Hydrogen and fuel cells: towards a sustainable energy future

Professor Peter P. Edwards
Head of Inorganic Chemistry
University of Oxford

Co-ordinator
UK Sustainable Hydrogen Energy Consortium

UK representative
Hydrogen Storage
International Partnership for the Hydrogen Economy (IPHE)

Dr Vladimir L. Kuznetsov
Research Fellow
University of Oxford
and
Secretary
UK Sustainable Hydrogen Energy Consortium

Professor William I. F. David
CCLRC Senior Fellow
ISIS Facility
Rutherford Appleton Laboratory

Visiting Professor in Inorganic Chemistry
University of Oxford

Professor Nigel Brandon
Shell Chair in Sustainable Development in Energy
Imperial College, London

Co-ordinator
Fuel Cells SUPERGEN Consortium

While the Office of Science and Innovation commissioned this review, the views are those of the authors, are independent of Government and do not constitute Government policy.

Abstract

A major challenge – some would argue *the* major challenge – facing our planet today relates to the problem of anthropogenic-driven climate change and its inextricable link to our global society's present and future energy needs. Hydrogen and fuel cells are now widely regarded as key energy solutions for the 21st century. These technologies will contribute significantly to a reduction in environmental impact, enhanced energy security (and diversity) and the creation of new energy industries. Hydrogen and fuel cells can be utilised in transportation, distributed heat and power generation and energy storage systems. However, the transition from a carbon-based (fossil fuel) energy system to a hydrogen-based economy involves significant scientific, technological and socioeconomic barriers to the implementation of hydrogen and fuel cells as the clean energy technologies of the future. This brief report aims to capture the current status, key scientific and technical challenges and projection of hydrogen and fuel cells within a sustainable energy vision of the future.

Why hydrogen and fuel cells?

Global drivers for sustainable energy vision of our future center on the need to:

- reduce CO_2 emissions and improve local (urban) air quality
- ensure security of energy supply
- create a new industrial and technological energy base, crucial for our economic prosperity.

Hydrogen is a very attractive alternative fuel. It can be obtained from diverse resources, both renewable (hydro, wind, solar, biomass, geothermal) and non-renewable (coal, natural gas, nuclear). Hydrogen can then be utilised in high-efficiency power-generation systems, including fuel cells for both vehicular transportation and distributed electricity generation. Fuel cells convert hydrogen or a hydrogen-rich fuel and an oxidant (usually pure oxygen or oxygen from the air) directly into electricity by an electrochemical process.

Fuel cells, operating on hydrogen or hydrogen-rich fuels, have the potential to become major factors in catalysing the transition to a future sustainable energy system with low-CO_2 emissions. The importance attached to 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. As just one potent example, Japan's Ministry of Economy, Trade and Industry has now set a target of 5 million hydrogen-fuel-cell vehicles and 10 million kW for the total power generation by stationary fuel cells by the year 2020!

At the present time, there are three major technological barriers that must be overcome for a transition from a carbon-based (fossil fuel) energy system to a hydrogen-based economy. First, the cost of efficient and sustainable hydrogen production and delivery must be significantly reduced. Second, new generations of hydrogen storage systems for both vehicular and stationary applications must be developed. Finally, the cost of fuel-cell and other hydrogen-based systems must be reduced.

The vision of such an integrated energy system of the future would combine large and small fuel cells for domestic and decentralised heat and electricity power generation with local (or more extended) hydrogen supply networks that would also be used to fuel conventional (internal combustion) or fuel-cell vehicles.

Unlike coal, gas or oil, hydrogen is not a primary energy source. Its role more closely mirrors that of electricity as an 'energy carrier', which first is produced using energy from another source and then transported for future use, where its stored chemical energy can be utilised. Hydrogen can be stored as a fuel and utilised in transportation and distributed heat and power generation using fuel cells, internal combustion engines or turbines, and, importantly, a hydrogen fuel cell produces only water and no CO_2.

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 therefore 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 feed stock, it is a genuinely green fuel. Moreover, locally produced hydrogen allows the introduction of renewable energy to the transport sector, provides potentially large economic and energy security advantages and the benefits of an 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 term of 'hydrogen economy'.

