Hydrogen and Fuel Cells: A Vision of our Energy Future

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1. Introduction

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 [1]. 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 utilized 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 socio-economic barriers to the implementation of hydrogen and fuel cells as the clean energy technologies of the future.

2. Key Features

At the present time, there are three major technological barriers that must be overcome for a transition from a carbon-based energy system to a hydrogen-based economy. First, the cost of efficient and sustainable hydrogen production and delivery must be significantly reduced. Second, new generation 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.

Even though hydrogen is the third most abundant chemical element in the Earth's 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. At present the vast majority of the world's hydrogen is ironically produced from fossil fuels by steam reforming of natural gas and partial oxidation of coal or heavy hydrocarbons. These methods are currently the cheapest and most established techniques of producing hydrogen, although they always lead to the production of CO2. Hydrogen can be produced by splitting water through various processes including electrolysis, photo-electrolysis, high-temperature decomposition and photo-biological water splitting, although the cost of this hydrogen is several times higher than that produced from fossil fuels [2]. Renewable sources of energy might provide local sources of hydrogen, but certainly will not meet the volumes of hydrogen required globally for the new energy source. Prospective sustainable technologies that may supply hydrogen in the future include photo splitting of water using direct sunlight and thermal splitting of water through high-temperature thermochemical cycles.

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 [3,4]. 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 (see Table).

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 (Li-ion battery)	0.55	1.69

Present storage options for hydrogen have centered upon high-pressure 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. 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. 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 $LiBH_4$, above), however, much more work is required to improve their hydrogen absorption/desorption characteristics.

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 a fuel reforming process) but using a hydrocarbon-based fuel inevitably leads to a carbon dioxide 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. All fuel cells, even those fuelled by hydrocarbon, 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. As fuel cells are not subject to 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 utilized in Combined Heat and Power (CHP) systems, an overall efficiency in excess of 85% can be achieved.

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 (see Fig. 1). 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. 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.

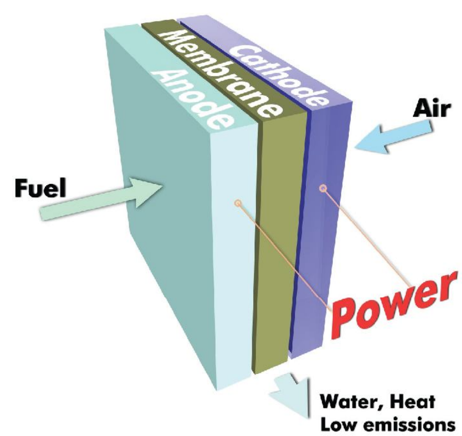

Fig. 1. Schematic diagram of a fuel cell.

Fuel cells have the potential to replace a very large proportion of current energy systems from mobile phone batteries through vehicle applications to centralized or decentralized 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, whilst 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.

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 [5,6]. However, as with any major changes in the energy industry the transition to a hydrogen economy will require several decades. To achieve a significant penetration of hydrogen into future energy systems the methods of hydrogen production, distribution, storage, and utilization must be dramatically improved beyond their present performance, reliability and cost.

3. Conclusions

The development of hydrogen storage and fuel cell 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. Together, hydrogen and fuel cells have the capability of producing a green revolution in transportation by removing carbon dioxide 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.

4. References and Bibliography

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Speaker's Biography

Peter P. Edwards received his B.Sc. (Hons I, 1970) and Ph.D. (1974) from Salford University. He remained at Salford for a further year as SRC Fellow engaged in a collaborative project with Professor Sir Nevill Mott of the Cavendish Laboratory, Cambridge. In 1975 he was awarded a British Fulbright Scholarship concurrent with a National Science Foundation Fellowship to work with Professor Michell (Mike) J. Sienko at the Baker Laboratory of Chemistry, Cornell University. In 1977 Edwards returned to the UK, to the Inorganic Chemistry Laboratory, Oxford, as SRC NATO Fellow and then Ramsay Memorial Fellow to work with Professor John B. Goodenough. In 1979 he was appointed Lecturer in Chemistry at the University of Cambridge and Director of Studies in Chemistry at Jesus College, Cambridge. In 1987 Edwards was awarded the Corday Morgan Medal of the Royal Society of Chemistry (RSC) for "*Innovative Experimental Studies of the Chemistry and Physics of Condensed Matter*". In 1988 he became Co-Founder and Co-Director in Cambridge of the first-ever Interdisciplinary Research Centre in the UK, that in superconductivity. During the period 1984-1986 Edwards was also Visiting Professor at the Baker Laboratory, Cornell University. In 1991 he moved from Cambridge to take up the Chair of Inorganic Chemistry at the University of Birmingham and subsequently became Head of Chemistry at Birmingham in 1996. In 1992 he was awarded the Tilden Medal of the RSC for his work on the Metal-Nonmetal Transition. In 1996 Edwards was elected Fellow of the Royal Society. In 1999 he became the first holder of the Chair of Chemistry and of Materials at the University of Birmingham. In 1999 he was awarded the Liversidge Medal of the RSC for "*Major Advances in the New Knowledge of Condensed Matter Science*". In October 2003 he moved to Oxford to become Professor and Head of Inorganic Chemistry. He is currently the Executive Director of the UK Sustainable Hydrogen Energy Consortium. In 2003 Edwards was awarded the Hughes Medal of the Royal Society, awarded in recognition of an original discovery in the physical sciences, particularly electricity and magnetism or their applications. The citation read "*For seminal Contributions to Fields Including High Temperature Superconductivity and the Behaviour of Metal Nanoparticles and for Advancing the Phenomenology of the Science of the Metal-Nonmetal Transition*".