could meet simultaneously all these criteria. One aspect of the problem of storing hydrogen on-board is illustrated in figure 2, where the volume and weight of storing of 4 kg of hydrogen is shown for different storage methods (4 kg of hydrogen is enough to drive a fuel cell car for 500 km).

For stationary applications, weight and volume restrictions of hydrogen storage are less critical than those for vehicles; stationary hydrogen storage systems can occupy a large area, operate at high temperatures and pressures and have extra capacity to compensate for slow kinetics. Nevertheless, hydrogen storage for stationary use also represents a major scientific and technical challenge, especially in the area of storage materials.

At present, hydrogen storage options have centred upon high-pressure gas containers or cryogenically cooled (liquefied) fluid hydrogen. Traditional steel cylinders can store hydrogen at 200 bar and have a gravimetric density of approximately 1 wt% (1 wt% of stored hydrogen is equal to 186 $Wh\,kg^{-1}$ of stored energy). Recently developed ultra-high density composite cylinders made of high-grade carbon fibre can store hydrogen at a pressure in the region of 700–1000 bar, with gravimetric hydrogen density of up to 10 wt%. However, these high-pressure cylinders are costly and require complex and expensive filling equipment.

Storage of hydrogen as a cryogenic liquid offers a significantly higher gravimetric density than compressed gas, since the density of liquid hydrogen is 70.8 $g\,l^{-1}$ at $-252.8°C$ and 1 bar. However, this density is still 14 times less that the density of water. Cryogenic liquid vessels require very efficient insulation in order to keep the hydrogen in the liquid phase. Even with the best available insulation, the boil-off rates are not less than 1% per day for small tanks for transportation use.

While with compressed and liquid storage options hydrogen is easily accessible for use, these storage methods cannot meet many of the requirements summarized above, as well as the mid- and long-term targets set for transportation hydrogen storage systems (US Department of Energy, Office of Science 2003). A serious

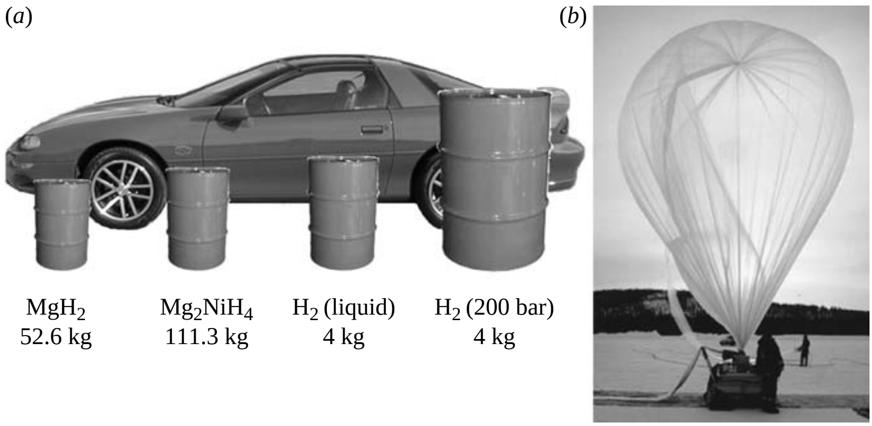

Figure 2. (*a*) The volume of 4 kg of hydrogen compacted in different ways, together with the weight of hydrogen storage material (note: weight and volume of a container are excluded). (*b*) At normal conditions, 4 kg of hydrogen occupies a volume of 48 m^3, the volume of a medium size balloon.

downside of these methods is also a significant energy penalty—up to 20% of the energy content of hydrogen is required to compress the gas and up to 30% to liquefy it. Another crucial issue that confronts the use of high-pressure and cryogenic storage centres on public perception and acceptability associated with the use of pressurized gas and liquid hydrogen containment.

It is clear that hydrogen storage requires a major technological breakthrough, and this is most likely to occur in the most viable alternative to compressed and liquid hydrogen, namely the storage of hydrogen in solids or liquids. The development of new solid-state hydrogen storage materials could herald a step change in the technology of hydrogen storage and would have a major impact on the transition to a hydrogen economy (Crabtree *et al.* 2004; Harris *et al.* 2004).

In figure 3, we display the gravimetric and volumetric energy densities of hydrogen chemically stored using various storage methods. It is seen that neither cryogenic nor high-pressure hydrogen storage options can meet the mid-term DoE targets for transportation use (US Department of Energy, Office of Science 2003). It is becoming increasingly accepted that solid-state hydrogen storage using ionic–covalent hydrides of light elements, such as lithium, boron, sodium, magnesium and aluminium (or some combination of these elements), represents the only method enabling one to achieve the necessary gravimetric and volumetric target densities.

