Hydrogen and Wales

A Vision of the Hydrogen Economy in Wales: Placing Wales in a Position to Take Full Advantage of the Hydrogen Economy

Report Number 3
ERDF part funded project entitled:
A Sustainable Energy Supply for Wales:
Towards the Hydrogen Economy

Authors:

Cherryman S J
Maddy J
Hawkes F R
Hawkes D L
Dinsdale R M
Guwy A J
Premier G C

http://www.H2Wales.org.uk

Hydrogen and Wales

ISBN: 1-84054-116-4

Published by:
University of Glamorgan
Pontypridd
Mid Glamorgan
Wales
UK
CF37 1DL

Before developing any hydrogen project in the UK consultation with the Health and Safety Executive and planning officers in the region are essential in order to comply with all current health and safety legislation.

Foreword

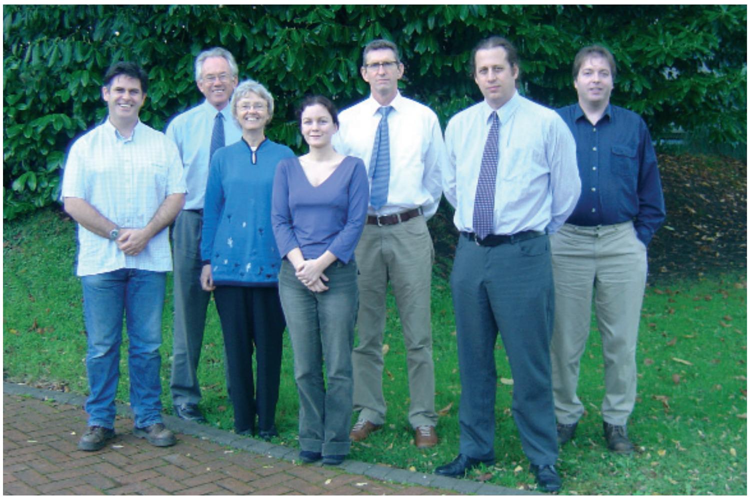
At the start of the twenty-first century we face a significant energy challenge. Fossil fuels have delivered energy and convenience, in our homes, for transport and for industry. However, the overwhelming scientific evidence is that the unfettered use of fossil fuels is causing the world's climate to change, with potentially disastrous effects. Despite recent improvements in the UK, industry and transport remain sources of air pollution that are significant contributors to poor health in certain areas. In addition, the supply of oil and natural gas is finite and most remaining reserves are controlled by a small number of politically troubled nations. Unabated consumption of this diminishing resource is potentially a source of increasing political, economic and social tension and significant environmental upheaval.

Hydrogen is attracting substantial attention from governments, industry, academia and others as a potential means to overcome these difficulties. Hydrogen is a clean fuel with no CO_2 emissions and can be sustainably produced through CO_2 free or neutral processes. Hydrogen can be produced and used locally to generate electricity or used as a clean fuel for vehicles. As a replacement for fossil fuels, there is significant potential for hydrogen to bring social and economic benefits, to such an extent that many are predicting a move from an oil energy economy to a hydrogen energy economy.

The use of hydrogen as a fuel is not a new idea. Town gas was used domestically until the 1950's and comprised 50% hydrogen. Industry has used hydrogen in the chemical, metal and food industries for decades. Man has been to the moon using hydrogen and the interest in hydrogen vehicles dates back to the 1800's. The hydrogen economy is no longer the preserve of a limited number of enthusiasts. In recent years, all the major motor manufacturers, oil companies and, importantly, governments have established or are considering programmes based on hydrogen energy. In the last year alone, the US and the EU have pledged billions of pounds worth of investment in research development and demonstration to make the transition to the hydrogen economy a reality.

A number of factors present significant opportunities for Wales in successfully achieving this transition. Strong policy direction, an inherent national expertise in manufacturing, engineering and agriculture, and the presence of substantial natural resources can all provide an advantage in moving Wales to a hydrogen economy. Wales is the first country to make a statutory commitment to review decisions sustainably and progressive conversion to a sustainable hydrogen economy in Wales would be a major reflection of this commitment.

The Project Team
November 2004



Executive Summary

This report outlines a framework for the transition to a hydrogen economy in Wales, combining research conducted by the CymruH2Wales project and the views of stakeholders. This has been presented as a hydrogen vision and route map for Wales characterised by four development phases. The technical, political, economic, social and environmental requirements to achieve a successful transition are described.

Hydrogen is increasingly seen as the versatile fuel of the future, with the potential to replace fossil fuels. Hydrogen, if produced sustainably, can be the basis of a low carbon economy, delivering a reduction in emissions of CO_2 and other atmospheric pollutants, with the associated benefit of improving security of supply and enabling the possibility of an infrastructure based on distributed generation. Hydrogen, like electricity, is an energy vector, extractable from water or organic compounds using external energy sources. It is at present mainly produced from fossil fuels, particularly from natural gas by steam methane reforming. Hydrogen can, however, be produced sustainably by a range of processes, which can operate at large or small scale, including biomass based processes or by linking renewable energy sources with water electrolysis.

Storage of sustainably produced hydrogen enhances the use of renewables in the energy mix and aids the achievement of national targets for CO_2 emissions. Current storage technologies exist, such as compressed gas cylinders or cryogenic liquid storage. However, to overcome some limitations of these methods, much research is focused on improving the gravimetric density of hydrogen storage technology. Hydrogen can be utilised in internal combustion engines, producing only water and reduced amounts of NOx, so contributing to a reduction in air pollution. Fuel cells, which efficiently and quietly convert hydrogen into electricity, are starting to become commercially available, but still have some way to go before having mass-market appeal. All major motor manufacturers are developing prototype hydrogen cars, using the internal combustion engine or fuel cells, with hydrogen stored compressed or in liquefied form. Hydrogen thus provides an effective bridge between renewable energy production and the growing needs of the transport sector. Storage efficiency, fuel cell viability and infrastructure development may be seen as potential barriers to the development of the hydrogen economy. There are currently numerous development programmes to overcome these barriers.

Presently there is world-wide interest in the hydrogen economy, with an increasing number of demonstration projects, particularly in USA, Japan and the EU. For example, the European Union funded CUTE bus project is one of the largest fuel cell demonstration projects in the world, demonstrating 27 fuel cell buses in 10 European capitals. Despite a number of UK based organizations being active in hydrogen and fuel cell technologies, the number of hydrogen energy demonstrations in the UK remains limited. Wales is well endowed with renewable energy resources and has a number of national competences that could be of benefit in developing a hydrogen economy, such as expertise in agriculture, manufacturing and engineering. The National Assembly for Wales is constitutionally committed to sustainable development, is supporting and promoting Wales as a global showcase for renewable energy, and sees the development of renewable energy as a source of employment. Wales has the opportunity to take a leading role in the development of sustainably-produced hydrogen and be at the forefront of the technology export market.

This report reviews what is currently known about the economics of hydrogen energy. Specific hydrogen energy policies and development programmes for hydrogen and associated industries are discussed, along with the impact of policy on the possibility of meeting CO_2 reduction targets. Hydrogen now compares favourably in properties and production methods with conventional non-renewable energy sources, but also needs to compare in terms of price. Social improvements can be gained through the introduction of the hydrogen economy, particularly in terms of improved air quality and potentially in relation to fuel poverty. Employment through the transition to a hydrogen economy will benefit people in the most economically deprived areas. Public perception and understanding of hydrogen is not well developed and acceptance of hydrogen technologies is variable at best. Each of the four phases in the transition to a hydrogen economy in Wales will need to be accompanied by a systematic programme of public education to increase awareness of these improvements to the quality of life.

Key Points

- Hydrogen has a significant part to play in overcoming increased dependency on the diminishing resource of imported fossil fuels.
- As an energy carrier, hydrogen can also significantly reduce the problem of greenhouse gas emissions and atmospheric pollution.
- Hydrogen is an ideal complement to electricity as an energy carrier. It can provide the required buffer between consumer demand and intermittent supply of renewable electricity from wind, solar or marine sources. At the same time the hydrogen produced has the flexibility to be used as a clean, safe and convenient transport fuel.
- Transition to a hydrogen economy in Wales cannot be seen in isolation from the rest of the world. Collaboration on an international scale will be necessary to overcome a number of the technological barriers that are currently faced in moving to the hydrogen economy. Wales should seize the opportunities available to become a significant global player in a future hydrogen economy. This ambition is not unrealistic if the latent ability and resource in Wales is put to work.
- The potential demand for new products and services in a hydrogen economy suggests that Wales can benefit significantly in economic and social terms. This benefit can come not only from a transition in Wales itself, but also through the establishment of new Welsh industries, hence new Welsh jobs and income from exporting hydrogen energy related technology to the rest of the world.
- The current emphasis of hydrogen energy development is on technology, but without consumer demandpromising hydrogen energy technologies may fail, as have numerous examples before. Significant efforts are required to increase public awareness, understanding and acceptance before a market pull towards the hydrogen economy can be established.
- Early demonstration projects have a fundamental role to play in addressing these issues of public acceptance, whilst proving the technologies to be employed.
- The level of fuel duty in the UK means that untaxed hydrogen, particularly from renewable sources, is a more competitive fuel in the UK than almost anywhere else in the world.
- The transition to a hydrogen economy will require a number of intermediate steps, rather than a single step change. These transition steps include the adoption of hydrogen as an additive to conventional fuels like CNG for internal combustion engines, electric vehicle drive development, hydrogen storage improvement and fuel cell developments.

Table of Contents

1. Introduction

It is important to realise that, unlike oil, coal or gas, hydrogen cannot be mined or pumped from the ground but must be generated. Hydrogen is one of the most abundant elements on earth but is locked into organic compounds and water so can only be obtained when an external energy source is used to extract it. Thus hydrogen, like electricity, can be described as an energy vector. The amount of primary energy needed to release the hydrogen is dependant on the methods used for extraction (reviewed in Chapter 5). Hydrogen, though at present mostly produced from fossil fuels, can be produced by renewable, CO_2 neutral processes. These production processes can be at the macro or micro scale, and allow distributed generation.

