Preface

The early history of the proposal to harness hydrogen as a clean and abundant form of energy has been well documented.[1] In brief, on 27 November 1820, the Revd. William Cecil presented a lecture to the Cambridge Philosophical Society in which he advanced the idea of replacing steam engines by a novel form of engine in which hydrogen was combusted in a cylinder. The resultant change in pressure could be converted into mechanical energy to perform work. He suggested that this would overcome certain disadvantages of the steam engine, notably the long start-up time from cold. There is no record that Cecil ever built such an engine. Later in the 19th century, the novelist Jules Verne wrote *The Mysterious Island* (1874): a story in which he proposed replacing coal as a fuel by hydrogen derived, via electrolysis, from inexhaustible supplies of water. In this, Verne showed considerable prescience, but failed to explain that a source of primary energy was required to generate the electricity. A hundred years after Cecil's seminal lecture, J.B.S. Haldane made the following statement in a paper read to the 'Heretics' Society of Cambridge University on 4 February1923:[2]

> *'Personally, I think that four hundred years hence the power question in England may be solved somewhat as follows. The country will be covered with rows of metallic windmills working electric motors which in their turn supply current at a very high voltage to great electric mains. At suitable distances, there will be great power stations where during windy weather the surplus power will be used for the electrolytic decomposition of water into oxygen and hydrogen. These gases will be liquefied and stored in vast vacuum jacketed reservoirs, probably sunk in the ground.'*

Many scholars consider Haldane's prophesy to be the first allusion to a 'Hydrogen Economy' – a term that, as will be seen below, was not coined until some fifty years later.

Hydrogen does not occur freely in nature; it is predominantly found in combination with oxygen as water and with carbon as fossil fuels. Energy has to be expended to extract hydrogen from these sources. It is therefore not a new form of primary energy, but merely an energy vector (or carrier) that is environmentally clean when combusted and therefore attractive, although not especially convenient to handle and use.

Little happened to advance the deployment of hydrogen energy until the 1930s and 1940s when Rudolf Erren, a German engineer, modified internal combustion engines to run on fuel–hydrogen mixtures or even on pure hydrogen. Commercial enthusiasm for hydrogen engines faded, however, after the *Hindenburg* airship disaster in 1937. It should be noted that later research has shown that the *Hindenburg* fire was more to do with the flammability of the fabric chosen for the airship's envelope than with the fact that it was filled with hydrogen.

Renewed interest in hydrogen energy was shown in the 1950s following the demonstration of the first practical fuel cell by the British scientist Francis T. Bacon, who, like Cecil and Haldane, also worked in Cambridge. Fuel cells of the Bacon type found an important application in space missions, particularly in manned flights of extended duration. Recently, the perfection of fuel cell technology for both the stationary generation of electricity and for powering road transportation has been seen as an important step towards energy security. Accordingly, much research and development of fuel cells is in progress.

Given the relatively low cost of fossil fuels, scant attention was paid to the use of hydrogen for terrestrial applications until 1973, when the shock of the first 'oil crisis' reverberated around the world. It was then widely understood that reserves of fossil fuels, especially petroleum, were finite and that, sooner or later, demand would exceed supply. Fossil fuels are laid down over geological time and, once used, cannot be replaced. Moreover, there are inequalities in the geographic distribution of these natural resources that make some countries wealthy and others relatively poor; unabated consumption will intensify political, economic and social tension. Thus, it has been deemed necessary to turn increasingly to 'renewable' sources of energy such as solar, wind, wave and tidal energy. These are mostly periodic or irregular in output and require some type of storage as a smoothing device, together with a vector to convey the primary energy from where it is produced to where it is needed. Many of these renewable forms of energy serve to generate electricity directly. While electricity is a highly versatile carrier of energy, it is not easy to store and is of limited value as a fuel for road and air transportation, although it is employed widely for rail traction.