Hydrogen production, distribution and storage

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

Hydrogen can be produced from natural gas, coal, hydrocarbons, biomass and even municipal waste using a variety of techniques as well as by splitting water. Such a diversity contributes significantly to the security of fuel supply (Figure 1).

Today, hydrogen is produced in large quantities by steam reforming of hydrocarbons, generally methane. This method yields CO_2 as a by-product but no more than from burning the same amount of methane. CO_2 emissions, the principal cause of global climate change, can be managed at large-scale facilities through CO_2 sequestration, which involves the capture and storage of CO_2 underground (e.g. in depleted natural gas and oil wells or geological formations). However, CO_2 sequestration is not yet technically and commercially proven. Another promising route would appear to be 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 higher than that of steam reforming of natural gas.

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 70–75%. However, the cost of hydrogen is several times higher than that produced from fossil fuels (Dutton 2002; International Energy Agency 2006). Renewable sources of energy (e.g. wind, tidal, biomass) might provide local sources of hydrogen, but certainly will not match the volumes of hydrogen required globally for the new energy source. The use of nuclear energy (both fission and fusion) to supply future needs for hydrogen energy is also under consideration. A recent US Department of Energy report suggests that solar is most likely the only source of energy capable of producing enough hydrogen required to supply a hydrogen economy.

The present options for transporting hydrogen include compressed gas (200 bar) in tube cylinders, liquid hydrogen tanks and a few examples of local networks of hydrogen pipelines. All these options contribute significantly to the cost of hydrogen for end users and, in some cases, decentralised local hydrogen production using methane reforming or electrolysis of water will be economically feasible.