A major feature of hydrogen as an energy vector is that it allows energy to be stored. This is particularly useful when developing a sustainable economy based on renewable energy sources characterised by intermittency (DTI, 2002b and Sorensen, 2002). If the capacity for hydrogen storage was realised and inplace, national targets for the contribution of energy from renewables such as wind and solar could be increased. When visualizing a hydrogen future, storage and distribution are important factors.

Hydrogen is currently being seen as the fuel of the future (POSTNOTE, 2002) as its combustion to produce energy and its use in fuel cells to generate electricity produce only water, and a small amount of NOx if hydrogen is burnt in air. It can be used for transport and in static applications to provide electricity and heat, at micro and macro scales. The versatile nature of hydrogen coupled with little or no polluting emissions at end use makes this option for a low carbon sustainable future very appealing (DTI, 2002b).

The combination of hydrogen with fuel cell technology carries great promise for a cleaner, more efficient energy future, particularly for the automotive sector, but also for static energy generation and mobile power applications. Since Sir William Grove of Swansea invented the fuel cell in 1839, the technology has remained largely underdeveloped, that is until recently. Over the last ten years, fuel cell technology has emerged from the laboratory to an initial commercialisation stage, with a number of organisations introducing products to early niche markets. Wales, with its expertise in the automotive and high technology sectors and supportive business climate, is ideally placed to take advantage of this emerging industry. The Welsh Development Agency's (WDA) Hydrogen Valley project provides the perfect stimulus for the establishment of a Welsh hydrogen and fuel cell industry, with the potential to secure early mover competitive advantage for firms in Wales.

Hydrogen Valley Vision

"To achieve a zero emission energy based economy supported by a sustainable business community through the exploitation of leading edge technologies and stimulation of emerging niche markets."

A vision of a hydrogen economy for Wales is not one that can be considered in isolation. The magnitude of the required change means that progress needs to be synchronised with the rest of the UK, with Europe and the wider world for a sustainable hydrogen economy to become a reality. The supportive policy framework in Wales is entirely in step with activities in the rest of the UK, Europe and the rest of the world. Some countries have already taken the first steps towards a hydrogen economy. The USA, Canada, Japan and Germany all have established programmes. Significantly for Wales, smaller countries like Iceland have also demonstrated that the development of a hydrogen economy is not just the preserve of economic super powers. If the actions proposed in this report become a reality, Wales will be firmly placed on the hydrogen energy map. Actions such as the early establishment of working demonstration projects building on Wales's existing strengths will represent a significant step towards realising the vision of the National Assembly that Wales becomes a showcase for renewable energy.

"The Hydrogen Economy is not going to happen tomorrow, but if it happens in the next 20, 30, 40 or 50 years time, as I think most people accept it almost certainly will, because it will have to in terms of controlling global warming, the greater the contribution that we have made [in Wales] the better."
Rt. Hon. Rhodri Morgan

The CymruH2Wales project runs from January 2003 to January 2005 with funding from the European Regional Development Fund, Welsh Assembly Government and the University of Glamorgan. The project has researched the social, economic and technical implications of moving to a hydrogen fuel economy. This report outlines a framework through which a move to the hydrogen economy in Wales can be achieved.

The aim of this project is to place the Objective 1 region in Wales in a position to create wealth and employment by taking full advantage of the opportunities presented by the ongoing transition to a hydrogen economy.

This project:

- Investigates the potential to develop an industry for the sustainable generation (from biomass, waste and by electrolysis from wind power), storage, distribution and utilisation of hydrogen.
- Identifies the opportunities for growth in the rural economy through agricultural diversification and utilisation of a variety of energy crops for hydrogen generation.
- Brings together the main players with a stake in the development of the hydrogen economy to work together strategically.
- Develops an expert knowledge base to inform industry and to support decision-making by those responsible for developing a sustainable energy policy in Wales.
- Identifies the most viable demonstration projects for the next phase, including costs and sources of funding.

A launch event on 11th June 2003 at the Glamorgan Business Centre, University of Glamorgan, was a forum for sharing information on technical, social, economic, and policy matters affecting the implementation of hydrogen energy in Wales. It was well attended by stakeholders in the hydrogen economy and was a launch platform for the scoping study produced in the first 5 months of the project, Hydrogen 2003 (Maddy *et al.* 2003) and the project website www.H2Wales.org.uk. Both Hydrogen 2003 and the website from which it has been freely downloadable have proved a valuable state-of–the–art resource for those within and outside Wales seeking an authoritative and compact review.

A further dissemination event "First Steps to Hydrogen: Realising the European Vision" was held on March 1st 2004 in Brussels as part of the Wales European Centre Wales Week. Presentations from the Minister for Environment, Planning and Countryside, National Assembly for Wales, Welsh industry, the National Assembly Sustainable Energy Group, WDA and the H2Wales project raised the profile of Wales and its contribution to hydrogen strategy before a pan-EU, well-connected audience.

A valuable outcome of this project is the growth of a recognisable community of interest in the development of the hydrogen economy in Wales, represented by the Steering Group (Section 3.9), those participating in the Launch Event, Wales Week event, Hydrogen Vision seminars (Chapter 2) and the Hydrogen Conference (8th Dec 2004 at the University of Glamorgan). Work resulting from research undertaken by the CymruH2Wales project will continue to be published after January 2005 and demonstration projects are currently being developed. This report provides a knowledge base to inform industry and to support decision-making and points to a way forward for Wales towards the hydrogen economy.

2. Hydrogen: Future Energy Vector

The vision for a hydrogen economy in Wales presented in Sections 2.1 and 2.2 have been produced following a thorough consultation exercise with over 100 key stakeholders in the future hydrogen economy in Wales. Central to this process were two seminars held in March and June 2004 in collaboration with the WDA led Hydrogen Valley Initiative. These seminars helped to identify the important aspects of a future hydrogen economy in Wales and ways in which Wales could gain an advantage through the transition. The information from this consultation exercise and the views of the participants have been collated into a vision of a hydrogen economy for Wales (section 2.1) and a route map defining potential strategic development towards the hydrogen economy in Wales (section 2.2). Section 2.3 presents the requirements for the successful introduction of a hydrogen economy in Wales.

2.1. The Hydrogen Vision

Imagine:

- Wales utilising its natural energy resources to meet all of its energy needs.
- Wales not being dependant on imported fossil fuels.
- Transport in Wales that does not emit CO_2 or significant levels of any other pollutants.
- A thriving Welsh industry based on the manufacture of cutting-edge energy and automotive equipment.
- A flourishing rural economy in Wales that gains a significant amount of its income through the cultivation of energy crops.

However, at present this vision is some way from reality. Global demand for energy continues to grow dramatically (BP, 2004). Whilst predictions vary, this trend is likely to continue for the foreseeable future. The bulk of this increasing energy consumption is being met from diminishing reserves of fossil fuels, resulting in continued emissions of carbon dioxide and other atmospheric pollutants. Wales has followed this trend, with the significant majority of our energy needs currently being met from non-renewable sources. Over the last thirty years the most significant increase in energy consumption has been in the transport sector, which remains almost entirely dependant on fossil fuels.

" Hydrogen has the greatest potential to deliver a low carbon economy future as a fuel source for both the energy and transport sectors"
Rt.Hon. Rhodri Morgan

2.1.1. The Carbon Energy Problem

Environmental concern over traditional fossil fuel is a driver in the move away from a carbon based economy. In the UK 90% of carbon dioxide and 83% of other greenhouse gas emissions come from the production and use of energy (DTI, 2002a). The release of these gases produces global warming and acid rain. In the last 150 years there has been a 1^{0}C rise in global temperature and scientific consensus is that if the world continues with 'business as usual' the trend will accelerate. Problems will become more noticeable with an increase in flooding and global weather systems in chaos. Consequently many nations including the UK have signed the Kyoto protocol, a legal obligation to reduce emissions below 1990 levels. A transition to a less polluting source of energy will be required to meet these targets; hydrogen is seen as one way to enable this transition (DTI, 2003a).

Financial concern over energy in the future is also a driver in the move away from fossil fuels. Energy companies contribute to the UK GDP by 3 percent (DTI, 2002a) and there is a projected increase in energy demand in the next fifty years (Metcalfe, 2003). The combination of the finite nature of fossil fuels and the projected increase in demand along with geo-political uncertainties will drive energy prices up in time (Thomas, 2001a). Currently many areas of fossil fuel production are at their peak and a decrease in production levels is expected over the next twenty years (BP, 2004). Recent predictions indicate that oil will be depleted by 2040 and gas twenty years after that. In the coming years the remaining fossil fuel will be only available in the most politically unstable regions, making security of supply paramount (DTI, 2003a). Simple supply and demand economics indicate that our current dependence on oil-based products is going to have to cease in the future.

It is against this background that the development of the hydrogen energy economy is being undertaken. In the UK government's recent White Paper on energy (DTI, 2003a) the role of hydrogen in future markets was highlighted and there was emphasis placed on developing a hydrogen economy.

Here we review the issues in more detail:

- **Demand for Energy**
  Worldwide energy demands are likely to double over the next 50 years, driven by increasing population and economic growth particularly in the developing countries. At the same time, reserves of oil have passed their peak in most producing nations. The majority of the remaining oil is in the potentially unstable Gulf states. Natural gas demands are also growing and despite our natural gas reserves in the North Sea, the UK is set to become a net importer of natural gas in the next two years (EIA, 2004). Whilst demand for energy in Wales is not growing at the pace of certain countries, if we continue on our present course for sourcing our energy needs, the competing demand for reducing resources will lead to significantly increased energy costs and potential economic difficulties.