The dawning realization of the future importance of hydrogen as an energy vector and new fuel led, in 1974, to the formation of the International Association for Hydrogen Energy (IAHE) and to its biennial World Hydrogen Energy Conference (WHEC) that is still taking place today. The latter is held in cities around the world. In 1975, the *International Journal of Hydrogen Energy* was launched and its publication continues. Also, in the same year, one of the present authors was a contributor to a paper entitled 'Hydrogen the Ultimate Fuel', in which the attributes of hydrogen as an energy vector and fuel were examined.[3] To quote from that review:

> *'In the long term, when world supplies of natural gas and petroleum are largely exhausted and society is increasingly dependent upon nuclear power or new sources of energy, hydrogen will appear attractive as an energy vector and energy storage medium. Key questions are how and over what*

timescale should the transition be made from the present situation, where we have neither the technical ability nor the financial incentive to introduce hydrogen as a fuel, to the distant future where it may be a vital component of the world energy scene.

To answer these questions it will be necessary to estimate in some detail the magnitude of the problems involved in implementing the Hydrogen Economy, in technical, industrial and financial terms, and also the lead times for society to make a smooth transition from one energy basis to another. It is then necessary to compare these findings with some estimate of when hydrogen will be required in bulk quantities to replace fossil fuels. Even without this analysis it is evident that the lead times will be measured in decades and the capital requirements will be enormous, so that planning on a national or international scale will be vital.'

The 1975 paper went on to estimate the number of 1000 MW_e nuclear power plants, for example, that would be necessary to produce (by means of electrolysis at 60% efficiency) the hydrogen needed to fuel various aspects of the UK industrial and transportation markets as they then existed. To substitute hydrogen for all the fossil fuel consumed in the UK in 1974 – a hypothetical concept – would have required 377 such power stations. This gives some idea of the magnitude of the problems that would be encountered in implementing a full Hydrogen Economy based on nuclear electricity. The challenge today for a hydrogen future centred on renewables would be even greater, especially given the growth in overall energy consumption since 1974.

In the intervening years, there has been comparatively little progress in facing up to the task of establishing a Hydrogen Economy, again thanks largely to an abundance of cheap fossil fuels. The situation is now changing with world production of petroleum expected to peak in the near future and that of natural gas within a few decades – just as the global demand for energy is growing rapidly.[4] Coupled with this concern over finite resources, there are two other pressing threats to society: (i) climate change, which is attributed largely to carbon dioxide formed by the burning of fossil fuels, and (ii) worries over the security of energy supplies in a world where the major reserves are in the hands of comparatively few countries.

There is much debate among geologists and petroleum engineers over exactly how much oil and gas remain to be exploited and how many decades these reserves will last as world consumption rises. The precise reserves are not too relevant in the greater scheme of things; even children alive today face an uncertain energy future unless totally new technology is developed. The growth in world population and the expectation of a rising standard of living in developing countries make a greater use of fossil fuels inevitable. The World Bank has stated (2002) that:[5]

'Reliable energy is a key component of economic and social development... lack of energy is among the key forces slowing down poverty reduction and growth of the rural sector.'

Increasing the availability, affordability and use of energy is vital if poor nations are to achieve their potential. This is a short-term objective for the next decade or two.

Looking further ahead, the world has an even more challenging goal that was set in 1987 by the World Commission on Environment and Development (the Brundtland Commission) when it defined 'sustainable development' as a process that: 'meets the needs of the present without compromising the ability of future generations to meet their own needs'.[6] In energy and environmental terms, this reduces to 'devising a set of energy technologies that meets humanity's needs on an indefinite basis without producing irreversible environmental effects'. It is now generally accepted that mean global temperatures are rising steadily and are resulting in a change of climate. This, in turn, is thought to account for the increased incidence of violent storms and flooding, while in other parts of the world more droughts and crop failures are occurring.

Fortunately, there are unlimited supplies of renewable energy potentially available in many different forms. The challenge is therefore to find practical ways to exploit them as efficiently and cheaply as possible on a world-wide scale. Hydrogen is seen as one such option; it presents a means to convey renewable energy from the site of generation to the end-user, it serves as an energy store and it also offers the prospect of a new, emission-free fuel for transportation applications. This is a vision that is extremely attractive to environmentalists, politicians and informed members of the public. Nevertheless, any decision to adopt hydrogen as an energy vector has to be backed up by hard numerical analysis of the associated energetics and by rigorous evaluation of the capital and operating costs.