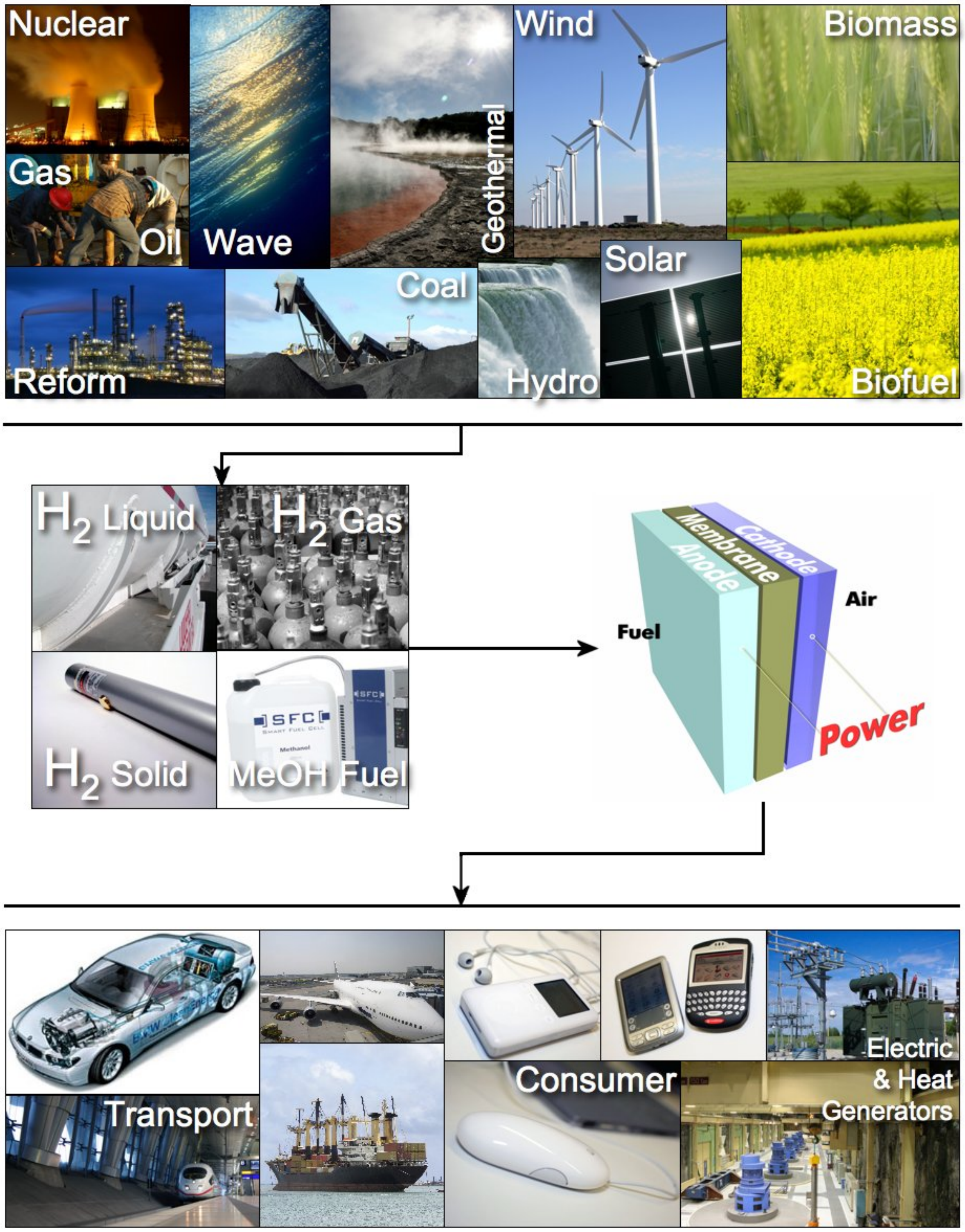

Figure 1: Hydrogen as an energy carrier linking multiple production methods and sources to various fuel cell applications (figure by Karl Harrison, University of Oxford)

One of the crucial technological barriers to the widespread use of hydrogen as an effective energy carrier is the lack of a safe, low-weight and low-cost hydrogen storage method with a high energy density (Harris et al. 2004; Crabtree 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, it also has a very low energy density per unit volume (Table 1).

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

Fuel	Specific energy (kWh/kg)	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 (Lithium-ion battery)	0.55	1.69

Present storage options for hydrogen have centred upon high-pressure (up to 700 bar) gas containers or cryogenically cooled (liquefied) fluid hydrogen. One downside of these methods is a significant energy penalty – up to 20% of the energy content of hydrogen is required to compress the gas and up to 40% 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 pressurised gas and liquid hydrogen containment. Hydrogen storage requires a major technological breakthrough and this is likely to occur in the most viable alternative to compressed and liquid hydrogen, namely the storage of hydrogen in solids or liquids. Several classes of solid-state hydrogen storage materials demonstrate higher energy density than that of liquid hydrogen (for example, $LiBH_4$, see Table 1). However, much more work is required to improve their hydrogen absorption/desorption characteristics.

Fuel cells

Fuel cells are emerging as a leading alternative technology to replace more polluting internal combustion engines in vehicle and stationary distributed energy applications. In addition, the future demand for portable electric power supplies is likely to exceed the capability of battery technology.

A fuel cell is a device akin to a continuously recharging battery and generates electricity by the electrochemical reaction of hydrogen and oxygen from the air. An important difference is that batteries store energy, while fuel cells can produce electricity continuously as long as fuel and air are supplied. 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 CO_2 emission. Hydrogen-powered fuel cells emit only water and have virtually no pollutant emissions, even nitrogen oxides, because they operate at temperatures that are much lower than internal combustion engines. However, even fuel cells fuelled by hydrocarbon fuels do have the potential to provide efficient, clean and quiet energy conversion, which can contribute to a significant reduction in both greenhouse gases and local pollution. Because fuel cells are not subject to the 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 utilised in combined heat and power (CHP) systems, an overall efficiency in excess of 85% can be achieved (Dutton 2002).

Several types of fuel cells suitable for different energy applications at varying scales have been developed but all share the basic design of two electrodes (anode and cathode) separated by a solid or liquid electrolyte (Figure 2). 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 enables the transport of ions between the electrodes, while the excess electrons flow through an external circuit to provide electrical current.