For transportation use, a suitable solid-state storage material should be able to store a high weight per cent and a high volume density of hydrogen and rapidly absorb and desorb hydrogen at—or close to—room temperature and pressure. Ideally, such a material should be made from cheap materials using a low-energy preparation method, be resistant to poisoning by trace impurities, have a good thermal conductivity in charged and uncharged conditions, be safe and reusable on exposure to air and have the ability to be regenerated and be readily recycled. This clearly represents a particularly challenging set of credentials for the ideal storage material; at present, no single material meets all of these requirements.

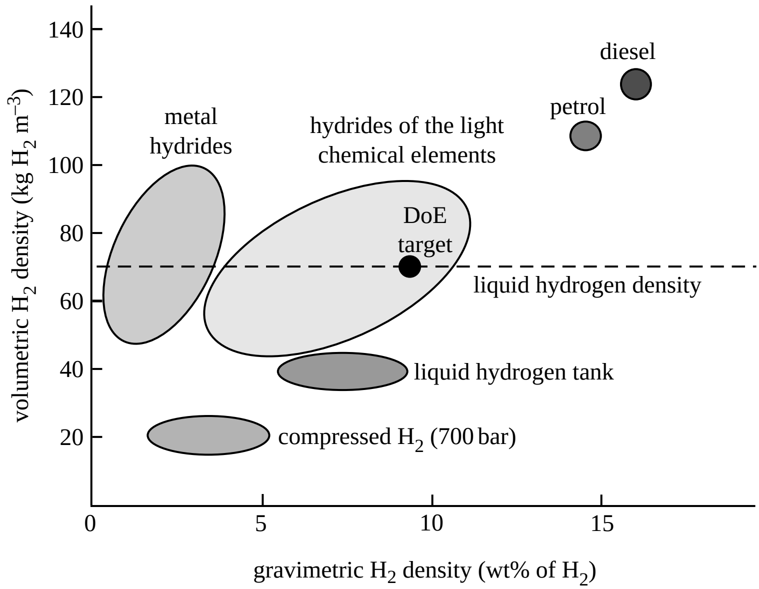

Figure 3. Gravimetric and volumetric densities of various hydrogen storage options (note: weight and volume of the storage container are included). 'DoE target' represents the US Department of Energy target for 2015 set for an 'ideal' hydrogen storage material. Metal hydrides are conventional, heavy metal hydrides such as $LaNi_5$, etc.

The intrinsic properties and behaviour of hydrogen storage materials depend upon the precise nature of the interactions of hydrogen with the host material. There are several types of such interactions, which are as follows:

— physical adsorption of H_2 molecules on the surface (exterior or interior) of the material,
— chemical absorption of hydrogen by the material (and concomitant hydrogen dissociation) with the formation of chemical bonds, and
— the formation of 'chemical hydrides' characterized by distinct chemical covalent bonding.

Substantial efforts worldwide now focus on a detailed understanding of the chemical and physical processes governing the nature of hydrogen–material interactions as a prelude to the required 'step-change' advances necessary in this area.

Physical adsorption is the weakest of the hydrogen bindings. The hydrogen molecules usually form a monolayer on the surface, which means that a material with a very high surface area is required to achieve anything coming close to an attractive hydrogen storage capacity (figure 4). Several classes of high surface area materials have been studied, including zeolites, metal–organic framework compounds and various carbons. The highest hydrogen storage capacity of 8 wt% is achieved in carbon ball-milled in hydrogen. However, low temperature (−196°C) and high pressure (up to 50 bar) are required for effective hydrogen storage in carbon; in addition, the ball-milling process is long and energy intensive.

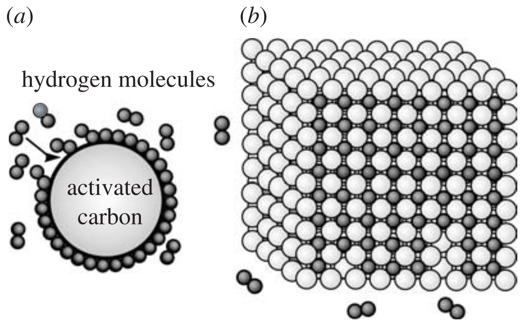

Figure 4. Schematic of hydrogen (*a*) adsorption (physisorption) and (*b*) absorption (chemisorption). In adsorption, hydrogen molecules remain intact; in chemisorption, molecular hydrogen is dissociated and occupies interstitial sites in the metallic (alloy) matrix.

In conventional metal hydrides (e.g. $LaNi_5H_6$, $FeTiH_{1.7}$, $MgNiH_4$), the maximum hydrogen storage capacity of chemically absorbed hydrogen is around 4 wt%. Such metal hydrides can safely and effectively store hydrogen within their crystal structure. Hydrogen is first 'sorbed' into the material and is released under controlled heating of the solid. Though the hydrogen volumetric density in these materials is higher than that in liquid hydrogen (figure 3), the weight of the materials is unpractical for on-board storage of hydrogen in vehicles. Higher gravimetric hydrogen density can therefore only be achieved using hydrides of the light chemical elements of the periodic table.