Hydrogen is a clean form of energy that can be produced from water using many different primary sources of energy, *e.g.*, various fossil fuels, assorted renewables and nuclear power. This flexibility is attractive politically since it reduces the chances of a hydrogen cartel being established. During the early stages of transition to a Hydrogen Economy, it is likely that the hydrogen will derive mostly from fossil fuels while awaiting the establishment of further renewable energy systems.

The title of this book – *Hydrogen Energy: Challenges and Prospects* – has been chosen carefully. Essentially, the work presents an account of the state-of-the-art of hydrogen energy and the challenges to be met if it is to play an important role in the world's energy scene, together with an assessment of the prospects for success in such a venture. Just as coal and the steam engine gave rise to the Industrial Revolution and petroleum and the internal combustion engine brought about the transportation revolution of the 20th century, enthusiasts for a Hydrogen Economy see this as the start of a major technological and social revolution that will determine our way of life in the 22nd century. Inevitably, much will change in society during the course of the present century and forecasting events so far ahead can only be an exercise in crystal-ball gazing, albeit one based on the science and technology in place today. Nevertheless, we have endeavoured to peer into that crystal ball, with due regard for physical principles, numerical values and economics.

There are particular difficulties in writing a book that addresses the future. For example, it is not easy to evaluate the prospects for new forms of energy without sound information on the attendant costs, which are hard to determine in advance of large-scale prototype demonstrations. Costs tend to vary from place to place and certainly from time to time, as technology progresses and the benefits of replication are felt. Also, when looking decades ahead, one does not know what advances will be made in the utilization of competing fuels, or the environmental regulations that will exist. For these reasons, we have confined ourselves mostly to an evaluation of the technical aspects and, where appropriate, have made just a few generalizations on costs.

A further problem is that the overall subject of hydrogen energy is multifaceted, with many component considerations, all of which are highly interactive. These include the primary energy source (or the fuel) employed, the means of conversion to hydrogen, the scale of operations, the mode of distributing and storing the hydrogen and the intended end-use. With so many contributing factors, it is difficult to subdivide the book into discrete, self-contained chapters. We have been obliged, therefore, to cross-refer the reader between chapters.

Finally, the world literature on energy production and consumption is plagued by a proliferation of measurement units. Variously, data are presented in terms of the International System of Units (SI, *e.g.*, metres, pascals, joules), traditional industry-based units (*e.g.*, barrels of oil, kilowatt hours of electricity, million tonnes of oil equivalent) and, especially in the USA, Imperial units (*e.g.*, miles, British thermal units of heat, quads of energy, cubic feet of natural gas, bars of pressure). For the expression of time, however, units of days and years are generally more appropriate than the SI unit (seconds) in this field. In order to assist readers in translating units into those with which they are familiar, a set of conversion factors has been included.

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References

1. P. Hoffmann, *Tomorrow's Energy: Hydrogen, Fuel Cells and the Prospects for a Cleaner Planet*, MIT Press, Cambridge, MA, 2001.
2. J.B.S. Haldane, *Daedalus; or, Science and the Future*, E. P. Dutton, New York, 1924.
3. R.M. Dell and N.J. Bridger, *Appl. Energy*, 1975, **1**, 279–292.
4. R.M. Dell and D.A.J. Rand, *Clean Energy*, Royal Society of Chemistry, Cambridge, 2004.
5. D. Lallement, *Roundtable on Energy for Sustainable Development: Partnerships for Action*. Seminar: *Energy for Sustainable Development*, United Nations Development Programme – European Commission, Brussels, 25–26 April 2002.
6. G. Bruntland (Ed.), *Our Common Future*, World Commission on Environment and Development, Oxford University Press, Oxford, 1987.

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