- **Security and Continuity of Supply**
  Recent damaging power outages in many parts of the world have highlighted the potential problems when demand cannot be satisfied by supply, or where significant centres of population are dependant on a centralized energy infrastructure. The effect of power black-outs in Cardiff, for example, similar to those experienced in the North Eastern US, Italy and London over recent years, could have a damaging economic impact. The fuel blockades of September 2000 also demonstrated the extent to which our economy is currently dependant on continued supplies of fossil based fuels and the potential difficulties surrounding even short-term interruptions to supply. On a global scale we continue to see evidence of the potential uncertainties surrounding countries with reserves of fossil fuel. Without changes to our energy provision, the issues of security and continuity of supply will become more significant.

- **Global Climate Change**
  The overwhelming balance of scientific evidence supports the belief that emissions from human activity are having a detrimental effect on the world's climate. The most prominent of these emissions, carbon dioxide, is an unavoidable consequence of our inexorable use of fossil fuels. Without drastic reductions in the amount of carbon dioxide that we release from our activities, there will be dramatic and potentially disastrous consequences for our global climate and devastating human impact. Climate change in Wales has the potential to adversely affect natural and cultural habitats, have a bearing on health, and to damage the Welsh economy.

- **Poor Air Quality**
  The absence of visible smog from most parts of Wales conceals the remaining problem caused by non-visible oxides of nitrogen, carbon monoxide and particulates emitted from our vehicles and industry. Up to 24,000 people are estimated to die prematurely each year in the UK due to the effects of air pollution (DEFRA, 2004). Worldwide this figure is estimated to be over 3 million. Traffic in Wales's towns and cities and our industry currently contribute to poor air quality and consequently to health problems of the people of Wales. To overcome this, we in Wales, as in the rest of the world, have an obligation to come up with clean energy solutions for transport. Use of hydrogen as a vehicle fuel can dramatically reduce or eliminate these harmful emissions.

2.1.2. The Hydrogen Energy Answer

Supply of hydrogen is potentially inexhaustible and it can be produced in several ways from a range of primary energy sources. Unlike fossil fuels, the resources to produce hydrogen are not limited to any country or region and a number of different technologies can be used to produce the hydrogen, appropriate to the location.

Widespread application of renewably produced electricity, appropriate to local resources, is an important way to address many of the problems of carbon-based energy. However, most forms of renewable energy are intermittent and require some form of long-term energy storage to allow supply and demand to be matched. Hydrogen, used as an energy carrier in conjunction with renewable energy resources can provide an effective store for intermittent renewable energy, addressing the imbalance between supply and demand. Renewably produced hydrogen can also enable us to maintain the freedom that we currently enjoy for personal transport, whilst achieving the necessary reductions in carbon dioxide and other emissions.

Hydrogen can be generated using electricity from renewable sources by electrolysis from water, producing hydrogen and oxygen. This is a tried and tested technique but can be an expensive method of production as the price of renewable energy is currently higher than fossil fuels and the process of electrolysis is in itself expensive. However, niche markets, for example wind power, are best placed to take advantage of technology where surplus power can be used to create hydrogen for storage (DTI, 2002b). Hydrogen generation and distribution may provide a cost-effective alternative to installing or upgrading the electricity grid in remote locations, where it is necessary to accommodate new renewable energy developments e.g. tidal power. Hydrogen can also be produced from biomass, organic waste materials and energy crops. Biomass production creates a carbon dioxide neutral, sustainable source of hydrogen (the carbon release is part of the natural carbon cycle). Production of hydrogen from biomass meets the targets of sustainable development, security of supply, agricultural diversification and should bring benefit to rural Wales (Hawkes *et al.*, 2002a).

Hydrogen technologies are ideal for rural communities as hydrogen can be produced and stored locally with no need for a national infrastructure (POSTNOTE, 2002). A centralized infrastructure is also possible for a hydrogen economy, which would benefit from an economy of scale for production, but storage and delivery could be major hurdles. A combination of these two infrastructure models could be applied depending on the geographical location of the site and natural resources. The various infrastructures will be reviewed in Chapter 7.

Hydrogen can be burned as a clean efficient fuel, emitting water and no CO_2. Hydrogen can also be mixed with more traditional vehicle fuels, such as diesel, petrol or natural gas to extend the lean flammability limit of conventional fuels to achieve higher thermal efficiency and lower exhaust emissions. Alternatively, hydrogen can be used in a fuel cell. The fuel cell combines hydrogen and air and produces water, electricity, and heat. It has no moving parts, is quieter than traditional engines and in peak operating conditions three times as efficient (US DoE, 2003a). Hydrogen is versatile enough to provide power for buildings, transport or for portable equipment.

Renewably produced hydrogen used in conjunction with a fuel cell can dramatically reduce, if not eliminate the emission of pollutants such as carbon dioxide, carbon monoxide, oxides of nitrogen. Additionally, hydrogen when mixed with conventional fuels such as diesel or natural gas can dramatically reduce emissions, even when burned in an internal combustion engine. The reduction in atmospheric pollutants that hydrogen can bring about would result in significantly improved health for a significant number of people in Wales.

2.1.3. The Future Energy Mix

Clearly our immediate energy future will continue to be dependant on fossil fuels, with a transition away from oil towards natural gas a consequence of diminishing supplies. Wales is very aware of this issue as preparations are made for liquid natural gas imports from Malaysia to Milford Haven This is particularly likely to be the case for transport (especially road transport), which is almost entirely dependent on fossil fuels at present. A whole-scale transition to hydrogen as a transport fuel is unlikely in the short term, particularly due to the absence of a viable hydrogen-refuelling infrastructure. The best way to overcome this hurdle is to progressively adopt hydrogen mixture fuels, such as natural gas/ hydrogen mixture or hydrogen injected diesel engines. These will allow the development of a hydrogen-refuelling infrastructure with time prior to the widespread introduction of pure hydrogen fuelled vehicles (combustion engine or fuel cell).

The Renewables Obligation and policy commitments in Wales place a requirement for increasing proportions of our electricity to be sourced from renewable energy. Where possible, it is thermodynamically better for this energy to be used in the form of electricity. However, the variability of most renewable sources suggests that balancing supply and demand on the grid will be a significant issue, particularly as the proportion of renewables increases. Hydrogen, amongst other mechanisms, can have a role in storing energy during periods of excess renewable electricity production and releasing when there is a shortfall. Hydrogen scores over many other storage mechanisms in that the hydrogen produced can be used flexibly for conversion back to electricity, or for transport.

Bio fuels may also have a part to play in a future energy mix, although it is unlikely that energy crops grown for bio fuels will entirely supply our transport fuel requirements in Wales. Hydrogen can be produced from biomass resources, either grown or from waste streams. In many cases this will be accompanied by co-produced methane, which lends itself to a hydrogen / methane mixed fuel application. More work is needed to determine the most appropriate use of biomass within the energy mix in Wales. However, the production of hydrogen from biomass provides a number of promising economic possibilities, not least for rural Wales.

Nuclear energy will continue to play a role in the energy supply for Wales for the rest of this decade. British Nuclear Group's Wylfa power station on Anglesey is due to cease production of electricity in 2010, subject to continuing satisfactory safety reviews. Although nuclear power production does not give rise to carbon dioxide *per se*, unattractive economics and ongoing concerns about nuclear waste mean that the building of new nuclear power stations is not currently supported by the UK government. However, changes to this decision in future have not been ruled out.

2.1.4. Hydrogen in the Energy Mix

It must be emphasized that no one is advocating the entire energy system revolve around hydrogen. This could potentially waste a significant amount of energy. Instead, hydrogen should take an appropriate place within the overall energy mix and at the appropriate time. However, the availability of numerous production techniques means that hydrogen can be produced from any locally available energy source. If we harness our renewable potential in Wales, we can start to displace oil products, particularly in the transport sector. Whilst the transition will not be immediate, there is plenty of scope for early introduction of hydrogen via mixed fuels in combustion engines. This will help to build a hydrogen production and distribution infrastructure in Wales and in turn reduce our dependence on foreign sources of oil.

The case for the transition to a hydrogen economy can be made on environmental grounds and on financial grounds in specific cases. Hydrogen is a versatile energy vector with a mix of generation technologies, able to be stored, and with applications at micro and macro scale for both transport and stationary use. When generated renewably it brings the benefits of security of supply and the possibility of distributed generation, with associated local ownership. The transition can benefit both rural and urban economies by creating employment and can be a basis for sustainable development.

2.2. The Hydrogen Route Map

Timeline to the Hydrogen Economy in Wales.

The transition to a hydrogen economy in Wales can be characterized as follows:

Phase 1	Development and demonstration of technologies, establishment of policies and stimulation of early demand
Phase 2	Commercial exploitation of early markets and creation of public acceptance
Phase 3	Market growth, establishment of supporting infrastructure and sustainable production routes
Phase 4	Achievement of the hydrogen energy vision

Phase 1
(The next 5 years)

Technology Development and Demonstration

Significant hydrogen energy R&D progress is being made internationally and Wales is currently making some important contributions to this. Successful early steps towards a hydrogen economy will depend on a combination of indigenous research, development and deployment of hydrogen technologies and the early adoption of new technology developed elsewhere. The strength of existing automotive industry in Wales, coupled with the links between Wales and the rest of Europe, USA and Japan can all be beneficial in attracting early hydrogen energy developments to the country.

The development and deployment of hydrogen enabling technologies into operational demonstration projects is important for the early stages of a hydrogen economy in Wales. As well as proving technology in a real world situation, high profile demonstration of hydrogen technology builds public awareness and confidence in the technology to be employed. Not all demonstration projects have to be world firsts as there are significant benefits to be gained by proving the technology in Welsh conditions and through the exposure of the public in Wales to new technologies. Early steps would include proving the concept of hydrogen as a transport fuel in Wales, in a range of different vehicles. Whilst there is significant merit in the development and demonstration of fuel cell technology in vehicles and for stationary applications, hydrogen in combustion engines will provide a useful bridging technology. Wales possesses one of Europe's largest car engine plants and numerous component and sub assembly suppliers. This significant expertise in the design, development and manufacture of internal combustion engines suggests that Wales could be at the forefront of hydrogen ICE development.