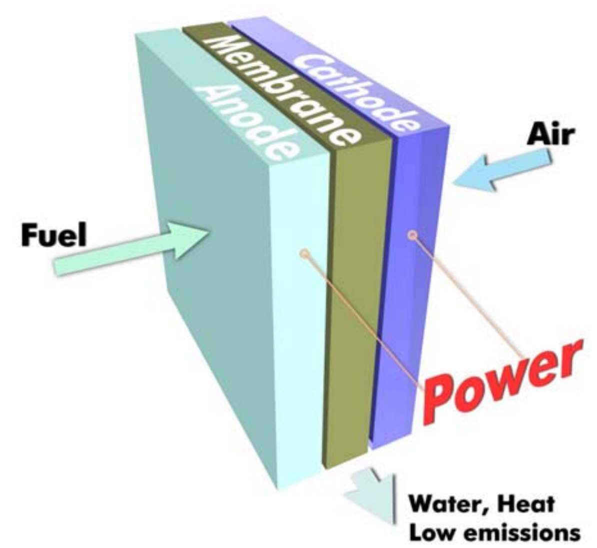

Figure 2: diagram of a fuel cell model (figure by Karl Harrison, University of Oxford)

Fuel cells are classified according to the nature of their electrolyte, which also determines their operating temperature, the type of fuel and a range of applications. The electrolyte can be acid, base, salt or a solid ceramic or polymer that conducts ions. Table 2 summarises the characteristics of various fuel cell types.

Table 2: Summary of fuel cell types and their present characteristics (Appleby and Foulkes 1993; Powell et al. 2002; US Department of Energy 2003)

Fuel cell type (type of electrolyte)	Operating temperature (^oC)	Applications	Electrical power range (kW)	Electrical efficiency (%)
Proton exchange membrane (PEMFC)	60–110	Mobile, portable, low power generation	0.01–250	40–55
Alkaline (AFC)	70–130	Space, military, mobile	0.1–50	50–70
Direct methanol (DMFC)	60–120	Portable, mobile	0.001–100	40
Phosphoric acid (PAFC)	175–210	Medium- to large-scale power and CHP	50–1,000	40–45
Molten carbonate (MCFC)	550–650	Large-scale power generation	200–100,000	50–60
Solid oxide (SOFC)	500–1,000	Medium- to large-scale power and CHP, vehicle APUs, off-grid power and micro-CHP	0.5–2,000	40–72

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 phones to large-scale power generation. However, at present, fuel cells can't compete with conventional energy conversion technologies in terms of cost and reliability.

High-temperature solid oxide fuel cells (SOFCs) and molten carbonate fuel cells (MCFCs) are ideal for distributed energy supply operating today with natural gas, which enables the development and use of this technology independently from the establishment of a hydrogen infrastructure. Indeed, they offer an interesting transition to the hydrogen economy, with significant efficiency gains on today's commercially available hydrocarbon fuels, while operating effectively on renewable biofuels should these become cost-effective, and ultimately operating with high efficiencies on hydrogen when this becomes widely available. They are also being pursued for use as auxiliary power units (APUs) for vehicles, and in off-grid applications to replace small diesel generators. These types of fuel cells do not require an external reformer to convert hydrogen-rich fuels to hydrogen, which enables the use of a variety of fuels and reduces the cost associated with adding a reformer to the system. They are particularly well suited to CHP applications as they produce high-grade waste heat (or cooling) as well as electrical power. The technology has been already proven by several demonstration projects showing continuous operation over tens of thousands of hours.

Low-temperature proton exchange membrane (PEM) and alkaline fuel cells offer an order of magnitude higher power density than any other fuel cell systems. A major drawback, however, is that they require a costly platinum catalyst and need very pure hydrogen. PEM and alkaline fuel cells have been developed since the 1950s and used in the NASA space programme. PEM fuel cells are most favoured for mass-market automotive and small-scale CHP applications, and there is a massive global effort to develop commercial systems.

Phosphoric acid fuel cells (PAFCs) are more tolerant to impurities in hydrogen than PEMFCs or AFCs. PAFCs are typically used for stationary power generation but also to power large vehicles such as city buses. They are commercially available today, but their relatively high cost has restricted market uptake. Direct methanol fuel cells (DMFCs) are powered by methanol and are considered for a number of applications, particularly those based around replacing batteries in consumer applications such as mobile phones and laptop computers.

The key scientific and technical challenges

By 2050, the global energy demand could double or triple and oil and gas supply is unlikely to be able to meet this demand. Hydrogen and fuel cells are considered in many countries as an important alternative energy vector and a key technology for future sustainable energy systems in the stationary power, transportation, industrial and residential sectors (European Commission 2003; US Department of Energy 2004). However, as with any major changes in the energy industry, the transition to a hydrogen economy will require several decades.