The most promising hydrogen storage materials are a class of ionic–covalent hydrides formed by light elements, such as lithium, boron, sodium, magnesium and aluminium. Hydrogen absorption/desorption in these materials usually involves high-temperature solid-phase transitions, which until recently were believed to be irreversible; the exception appears to be $NaAlH_4$, which can function as a reversible store with suitable catalysts. Recently, new chemical routes have been developed for activating hydrogen uptake/release under mild conditions (Johnson 2005) and novel promising hydrogen storage materials have been discovered (Chater *et al.* 2006). However, much more fundamental research is required to understand the physical and chemical processes governing the hydrogen storage and release and to improve the hydrogen absorption/desorption characteristics in this class of materials to meet hydrogen storage requirements.

4. Hydrogen utilization

The widespread use of hydrogen as an energy carrier will depend significantly on the availability of efficient, clean and economic techniques for its utilization and conversion to electricity/heat. The synergistic complementarity of hydrogen and electricity represents one of the most appealing routes to a sustainable energy future, and fuel cells provide, arguably, the most efficient conversion device for converting hydrogen and other hydrogen-bearing fuels into electricity.

A fuel cell is a device akin to a continuously recharging battery; a fuel cell generates electricity by the electrochemical reaction of hydrogen and oxygen from the air. An important difference is that batteries store energy, while fuel

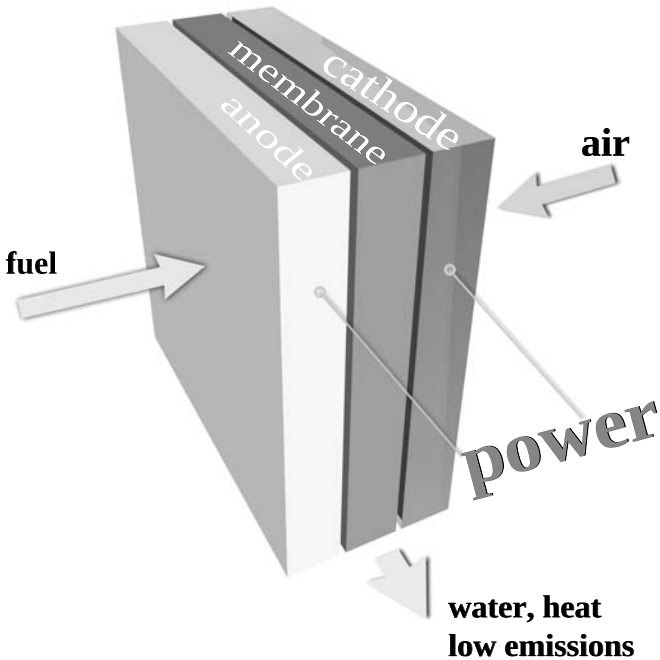

Figure 5. Schematic of a fuel cell (figure drawn by Karl Harrison, University of Oxford).

cells can produce electricity continuously as long as fuel and air are supplied. Several types of fuel cells operating on a variety of fuels and suitable for different energy applications have been developed, but all share the basic design of two electrodes (anode and cathode) separated by a solid or liquid electrolyte or membrane (figure 5). Hydrogen (or a hydrogen-containing fuel) and oxygen are fed into the anode and cathode of the fuel cell and the electrochemical reactions assisted by catalysts take place at the electrodes. The electrolyte or membrane enables the transport of ions between the electrodes while the excess electrons flow through an external circuit to provide electrical current.

Because fuel cells are not subject to the intrinsic limitations of the Carnot cycle, they convert fuel into electricity at more than double the efficiency of internal combustion engines. In transportation, hydrogen fuel cell engines operate at an efficiency of up to 65%, compared to 25% for present-day petrol-driven car engines. When heat generated in fuel cells is also used in combined heat and power (CHP) systems, an overall efficiency in excess of 85% can be achieved (Duttons 2002). Unlike internal combustion engines or turbines, fuel cells demonstrate high efficiency across most of their output power range. This scalability makes fuel cells ideal for a variety of applications from mobile phone batteries through vehicle applications to large-scale centralized or decentralized stationary power generation.

Fuel cells are now emerging as a leading technology to replace more polluting internal combustion engines in vehicle and stationary distributed energy applications. Hydrogen fuel cells emit only water and have virtually no pollutant emissions, even nitrogen oxides, because they operate in the temperature range of 60–120°C, which is much lower than the normal operating temperature of internal combustion engines. Hydrogen-powered fuel cell vehicles provide a route, in theory, to real (i.e. complete life cycle) zero emissions if the hydrogen fuel could be sourced from renewable routes.