Significant benefit can be achieved by the early creation of a flagship centre in Wales for the demonstration of future hydrogen focused transport and energy technologies. Together with the right economic incentive this would provide encouragement of leading edge technology businesses to locate in Wales. Such a centre would provide a base for the development and demonstration of commercially viable vehicle products and the foundation for a high profile technology based cluster, incorporating combustion and fuel cell applications.

Policy Establishment

The transition to a hydrogen economy in Wales requires policy direction that embodies the principles of sustainable development for future energy supplies. Built into its constitution through Section 121 of the Government of Wales Act, The National Assembly for Wales has a binding legal duty to pursue sustainable development in all it does. On the basis of present day costs, it would be difficult for hydrogen energy to compete against current, more polluting technologies. Hence energy policy in Wales must include the environmental costs of energy provision and use.

As it is unlikely that the hydrogen economy can be achieved by Wales acting alone, there needs to be consistency with policy from Westminster and from the European Parliament. This extends from the application of codes and standards to regulatory and fiscal policies and financial support to nurture the development of hydrogen and alternative clean fuels and energy systems. Hydrogen energy policy in Wales needs to provide a degree of long-term consistency to allow investors and other organizations to manage their investment risk.

Stimulation of Early Demand

In addition to existing strengths in the automotive industry, fiscal measures and financial support, early demand for hydrogen will be stimulated by the provision of a useable hydrogen supply infrastructure. Although hydrogen exists in greater industrial volume on Teesside, Wales is unique in the UK in the existing spread of hydrogen infrastructure from Newport to Swansea, along the M4 corridor, the country's major transport route. Most commentators recognize that early hydrogen transport developments are likely to be based around fleet vehicles returning to a central base. Council vehicles, bus fleets, refuse vehicles and airport vehicles are all examples suitable for early conversion to hydrogen technology. Although existing hydrogen assets are operated by a number of organizations, there is the potential for Wales to overcome the early infrastructure problems that other regions may face.

Phase 2
(5-15 years)

Commercial exploitation of early markets

For any market to develop, the technology-push from researchers, developers and manufacturers needs to be overtaken by customer-pull. Clearly one of the most significant factors that allows for this transition to take place is the reduction in cost of the new technology, when compared with existing alternatives. Hydrogen vehicles, powered by internal combustion engines or by fuel cells, are available today but current costs of such vehicles are prohibitive for consumer uptake. Component costs, hence vehicle costs, will reduce significantly if mass manufacture can be adopted, but in the mean time developers will continue to need support to develop cost competitive products.

Turning to the hydrogen itself, it is often argued that hydrogen is much more expensive than existing fuels. This may be the case in countries where fuels are lightly taxed, such as Canada, USA or Australia. However, in the UK, the level of fuel duty means that untaxed hydrogen (particularly from fossil fuel sources) would be competitive on an energy basis with petrol or diesel. This is significant and potentially a source of advantage in the early development of a hydrogen economy in Wales. As long as government policy remains to avoid taxing hydrogen, its use as a fuel will be more attractive in the UK than almost anywhere else in the world. This would help to stimulate early markets and allow organizations in Wales to establish early market experience and advantage.

At the same time, international efforts to reduce the cost of hydrogen technologies and the hydrogen itself can also be adopted in Wales, further improving competitive advantage and allowing the tapered introduction of taxation on hydrogen fuels.

Public acceptance
Consumer pull is unlikely to occur without acceptance of a technology as something desirable, impossible where there is no awareness. Three critical factors are required to address the issue of public acceptance; these are education, marketing and exposure to the product.

The incorporation of the benefits of hydrogen energy in the context of broader alternative energy teaching in schools captures those still within formal education. However, there is also a need to inform people that are no longer in formal education and exhibits, road shows and other accessible means of information are useful in this respect.

Effective marketing, on the benefits of hydrogen in general as well as on specific products, has the possibility of creating awareness and influencing the public. Both education and marketing of this general nature will require a combination of government policy direction and input from commercial organizations.

The current dearth of hydrogen energy demonstration projects in the UK (particularly when compared to Germany, Canada or USA where numerous examples exist) means that there is almost no public exposure to the product and hence little public awareness of the benefits of hydrogen as an energy carrier. The broader inception of hydrogen energy demonstration projects, made accessible and welcoming to the public, will help to move from awareness to acceptance and finally to demand.

Phase 3
(15-30 years)

Market growth and establishment of supporting infrastructure
By this stage it is anticipated that technological progress will have reduced the cost of hydrogen energy products to a level where products become attractive to more than small niche markets. At the same time demands on reducing fossil fuel resources are likely to make hydrogen a more attractive fuel alternative.

The development of numerous demonstration and development projects, typically based around tied fleets progresses to the creation of a viable infrastructure for consumer utilization. The small number of strategically located hydrogen supply sources coalesces to a national network of hydrogen supplies, throughout Wales, the rest of the UK and Europe.

Whilst it may seem to be obvious that this will happen slowly and incrementally, the sizeable investment required for auto manufacturers to establish the mass market vehicle products required in this phase may mean that the step up to a workable infrastructure occurs more quickly than anticipated.

Sustainable production routes
Much of the hydrogen to satisfy early demands is likely to come from hydrocarbon sources, probably from steam methane reforming or partial oxidation of oils. However, in anticipation of stricter legislation on CO_2 emissions, these technologies will need to incorporate carbon sequestration, adding to their cost. Production from hydrocarbons will also suffer from increasing feedstock costs. Hydrogen production from renewable sources becomes more attractive commercially and environmentally and starts to compete with the production of fossil fuel based hydrogen. Local, distributed production obviates the need for the development of extensive national hydrogen distribution networks in Wales. Where hydrogen pipeline networks do exist they are cost competitive with distribution of energy by electricity.

Planning rules and administrators will also become more familiar with hydrogen energy applications and current over-caution will be replaced by rationalized consent procedures. The development of recognized international codes and standards support this transition.

Phase 4
(30 years +)

Achievement of the hydrogen energy vision
Hydrogen will eventually displace fossil fuels as the fuel of choice in Wales. Hydrogen production processes are numerous and appropriate to local resources. A truly national and international infrastructure for hydrogen will exist. Despite growth in global population and energy demands, this energy burden is met with significantly lower levels of CO_2 emission than at present.

Companies from Wales having established expertise and experience in hydrogen energy are exporting products worldwide, making a significant contribution to the economy in Wales and providing a significant level of high skilled jobs.

2.3. Requirements for the successful introduction of a hydrogen economy in Wales

Technical Requirements

Technology Focus - On-going research is required to identify the most promising/likely technology options for exploitation by Wales/UK. This should only be undertaken in Wales where no other region is undertaking similar activity. Research should be aimed also at providing better focus for the deployment of limited resources.

Technology Piloting/Demonstration – Demonstration projects should be selected and designed to maximise the promotion of potentially commercial products in order to encourage maximum private sector investment. Accordingly demonstration projects should be supported by market evaluation that confirms a high degree of market potential contributing to a more likely product launch and roll-out. This focus will make lobbying of EU/Government organisations for grant support more effective and likely to succeed.

Energy Density – Current problems with hydrogen storage density force a route to development that is focused on hydrogen supply limitations. Market opportunities have to be developed that can function within the limitations of hydrogen storage and an embryonic infrastructure and create a growth industry that will encourage subsequent investment in an expanding infrastructure.

Life Cycle Understanding – Full life cycle analysis will be required to identify those transport technology options that provide a balanced potential for commercial exploitation with positive environmental impact.

Synchronisation of Technologies – The route to a hydrogen economy requires the synchronisation of technology development in relation to fuel production, bulk fuel storage and transportation, fuel decanting, 'on-vehicle' storage and powertrain systems. The speed of development and introduction is dependent on the slowest element and significant investment in any single part that takes it ahead of the collective game could be wasted and even damaging to the organisation concerned. Joint project management through a significant cluster may reduce the potential for such a situation.

Fuel Cell vs. IC – Market drivers will determine if and when fuel cell technology is commercially viable in transport applications. Transitional technologies in the form of IC powered electric hybrid vehicles are already in production and volumes are rapidly becoming commercially viable. Pure electric vehicle technology is also improving putting pressure on the need to introduce complex fuel cell based powertrain.

Safety and Standards – There needs to be close co-operation with all bodies that can influence or implement safety standards and provide guidance to suppliers and customers alike, both nationally and internationally.

Market Acceptance – Products need to be developed and demonstrated to create a niche market demand in the first instance that can be supported from a very limited infrastructure. That in turn should create a market pull that will justify investment in infrastructure and more generic products.

Infrastructure – Key players in Wales with existing hydrogen production facilities need to be brought together to develop a joint plan for the exploitation of hydrogen powered transportation and creation of standard filling facilities across South Wales as a first step to a corridor along the entire length of the M4.

Skills – Skill shortages are potentially as great a barrier as any. Academic institutions must be fully integrated into the transition to ensure that appropriate courses are developed and promoted to respond to this emerging industry's people requirements.

Political Requirements

Political Leadership – Political leadership stems from a clear vision and viable strategy. If this can be developed then there is a requirement to set targets which stand a real chance of being carried forward even in the event of a change of government. The combination of environmental and sustainability of fuel supply issues provides a powerful case for taking this activity forward, what ever the political scenario. Key stakeholders including the Hydrogen Valley initiative must work to provide the Assembly with a vision that is easily translated into a strategy, thus facilitating leadership.