The timescale and evolution of such a transition is the focus of many 'roadmaps' emanating from the USA, Japan, Canada and the EU (and many others). For example, the European Commission has endorsed the concept of a Hydrogen and Fuel Cell Technology Platform, with the expenditure of €2.8 billion over a period of 10 years. The introduction of hydrogen as an energy carrier has been identified as a possible strategy for moving the UK towards its voluntary adopted targets for CO_2 reduction of 60% of current levels by 2050 (Department of Trade and Industry 2003).

Table 3 summarises the forecasts of several roadmaps for deployment status and targets for hydrogen technologies and fuel-cell applications.

Table 3: Key assumptions on hydrogen and fuel-cell applications (International Energy Agency 2006; European Hydrogen and Fuel Cell Technology Platform 2005)

Technology	Today	2020–2025	2050
Carbon capture and sequestration (CSS) (€/ton CO_2)	20–30	4–8	3–6
Hydrogen produced from coal with CCS (€/GJ)	8–10	7–9	3–5
Hydrogen transportation/storage cost (pipeline, 5,000 kg/h, 800 km) (€/GJ)	10–15	3	2
PEM fuel cells (€/kW)	6,000–8,000	400	40
High-temperature fuel cells (€/kW)	8,000–10,000	800	200
EU: portable fuel cells, sold per year	N/A	250 million	N/A
EU: fuel-cell vehicles, sold per year	N/A	0.4–1.8 million	N/A
EU: stationary fuel cells (CHP), sold per year	N/A	2–4 GW	N/A
Japan: fuel-cell vehicles, cumulative sale target	N/A	5 million	N/A
International Energy Agency forecast: global fleet of fuel-cell vehicles	N/A	N/A	700 million

To achieve a significant penetration of hydrogen into future energy systems, the methods of hydrogen production, distribution, storage, and utilisation must be dramatically improved beyond their present performance, reliability and cost. Some of the key scientific and technical challenges for the hydrogen economy are summarised in Table 4.

- Lowering the cost of hydrogen production to a level comparable to the energy cost of petrol.
- Development of a CO_2-free route for the mass production of sustainable hydrogen at a competitive cost.
- Development of a safe and efficient national infrastructure for hydrogen delivery and distribution.
- Development of viable hydrogen storage systems for both vehicular and stationary applications.
- Dramatic reduction in costs and significant improvement in the durability of fuel cell systems.

Table 4: Scientific and technical challenges for the hydrogen economy

Until 2020, hydrogen production from fossil fuels and by electrolysis of water using grid electricity is expected to be the most important sources of hydrogen. During this transition period, advanced and clean reformation/gasification processes, CO_2 capture and sequestration and new efficient and low-cost electrolysers will have to be developed. However, in the long term, sustainable hydrogen production technologies based on renewable energy resources should become commercially competitive, gradually replacing fossil-fuel reformation/gasification. Hydrogen, produced by electrolysis of water using electricity generated from renewable resources, has the potential to be the clean, sustainable and, therefore, climate-neutral energy carrier of the future, eventually eliminating greenhouse gas emissions from the energy sector.

Prospective sustainable technologies that may supply hydrogen in the future include photosplitting of water using direct sunlight, and thermal splitting of water through high-temperature thermochemical cycles. Current nuclear technology generates electricity that can be used to produce hydrogen by electrolysis of water, enabling the nuclear energy industry to supply fuel to the transportation sector. 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 the ultimate source of a clean, abundant, and carbon-free resource for hydrogen production.

The components of a national hydrogen delivery and distribution network (including hydrogen pipelines) will need to be developed, providing a reliable supply of low-cost hydrogen to end users. If the hydrogen is produced from hydrocarbons, the hydrogen network will need to be coupled to the infrastructure necessary for carbon capture and storage. The use of hydrogen-fuelled vehicles will depend on the successful development of an affordable and widespread refuelling infrastructure. The basic components of a hydrogen delivery and dispensing infrastructure need to be developed, initially to supply local refuelling stations.