Hydrogen-fuelled fuel cell vehicles are also increasingly seen as an attractive alternative to other zero-emission vehicles such as battery-driven electric cars, because the chemical energy density of hydrogen is significantly higher than that found in electric battery materials (Winter & Brodd 2004). Hydrogen fuel cells could also deliver much longer operational lifetime than that of electric batteries and simultaneously provide the same high specific energy as traditional combustion engines.

Any hydrogen-rich fuel can be used in different types of fuel cells (employing an external or internal fuel reforming process), but using a hydrocarbon-based fuel inevitably leads to a carbon dioxide emission. However, owing to a high efficiency of fuel cells, at least twice as much useful energy for a given amount of hydrocarbon fuel can be produced in fuel cells than using direct combustion of the fuel. Therefore, even fuel cells fuelled by hydrocarbon fuels do have the potential to provide much more efficient, clean and quiet energy conversion, which can contribute to a significant reduction in both greenhouse gas emission and local pollution.

Fuel cells have the very real potential to replace a large proportion of current energy systems. They offer a very attractive technology evolution path delivering significant efficiency gains on today's commercially available hydrocarbon fuels, while also offering high efficiency in the future when hydrogen becomes an alternative energy carrier. However, various major technological hurdles must still be overcome before fuel cells can compete effectively with conventional energy conversion technologies. The key scientific and technical challenges facing fuel cells are cost reduction and increased durability of materials and components. This requires an intensive research in the development of improved or new materials and could provide commercial viability of fuel cells in both stationary and mobile applications. Fuel cell cars, currently the focus of intense development activity worldwide, are not expected to reach mass market until 2015, or indeed beyond.

5. Hydrogen safety

Safety concerns will present a potential barrier to the early introduction of hydrogen technologies. Despite its perceived reputation, hydrogen is at least as safe as other fuels and as a chemical component (so-called 'merchant hydrogen') has an extraordinary safety record during many decades of use in industrial applications. Hydrogen poses safety risks of the same order of magnitude as petrol or natural gas and like other fuels hydrogen can be used safely with appropriate handling and system design. Apart from hydrogen flammability, there are also safety concerns associated with very high pressures and low temperatures of presently available high-pressure and cryogenic hydrogen storage methods. Many solid-state hydrogen storage materials, like metal hydrides, are inherently safer for hydrogen storage.

Safety is not only a technological issue, but also the major psychological and sociological issue facing the adoption of the hydrogen economy. To be accepted by the public, hydrogen must be considered safe. Consumers will undoubtedly have concerns about the safety and dependability of fuel-cell-powered equipment, new dispensing technology, etc., just as they had about other modern devices when they were introduced. The confidence building is necessary for transportation, stationary, residential and portable applications, where customers will interact directly with hydrogen and fuel cell technology. An important factor in promoting public confidence will be the development and adoption of internationally accepted codes and standards. Education projects, product exposure and marketing should be developed in order to facilitate a successful introduction and acceptance of hydrogen as an alternative fuel (Schulte *et al.* 2004).

The widespread use of hydrogen could, of course, have unknown environmental effects due to increased anthropogenic emissions of molecular hydrogen to the atmosphere (Tromp *et al.* 2003). It is recognized that hydrogen participates in stratospheric chemical cycles of H_2O and various greenhouse gases and a substantial increase in its concentration might lead to changes in equilibrium concentration of constituent components of the stratosphere. More accurate modelling of the stratospheric processes as well as better understanding of several other factors such as hydrogen uptake in soil and its effect on microbial communities is required to assess potential adverse effects of hydrogen economy. We have 10–20 years before hydrogen is widely used as an energy carrier to take necessary actions to understand and prevent its possible environmental impact. This situation is radically different from those occurring in the past when the harmful effect of freon and other chemicals was understood only *after* significant damage to the environment had been done. Counterbalanced against these potential concerns for hydrogen are the very real dangers associated with CO_2 emissions—*now occurring*!

6. Conclusion

Hydrogen has an outstanding potential for becoming a major factor in catalysing the transition of our carbon-based global energy economy ultimately to a clean, renewable and sustainable economy. The development of hydrogen production, storage and utilization technologies is set to play a central role in addressing growing concerns over carbon emissions and climate change, as well as the future availability and security of energy supply. Hydrogen and fuel cells are considered in many countries as an important alternative energy vector and key technologies for future sustainable energy systems in the stationary power, transportation, industrial and residential sectors. However, the challenges of creating a new energy economy—and one that no longer centres on carbon fuels—are substantial and require scientific breakthroughs and significant technological developments coupled with a continued social and political commitment. There is still a long road to travel before a true hydrogen energy revolution can occur—but this will be a compelling, exciting journey!

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