Opposing Lobby Groups – Vested interests have the power to influence for good or bad the support for activities necessary to take development activity forward. Interested parties should work together to maximise positive influence in the political arena. This is particularly the case with major energy industry players and OEM automotive manufacturers.

Energy Options – The confusion about the selection of the most appropriate fuels for transition or long term operation is leading to a 'wait and see' approach. The vision and strategy must encompass recommendations regarding potential transitional and long term fuel solutions.

Fiscal Policy – Long term fiscal policies need to be adopted that give incentivied investment at the appropriate time in transitional technologies and fuels.

Local Politics – Relationships must be developed with those local authorities most receptive to supporting these technology/community developments. As activity and its benefits become apparent then less supportive authorities will want to participate.

Legislation – All appropriate government organisations should be engaged to advise and promote the need for health & safety as well as environmental legislation to catch up with hydrogen potential for domestic and private transport and energy applications.

International Competition – Wales cannot compete with the level of funds being deployed by the governments of USA, Canada, Japan and Germany. However, we can provide an environment for their companies to develop and test the technologies and perhaps share their knowledge with local companies.

Economic Requirements

Raising Capital Funds – Early stage capital funds are difficult to raise. Availability of EU/Government finance is patchy. A strong strategy for the development of commercially viable products and an embryonic infrastructure needs to present. A holistic approach to the development of a Hydrogen Economy is more likely to attract grant funding and thus private sector investment.

Cost of Alternatives – Even with energy costs rising they are still relatively cheap compared with the current cost of hydrogen. This favours the status quo requiring consideration of the mitigation of costs for specific demonstrations or commercial applications as well as continuing to support research into the commercial production of sustainable hydrogen.

Customer Demand – Many local authorities are keen to be seen as market leaders in the application of clean vehicle technologies. Depot based local delivery fleets lend themselves to an emerging niche urban delivery vehicle market that can with fiscal support become viable very quickly.

IPR Protection – Advice and support on the schemes available in Wales to subsidise IP application can be provided by the Welsh Development Agency.

Infrastructure Investment – This is the largest single problem requiring a long term approach. Investment in pilot infrastructure schemes by key players such as BOC, Air Products, BP and Corus may be possible to develop limited commercially viable activity. This is likely to require some support from grants to take place.

High Costs of Technology – All stages of hydrogen technology are currently too costly to be competitive. However, it may be possible to identify very local projects where conditions allow developments to proceed commercially. These need to be supported to begin creating critical mass necessary to develop competitive costs.

Regional Advantages and Disadvantages – Wales has a small population and comparatively small economic strength. However, its population distribution, location, geography, political structure and existing hydrogen infrastructure make it an ideal place to pilot a hydrogen economy. Doing so could bring economic, technology and environmental benefits disproportionate to the level of investment required.

Knowledge/Expertise – To draw activity to Wales will require the relocation of expertise which is currently in short supply. However, by becoming a leading pocket in hydrogen activity it provides Welsh universities with the opportunity to become centres of excellence for these emerging technologies and markets with broader commercial economic gain.

Social Requirements

Cultural Acceptance – As a matter of priority, public demonstrations and educational events should be set up to begin the process of gaining public acceptance of hydrogen and its safety.

Understanding – This issue strongly links with understanding of the benefits and needs for a transition to a hydrogen economy because of energy sustainability and the environment.

Socio-Economic Leakage – To entice and relocate companies in Wales (thus avoiding monetary leakage, and improving the social conditions of the workforce through education and training) is preferable to importing the technologies (in form of goods) into Wales.

Transport Strategy – There is a lack of an integrated transport infrastructure. Regional and local government and significant transport companies should be encouraged to work together to develop such an infrastructure and at the same time identify opportunities for the viable operation of alternatively fuelled transport.

Environmental Requirements

Clean Bulk Hydrogen Production – Wales should be at the forefront of determining whether hydrogen can be economically produced from sustainable or carbon neutral processes.

CO_2 Sequestration – If this is feasible and safe then it could have a significant impact on the speed of transition as hydrogen can be produced from existing hydrocarbon stocks until clean hydrogen becomes economically

viable. Progress on this issue needs to be closely monitored.

Material/Chemical Issues – The impact of the reliance on precious metals in fuel cells and chemical hydrides needs to be understood. This may affect the selection of the preferred technology option so progress on this issue must be closely monitored.

Environmental Perception – The visual impact of renewables, NIMBYism, provides a substantial barrier. Projects need to be developed in acceptable locations and with a positive visual impact. Consideration must be given to raising awareness in the delivery of all projects with the people directly involved or affected.

It is hoped that this framework document can be used as an initial outline of the path that Wales can follow to become part of this international advance towards the hydrogen economy.

3. Wales's Advantage in the Hydrogen Economy

3.1. Wales as a sustainable energy showcase

The National Assembly for Wales (NAfW) has a duty under Section 121 of the Government of Wales Act 1998 to promote sustainable development in the exercise of its function. In order to fulfill these legal obligations, sustainable development must be mainstreamed into the operation of the Assembly. The Assembly clearly stated that it would "seize opportunities to place Wales in the vanguard of the hydrogen economy"(NAfW, 2003d). The Assembly has begun by setting achievable targets for Wales of 10% renewable energy uptake by 2010 and 20% by 2020 (NAfW, 2003b). These targets have been informed and encouraged by stakeholders in the cross party National Assembly Sustainable Energy Group (NASEG).

The Assembly has supported and promoted Wales as a global showcase for renewable energy. This is partly due to the abundance of natural resources in Wales and the potential for growth of the renewable energy industry (Sustainable Energy Ltd, 2001). The Assembly aims to "achieve a reputation for strength in renewable energy comparable with Denmark or the Netherlands". The Assembly sees Wales as "ideally placed to benefit from new technologies". As far as is known the National Assembly for Wales is the first government to have an obligation to develop environmental, economic, and social policies leading to sustainable development. Policies are developed to protect the Welsh environment and tackle global environmental threats (global warming) where possible.

Wales is dependant on heavy industry, but the strong policy decisions made by the Assembly have reduced emissions from 1995 levels and will, it is hoped, encourage business diversification (NAfW, 2002a). The Assembly has led by example in this respect as 70% of the Assembly's power needs are met with renewable energy (NAfW, 2002a). The Assembly sees renewable energy as paramount to bringing employment through construction, operation and maintenance of sites. It is against this background that we consider the technical, economic and social implications for Wales of a move towards the hydrogen economy (see Chapter 10).

The introduction of hydrogen could provide Wales including the Objective 1 areas with opportunities at all stages of the hydrogen economy's development and Wales has the ability to become a supplier of the technology worldwide. It is hoped Wales will become a global showcase for renewably produced hydrogen and be at the forefront of the technology export market (NAfW, 2002a).

At the current time, Wales and the rest of the UK lag behind a number of other developed countries in bringing clean energy schemes to fruition in general and realising the importance of a hydrogen energy future in particular. A significant amount of research and development funding has been applied, particularly in USA, Japan, Canada and Germany amongst others. However, the transition to a hydrogen economy will not take place in these few countries alone, it will be a global movement. Admittedly, some countries will move at a different pace to others and some countries will extract greater benefit than others from the transition. It is our purpose to ensure that Wales is at the forefront of the countries to benefit from the development of a hydrogen economy and those organisations involved in the development contribute significantly to the economy in Wales.

3.2. Energy and the future economy in Wales

Wales, like every country in the world depends on a plentiful supply of adequately priced energy to ensure the competitiveness of industry, to power our homes, schools and hospitals, and to enable the mobility that has become an accepted part of modern life. As the twenty first century unfolds, provision of this energy will become an increasingly important issue as competition grows for diminishing oil and gas resources and as the impacts of climate change and poor air quality are realized and understood. In the nineteenth and twentieth centuries, energy, particularly coal, had a pivotal role in the economy in Wales.

Utilising our abundant indigenous renewable resources, particularly wind, tidal, wave and biomass and capitalizing on our distinctive competences in automotive, chemical, materials, high-tech and agricultural industries can give Wales a distinctive advantage in the development of new energy industries and specifically in a future hydrogen economy. The strong automotive sector in Wales is of particular advantage in the development of industry for hydrogen and clean energy transport. If automotive organisations in Wales can be encouraged to embrace the development and commercialization of hydrogen and related enabling technologies, then there can be a bright future for the sector. Conversely, if nothing is done and focus remains on existing fossil fuel based engine technology, there could be a major threat to future jobs in the automotive sector in Wales.

3.3. The potential for renewable energy in Wales

Hydrogen generation is most environmentally beneficial when produced from renewable sources. Wales is unique in that it has a high level of natural resources available to utilise in achieving sustainability (Sustainable Energy Ltd., 2001). The main renewable energy sources are wind, wave, tidal and biomass, and all have the potential to create hydrogen.

There are a number of predictions of the possible future potential renewable energy capability of Wales. Table 3.1 indicates Wales's renewable energy targets for 2010. It is clear from Figure 3.1. that Wales needs to embrace a green future in order to achieve the targets set by the National Assembly of ~ 4 TWh by 2010. This will need a quick uptake of new renewable technologies.