For hydrogen to become a viable energy carrier, advanced hydrogen storage technologies will be required. For hydrogen fuel-cell transportation use – widely regarded as the first major inroad into the hydrogen economy – neither cryogenic nor high-pressure hydrogen storage options can meet the mid-term targets (US Department of Energy 2004). More compact, low-weight, low-cost, safe and efficient storage systems operating at near-room temperatures and low pressures will need to be developed for automotive as well as for stationary applications. It is becoming increasingly accepted that solid-state hydrogen storage using hydrides of light elements is the only method that will enable a high weight percent and high volume density of stored hydrogen. At present, no known material meets these critical requirements.

Fuel cells have the potential to replace a very large proportion of current energy systems, from mobile phone batteries through vehicle applications to centralised or decentralised stationary power generation. Fuel cells offer a very attractive technology evolution path in that they can deliver significant efficiency gains on today's commercially available hydrocarbon fuels while also offering high efficiency in the future when hydrogen becomes widely available. The key scientific and technical challenges facing fuel cells are cost reduction and increased durability of materials and components.

Conclusions

The development of hydrogen-storage and fuel-cell technologies is set to play a central role is addressing growing concerns over carbon emissions and climate change as well as the future availability and security of energy supply. A recent study commissioned by the Department of Trade and Industry found that hydrogen energy offers the prospect of meeting key UK policy goals for a sustainable energy future (E4tech, Element Energy, Eoin Lees Energy 2004). Together, hydrogen and fuel cells have the capability of producing a green revolution in transportation by removing CO_2 emissions completely. Across the full range of energy use, these technologies provide a major opportunity to shift our carbon-based global energy economy ultimately to a clean, renewable and sustainable economy based on hydrogen.

The challenges are substantial and require scientific breakthroughs and significant technological developments coupled with a continued social and political commitment. The UK, however, has world-leading scientific expertise and facilities, as well the renewable resources to accelerate this transition to a hydrogen era.

References

Appleby, A.J. and Foulkes, F.R. 1993. *Fuel Cell Handbook.* New York: Van Nostrand Reinhold.

Crabtree, G.W., Dresselhaus, M.S. and Buchanan, M.V. 2004. The Hydrogen Economy. *Physics Today*, 57(12):39–44.

Department of Trade and Industry 2003. *Energy White Paper: Our Energy Future: Creating a Low-Carbon Economy*: http://www.dti.gov.uk/energy/whitepaper/ourenergyfuture.pdf (accessed 2006).

Dutton, A.G. 2002. *Hydrogen Energy Technology*. Tyndall Working Paper TWP 17. Tyndall Centre for Climate Change: http://www.tyndall.ac.uk/publications/working_papers/wp17.pdf (accessed October 2006).

E4tech, Element Energy, Eoin Lees Energy 2004. *A Strategic Framework for Hydrogen Energy in the UK*, Final report to the Department of Trade and Industry: http://www.dti.gov.uk/energy/sources/sustainable/hydrogen/page26734.html (accessed 2006).

European Commission 2003. *Hydrogen Energy and Fuel Cells A Vision of Our Future*: http://www.europa.eu.int/comm/research/energy/pdf/hydrogen-report_en.pdf (accessed October 2006).

European Hydrogen and Fuel Cell Technology Platform 2005. *Deployment Strategy*: https://www.hfpeurope.org/hfp/keydocs (accessed October 2006).

Harris, R., Book, D., Anderson, P.A. and Edwards, P.P. 2004. Hydrogen Storage: The Grand Challenge. *The Fuel Cell Review*, 17–23, June/July.

International Energy Agency 2006. *Hydrogen Production and Storage, R&D Priorities and Gaps*: http://www.iea.org/Textbase/papers/2006/hydrogen.pdf (accessed October 2006).

Powell, J.C., Peters, M.D., Ruddell, A. and Halliday, J. 2002. *Fuel Cells for a Sustainable Future?* Tyndall Working Paper TWP 50. Tyndall Centre for Climate Change: http://www.tyndall.ac.uk/publications/working_papers/wp50.pdf (accessed October 2006).

US Department of Energy 2003. *Basic Research Needs for the Hydrogen Economy*. Report of the Basic Energy Sciences Workshop on Hydrogen Production, Storage and Use. Office of Basic Energy Sciences: http://www.sc.doe.gov/bes/reports/list.html (accessed October 2006).

US Department of Energy 2004. *Hydrogen Posture Plan*: http://www.hydrogen.energy.gov/ (accessed October 2006).