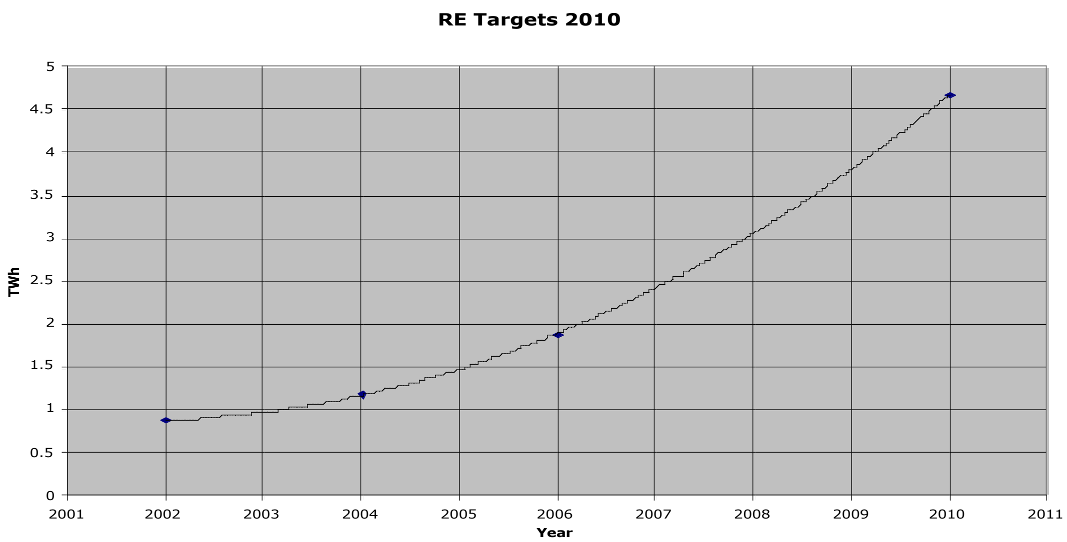


Figure 3.1. Wales's renewable energy targets.

Table 3.1. Targets for renewable energy output in Wales by 2010

	Figures for 2002 (1)	Current production (2)	Total expected (with agreed projects) (2)	2010 target (2)
Total capacity MW	327	381	615	1835
Total production TWh	0.88	1.18	1.88	4.68

(1) NAfW, 2002a, (2) NAfW, 2004

Table 3.2 Predictions on potential renewable energy output in Wales

Annual Total	Short term (2-5 years)	Medium term (10 years)	Long term (20-30 years)
Energy (GWh)	2,630	8,988	16,874
CO_2 savings (MtC)	0.400	1.168	2.179
New jobs	400	2,355	4,730

(Thomas, 2001a)

The National Assembly for Wales has set a renewable energy target of 20% of total production for 2020, this will equate to approximately 10TWh based on energy demand increasing at its current rate. The figures seen in Table 3.2 are predictions of our long-term renewable energy potential. These figures will be constrained by technical, economic, land use and planning and public concerns that will restrict the uptake (NAfW, 2002a and NAfW, 2003b).

The recent TAN 8 consultation document (NAfW, 2004) indicates that 800TWh of on shore and 200 TWh of off-shore wind needs to be harnessed to meet the 2010 targets. This will increase the amount of energy available from wind turbines by more than 40-50% in the next 6 years. Hydrogen has an important role to play in a future reliant on renewable energy especially if advances in hydrogen storage are able to flatten out the peaks and troughs that have become synonymous with renewable energy production. Hydrogen can also be used to help match energy availability and demand. This could allow Wales to rely more on renewable energy in the future with security of supply. It has been estimated that by combining hydrogen storage and energy production 10-15% of useful energy can be exported on to the grid and that the overall value of the wind power will increase by being able to sell guaranteed set amounts (removing the risk of intermittency).

The land available to produce biomass is an important resource. There are three methods by which hydrogen from biomass can be achieved: fermentation to hydrogen; anaerobic digestion to methane reformed to hydrogen (both suitable for wet fermentable biomass) and thermochemical processes (suitable for dry/woody biomass). The latter include gasification, pyrolysis and supercritical gasification. Currently hydrogen production through biological process is still in its infancy and development of large scale plants could be important in the medium to long terms. However, in Wales a research group at the University of Glamorgan is developing the biological production of hydrogen. Work is needed on the economics of using energy crops (e.g. high sugar fodder grasses as developed by IGER, Aberystwyth (IGER, 2003) and root crops). Throughout Wales extensive monocultures of energy crops must be avoided. It is possible that a variety of fermentable crops of species already well known to British agriculture could be grown in year-round rotation.

It is also possible to use woody biomass as a feedstock for the thermochemical production of hydrogen (see Chapter 5). The advantage of this route over fossil fuel thermochemical production is that biomass, whether woody or wet, is carbon neutral and a sustainable fuel. Woody biomass can be used in combined heat and power plants to create electricity and heat or simply as a source of heat through combustion (Dulas, 2002). However, when biomass is converted into hydrogen, it becomes a more versatile energy source, enabling the hydrogen to be used not only in stationary but also in transport applications.

3.4. Renewable and non renewable energy in Wales

Within the United Kingdom, Wales is a nation with a population of approximately 3 million people and an area of 20,640 km^2. It has a devolved government, the National Assembly for Wales (NAfW), which is mandated to implement sustainable development. Agriculture, coal mining and chemical and steel industries have been historically important in Wales. The decline of the coal industry, scaling down of steel and chemical industries and recession in agriculture had such major social and economical impacts that large areas in Wales are among the least prosperous in the European Union. Such Objective 1 regions have EU funding available specifically to support economic development. The vast majority of Wales's existing energy needs are met from non-renewable sources. In 2003, of the 33.5TWh electricity produced in Wales, some 79% came from carbon-based sources and a further 18% from nuclear. Only 2.6% is currently produced from renewable sources. Fuel poverty, commonly accepted as a household having to spend greater than 10% of their income on fuel for all uses, is a socio-economic problem in many parts of Wales.

Although Wales is an electricity exporter, the majority of the energy Wales produces is from fossil fuels with renewable energy accounting for a small percentage of the overall energy production (see Table 3.3). The carbon dioxide emissions equate to approximately ~ 14.1MtC per year (Sustainable Energy Ltd., 2001). Current trends indicate a growth in the energy industry of 35% over the next 10 years (Syred, 2003).

Table 3.3. Energy capacity in Wales

Energy production and capacity		Ref
Total energy production capacity in Wales	~5.5 GW	1
Electricity production from fossil fuel	~33.5 TWh	1
Nuclear capacity	~1GW	1
Renewable energy capacity	~0.6GW	2
Renewable electricity production	~1.18TWh	2
Additional approved renewable energy	~0.7TWh	2

(1)NAfW, 2002a (2)NAfW, 2004

Most of the energy needs of Wales are met by electricity. In some areas gas supply is not available, mainly due to the geographical location of the properties (NAfW, 2001b). Within Wales access to energy utilities can be imbalanced; this is most clearly demonstrated when reviewing the following figures:

- 0.1% of Welsh homes do not have mains electricity; Half these homes are in rural Wales (NAfW, 2001b).

- Of the 381,400 homes based in rural Wales just under half (44.1%) do not have access to mains gas; that equates to 168,197 homes. In the rest of Wales 11% do not have access to mains gas (NAfW, 2001b).

A hydrogen economy would allow local communities to have access to pollution free energy harnessed from locally available resources such as wind or crops. It is clear that rural Wales would benefit from a decentralised energy system as is reviewed in Chapter 7.

3.5. Building on Wales's current energy infrastructure

The current energy network consists of gas pipelines and electricity grid. In Figure 3.2. we see the electricity distribution network in Wales. The transmission network, which is operated by the National Grid Company (NGC), is used to transmit power over large distances and hence at very high voltages. The electricity is then distributed to customers through regional distribution networks, which are operated by Distribution Network Operators (DNOs).

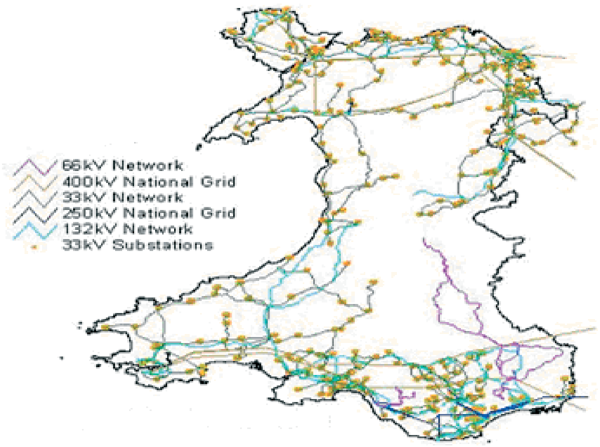


Figure 3.2. Welsh Electricity Network

The Assembly target for renewable energy means that the amount of embedded generation connected to the distribution network will need to increase fourfold. This trend is likely to be compounded by the rapid growth of combined heat and power (CHP) plants and non-renewable embedded generation.

The conventional wisdom is that frequency and voltage instability will result if intermittent renewables form greater than about 20% of the electricity market capacity, increasing the reactive power requirement. Current electricity trading arrangements (NETA and shortly BETTA) place the responsibility for energy balancing on the licensed supplier. The result will be a further constraint on where the renewable resource can be harnessed.

However, combining hydrogen with renewable energy gives the potential to smooth the output from intermittent RE schemes. In the longer term this may be important to minimise frequency and voltage disturbances with higher proportions of RE in the overall electricity supply system. There are also potential short-term benefits by including hydrogen as a balancing mechanism within the current electricity trading arrangements, although the economics of this would have to be judged on a case-by-case basis.

3.6. Wales's existing hydrogen network

Wales does have an existing hydrogen network and the expertise to forward a transition to a hydrogen economy. Wales's main hydrogen production plants are situated near the M4 corridor and are all linked with the current industrial uses of hydrogen, as can be seen in Figure 3.3. Producers include BOC based in Margam, Dow Corning and Cabot based in Barry and Inco based in Clydach, near Swansea.

Figure 3.3. Hydrogen Production Plants in South Wales

The total current hydrogen production capacity in Wales is estimated to be 5800Mm^{3}h^{-1}. All hydrogen plants in Wales are small to medium production size facilities. Recently a 800 Mm^{3}h^{-1} plant was built in Margam (NATCO, 2003) and a 500 Mm^{3}h^{-1} sized plant built for Dow Corning at the end of 2001 (Mahler, 2000). All of the hydrogen in Wales is currently produced for industrial use

It can be seen from Figure 3.3. that there may be a potential for a nodal network that could be the basis for a refueling system along the M4 corridor, thus avoiding the initial hurdles of infrastructure development. It is also worth noting that 60% of Wales's population is based in this region

3.7. Socio-economic factors influencing Wales

When evaluating benefits to Wales of the transition to a hydrogen economy it is important to understand the economic and social background in Wales:

- Of the 22 counties in Wales 15 are in Objective 1 areas (68%)(NAfW, 2001b).

- Wales has a population of ~3 million people and has ~1,157,300 homes; of these approximately one third are based in rural Wales (381,400 homes) of which nearly 90% are in the Objective 1 area (NAfW, 2001b).

As was demonstrated earlier, rural areas also have imbalanced access to energy utilities. Objective 1 areas also have higher unemployment rates and lower living conditions than the rest of the UK.

- More than one in four people of working age are deemed economically inactive (Waleswatch, 2000).
- The GDP of workers in Wales is on average 18% lower than the EU average
- In the Central Valleys workers earn 64% of the EU average (Waleswatch, 2000).
- 18 of the 22 local authority areas are in the top 100 of the index of multiple deprivation (NAfW, 2000a).

Decentralised hydrogen energy production would potentially create jobs in rural and deprived areas. As each area would have its own hydrogen production facility, local people could build, run and maintain these stations, bringing much needed revenues in to the surrounding communities and encouraging economic growth. Farming communities would benefit from growing energy crops e.g. on set-aside land or leasing land for renewable electricity generation activities.

3.8. Transport infrastructure

Wales has a population of ~3 million people; predictions estimate that the population growth will continue up to 2011. Over the last fifty years, the traffic in the United Kingdom has increased seven fold. Wales has achieved an increase in GDP per capita and an increase in income contributes to an increasing demand for road transport. Moreover, traffic in Wales is expected to grow by 17% by 2010. The UK has commitments to the Kyoto convention of green house gases emission reduction of 12.5% below 1990 levels by 2008-2012 and 20% reduction in CO_2 emissions by 2010. Pollutants arising from road transportation known to cause harmful effects on humans are: benzene, 1,3 butadiene, carbon monoxide, lead, nitrogen dioxide and particulates. Tight control in recent years has led to the reduction in the emissions by cars.

We must not forget that the environmental effects of road transport can increase climate change. The greenhouse gases that are emitted by vehicles are mainly carbon dioxide and nitrous oxide. In Wales road transport is the single largest source of greenhouse emissions after power generation and the iron and steel industry. Road transport contributes 12% of overall CO_2 emissions in Wales (4.7% of UK emissions). Over the last 5 years 0.6kT nitrous-oxide have been released from road transport, equating to a 5% rise in emissions. This is far less than for industry and power generation which have increased 17% over the same time period. This slower growth in emissions by road transport is due to the uptake of catalytic converters.

It is estimated 1,181,000 cars and vans are using Welsh roads (NAfW, 2001a). Bus links are mainly concentrated around the larger cities with half-hourly services between the closest large towns. Less than 5% of vehicles on the road are buses and 1% are taxis (NAfW, 2002b and NAfW, 2001c). Wales by its geographical nature does not have the same type of integrated transport infrastructure as many other countries. Road links between South and North Wales to England are strong and South Wales has a good road link running along the M4 corridor (NAfW, 2001c). However road links running from South Wales to West, Mid and North Wales are limited to trunk roads, some of which are in poor condition (NAfW, 2002b).

Rail networks suffer the same constraints as roads. The links along South and North Wales going in and out of England are strong, however travelling through Wales is difficult. With two main lines travelling into the centre of Wales the rail links in Wales are sparse and rely on connections outside Wales to go from north to south (NAfW, 2001c). This increases cost of transportation as the distance travelled is almost doubled when travelling from South West Wales to North Wales (NAfW, 2002b).

The bulk of air travel in Wales is confined to Cardiff International Airport which handled 49,000 flights in 2002, 1,287 of which were freight. Other airports include Swansea and North Wales; these are small airports that deal with flights within the UK and Ireland, (NAfW, 2002b).

For marine transport Wales has 10 major ports of which 6 are in South Wales, 2 in South West Wales and 2 in North West Wales. There are just under 10,000 arrivals per year in total (NAfW, 2002b).

The transport infrastructure is very good in South and North Wales along the main commuter belt. The infrastructure in the south along the M4 corridor and the A55 in the north would allow the easy transportation of hydrogen on the road or by rail which may be suited to centralised production in these areas. However, a high proportion of the Objective 1 area has poor transport infrastructure; this correlates with the idea that transport infrastructure is closely linked with the economic vitality of an area (Cole, 1998). In less serviced areas hydrogen could be produced locally through biomass processing or renewable energy sources and stored in order to generate uninterrupted electricity or for use as clean fuel for vehicles. This decentralised system reduces the amount of transportation from production site to end use and consequently reduces cost. The differences in the circumstances between areas can be dramatic; this will have to be taken into account when developing a hydrogen infrastructure.

3.9. Hydrogen Economy Stakeholders in Wales

Identification and contact with stakeholders in the hydrogen economy was acknowledged as one of the primary aims of Cymru H_2 Wales. This led to the creation of the project Steering Group, which includes key representatives from business, academia, governmental and non-governmental organisations. The members bring a wide range of expertise from the Objective 1 region and beyond from the public, private and voluntary sectors. Since the Steering Group's initial creation, the number of companies and organisations participating has increased 40%.

Steering Group members' organisations

Air Products
Anglesey Wind and Energy
Awel Aman Tawe
BOC
Carbon Trust Wales
Cardiff University
Corus
Eneco
Environment Agency Wales
Friends of the Earth
Groundwork Wales
Pembrokeshire Coast National Park Authority
Progressive Energy
PV Systems
Texaco Ltd
United Utilities
Vandenborre Hydrogen Systems GmbH
Welsh Assembly Government
WDA
West Wales ECO Centre

A larger group of stakeholders who are representatives from other interested organisations have also been involved in the project and now together form a recognisable community of interest.

The Welsh Assembly Government support the development of renewable energy in Wales, and sees the development of renewable energy as a source of employment. Combined with the close co-operation that exists between industry, academics and government agencies, Wales has the opportunity to take a leading role in the development of sustainably-produced hydrogen and be at the forefront of the technology export market.

Wales already has a hydrogen industry, satisfying the demand for hydrogen for metals processing, petroleum refining, chemical manufacturing, semiconductor manufacturing, pharmaceuticals, glass production and the food industry. However, the scale of this industry is relatively limited when compared to the eventual demands of a full hydrogen economy and the current hydrogen production is entirely based on fossil fuel conversion via steam methane reforming. Nonetheless, Wales is unique in the UK in that this hydrogen production is relatively evenly spread along the main transport route (M4) serving the major centres of population in Newport, Cardiff and Swansea and extends to Milford Haven. This existing hydrogen infrastructure could form a platform for an early hydrogen micro-economy in South Wales, particularly if augmented with additional renewable production to provide supply nodes for early hydrogen transport fleets.

4. Demonstration Projects

A successful demonstration project needs to be driven by local demand, consideration of regional resources and committed project partners.

4.1 International

Presently there is world-wide interest in the hydrogen economy, as a consequence international demonstration projects are flourishing. The following projects are examples of high profile hydrogen projects and programmes in countries most active in the hydrogen economy (additional information available in Section 10.7).

- In the USA President George Bush has pledged 1.2 billion dollars in additional funding to the development of fuel cell vehicles through the Freedom Car project. This is an alliance of the major car manufacturers in America in order to make fuel cell vehicles viable for the future and involves Ford, General Motors, and DaimlerChrysler. The California Air Resource Board has been a driving force in encouraging a transition to fuel cell vehicles via a mandate for air quality which stated that 15% of all new buses must have zero emissions by the year 2008 in the state of California. This has lead to the California fuel cell partnership being established, a collaboration between vehicle manufacturers, energy companies, fuel cell companies and government to make fuel cell vehicles viable, explore commercialisation and infrastructure and increase public awareness. The stationary fuel cell partnership has also been established in California (US DOE, 2003b and CARB, 2003).

- Japan has established the world's largest national hydrogen program (WE-NET). This project has an $88 million budget for 5 years and aims to spend $4 billion on the program by 2020. The program was set up to explore how hydrogen can contribute to the Japanese economy in order to reduce the reliance on fuel imports. The project aims to have five thousand fuel cell vehicles on the road by 2010 and one million domestic fuel cell generation systems. The program will establish standards and promote public awareness and demonstrations (WE-NET, 2003).

- Iceland is the first country to state its intentions to move wholly to hydrogen energy. Their aim is to eliminate their dependency on fossil fuels by 2030 and have 20% of all vehicles and fishing vessels converted to hydrogen. The Icelandic government's driver is the abundance of hydro and geothermal energy in the Icelandic region. Iceland has partnered with DaimlerChrysler, Shell and Norsk-Hydro and has already opened Iceland's first public hydrogen filling station (Chapman, 2002).

- Canada has the Canadian National Hydrogen R&D program which is administered by the federal government. The Canadians have run a number of high profile projects including the Euro – Quebec project that shipped liquid hydrogen from Canada to Europe. The Canadians are particularly interested in hydrogen for its off-grid application. They have a vast supply of hydro electricity to produce hydrogen cheaply, a valuable commodity for export if the hydrogen economy becomes a reality (Lakeman and Browning, 2001 and Fuel Cell 2000, 2003a).

4.2. European

4.2.1 Projects in European countries other than the UK

The CUTE project is one of the largest fuel cell demonstration projects in the world. The project is planning to demonstrate 27 fuel cell buses in ten metropolitan cities around Europe over two years. The project involves the design, construction and operation of infrastructure for hydrogen production and the collection of findings relating to the operating behaviour, and safety standardisation. In addition, ecological, technical and economical analysis of the life cycle will be compared with traditional methods of fuelling. Each of the designated cities has specific operating conditions:

- Iceland is carrying out a socio-economic study of the transport system and producing hydrogen through electrolysis via geothermics.
- Amsterdam is testing a municipal transport system and has hydrogen production onsite.
- London is testing in a mild climate with vehicles running on compressed gaseous hydrogen.
- Madrid is testing in a warm climate and hydrogen produced by steam methane reforming supplied through road distribution.
- Porto has a similar scheme where steam reforming of natural gas is done on-site.
- Stockholm is testing in cold climates with hydrogen production on site.
- Luxemburg is testing the local public transport system with centralised hydrogen production.
- Barcelona is testing in a warm climate with hydrogen produced using solar power.
- Hamburg is testing in a topographically even environment with hydrogen produced through wind power.
- Stuttgart is testing in a topographically demanding environment using hydrogen from steam reformed natural gas.

An outcome of the demonstrations is an exchange of experience under different conditions and geographical locations. However, a large part of the project is also concerned with informing the public about fuel cell technology.

Germany has a large hydrogen programme and in addition to the CUTE project in Stuttgart and Hamburg already has a number of large demonstration projects underway. One of these is the Munich airport project, where the ground vehicles serving Munich airport are fuelled with hydrogen. The airport has a refuelling station on site with an automated liquid refuelling system and a manually operated compressed hydrogen refuling system. The 450kW system works at 60-65% efficiency (Munich Airport, 2003).

HyWeb is a German hydrogen news grouping which publishes electronically a regular informative gazette, the news letter of L-B-Systemtechnik GmbH (LBST) and the German Hydrogen Association (DWV) (HyWeb, 2003).

HyNet, the European Hydrogen Energy Network, is a Thematic Network supported by the EU under FP5. It began in 1999, bringing together leading companies from a broad spectrum of European industries. HyNet is preparing a database mapping centres of excellence in hydrogen energy in Europe, and it is co-ordinating bids under EU Framework 6 (HyNet, 2003).

4.2.2 Projects running in the UK

H2NET, the UK Hydrogen Energy Network (H_2NET, 2003), is a network established with funding from EPSRC and currently DTI, with the objective of enhancing the profile of hydrogen energy research in the UK. The network encourages collaboration between industry and academia in order to promote research and discussion. The Network's events have been well attended and provide a forum for the discussion of research, development and implementation issues related to hydrogen energy exploitation.

Fuel Cells UK is an umbrella for UK fuel cell interests and activities, provides a focus for the growing UK fuel cell industry and works to foster its development (www.fuelcellsuk.org).

The UK Fuel Cell Network is a network established to bring together those people active in the area of fuel cells, in order to forge relationships and promote partnerships. It has held a hydrogen road show linked with Grove Fuel Cell Symposium. Currently funding is being pursued (http://fuelcellnetwork.bham.ac.uk/home.fcm).

The PURE project is based on the island of Unst, Scotland. The demonstration project will show how wind power and hydrogen technology can be combined to provide the energy needs for a remote rural industrial estate. This is the first community owned renewable energy project, the hydrogen provides an storage medium for the surplus energy produced by the wind turbines and can be used as and when required.

The most recent project in London is the CUTE (Clean Urban Transport for Europe) project. This project has introduced three hydrogen-fuelled buses supplied by DaimlerChrysler which run on route 25 from Ilford to Oxford Circus as seen in Figure 4.1. The buses run with the hydrogen storage tanks pressurised at 35MPa, the refueling station has recently received planning permission and will be based in Hornchurch east of London (CUTE, 2002 and Fuel Cell Bus Club, 2003).

Figure 4.1. London Hydrogen Bus

Teeside are currently developing a hydrogen infrastructure project in conjunction with BOC and Air Products to utilise the pipeline from their hydrogen producing plants. The group has recently had a number of smaller successful projects including a road sign powered by compressed gaseous hydrogen.

Projects in development:

- The London Hydrogen Partnership was launched in April 2002 in order to deliver the Mayor's policy and objectives. The Mayor's Draft Energy Strategy recognises the potential for the widespread introduction of hydrogen energy and fuel cells to tackle London's pollution problems and provide a boost to regeneration and economic development. The London Hydrogen Action Plan is one of the first outputs from the partnership, with demonstration projects on the drawing board (London, 2002).

- The Scottish island of Islay is currently undergoing a feasibility study to identify how the resources on Islay can be utilised to create a large scale hydrogen demonstration project that stretches over the whole of the island. The project hopes to use the island's groundbreaking Limpet wave power station to create the hydrogen and allow the island to be independent of the national grid (Staunton, 2003, personal communication).

- Hunterston Hydrogen Limited is developing the world's first commercially viable wind/ hydrogen system in North Ayrshire. Hunterston Hydrogen Limited is a joint venture between Hunterston Developments Limited and Wind Hydrogen Limited. The project will develop a 10MW hydrogen fuelled generator, which will be powered by a 53MW wind farm. This will be a flagship project for Scotland and the UK. Among the aims of the project is the demonstration of renewable low carbon technology and to contribute 0.6% to the 2010 renewable obligations target of 4 TWh.

Current, there are at least 22 UK universities working on hydrogen related topics, many of which can be located using the H2Net and EPSRC websites.

4.2.3. Projects in Wales

Wales has a number of planned projects but currently no active demonstration projects. However, there is considerable research ongoing in a number of Welsh Universities, a business development partnership and there are Welsh companies actively manufacturing components relating to hydrogen technology.

- The Hydrogen Valley Working Group is a business partnership run by the WDA, working to encourage hydrogen markets and infrastructure development in the area around the Neath valley. The Group is encouraging component manufacturers and system developers to move to Wales. They are also working with fleet vehicles wishing to convert to hydrogen. The aim of the group is to make Wales a hydrogen showcase and to bring hydrogen vehicles to the roads of Wales as soon as possible (Patterson, 2003).

- The Hydrogen Research Unit, part of the Sustainable Environment Research Centre (SERC) at the University of Glamorgan, has been active in the field of hydrogen research since 1998. This report is produced through the project "A sustainable energy supply for Wales: Towards the hydrogen economy," part funded by the European Regional Development Fund. Supported by the EPSRC and The Carbon Trust, the Research Unit is investigating fermentative production of hydrogen from non-sterile biomass and food industry co-product feedstock using mixed microflora in continuous processes. The group was selected to take part in the EPSRC SUPERGEN Sustainable Hydrogen Energy Consortium, one of the UK's largest research projects on sustainable hydrogen. It is undertaking research into the biological generation of hydrogen from renewable resources using fermentation, and will receive EPSRC funding until 2007 to support this work (Glam, 2003).

- Cardiff University is currently researching sustainable energy crop production (Randerson, 2003).

- Anglesey Wind and Energy Ltd. is the only company in Wales currently developing hydrogen-based products. The company was set up in 1994 to develop hydrogen production from wind. The company has patented systems to capture the wind turbines' energy in the form of hydrogen. The products are commercially available via the company website (AWEL, 2003).

Planned demonstration projects include:

- The University of Glamorgan's Hydrogen Research Unit has recently submitted a proposal to the European Regional Development Fund (Objective 1) for a renewable hydrogen production and utilisation centre at the Baglan Energy Park. This project is intended to demonstrate the viability of producing hydrogen from a range of renewable energy sources, to use this hydrogen in a range of vehicles and to demonstrate the benefits of using hydrogen as an energy storage medium for these intermittent renewables.

4.3. Web based resources

An extensive list of web resources is available at www.h2wales.org.uk

5. Production methods

5.1 Current production methods

Today most hydrogen production (95%) in the UK is generated by steam methane reforming (SMR) (Lakeman and Browning, 2001). This fossil fuel dependent route is not a sustainable option but could be a transition step to the hydrogen economy whilst renewable energy gets a foothold in the energy market. Options for hydrogen production and their status are shown in Table 5.1.

Table 5.1 Status of Hydrogen Production Processes

Production Processes	Status
SMR of Natural Gas	Mature
Partial Oxidation	Mature
Coal Gasification	R&D / Mature
Steam Iron Coal Gasification	R&D
Water Electrolysis	Mature
Thermochemical	R&D
Photo Chemical Process	R&D
Photo Electric	R&D
Photo Biological	R&D
Fermentative	R&D

(Momirlan and Veziroglu, 2002)

5.1.1 Steam Methane Reforming (SMR)

Steam Methane Reforming (SMR) is the most economical large scale route to produce hydrogen at the present time. SMR hydrogen production (Eqn. 1) is usually carried out on a packed bed reactor and is a four-stage process. Feedstock purification is followed by steam reforming, in which the natural gas and superheated steam are passed over a catalyst typically at 850 - 900°C. The carbon is oxidised to carbon monoxide and the hydrogen is released (Eqn. 2). The carbon monoxide then undergoes 'water-gas shift' where it reacts with the steam to produce hydrogen and carbon dioxide (Eqn. 3). Purification of hydrogen is the last step in the process most commonly in a pressure swing absorption (PSA) plant. The steam reforming process is a highly endothermic reaction and the conversion requires high temperature, steam and a highly active nickel catalyst (Hart *et al.*, 1999 and Dutton, 2002). The conversion reduces as the pressure is increased in most cases; the steam methane reforming process operates at < 4MPa (Dutton, 2002).

Overall reaction:

$CH_4 + 2H_2O \leftrightarrow CO_2 + 4H_2$ Eqn. 1

Steam reforming:

$CH_4 + H_2O \leftrightarrow CO + 3H_2$ Eqn. 2

Water-gas shift:

$CO + H_2O \leftrightarrow CO_2 + H_2$ Eqn. 3

The conversion efficiencies in this system can reach 65% - 75% in large production plants.

When hydrogen is produced through the steam reforming of natural gas, 10 tonnes of CO_2 are released into the atmosphere per tonne of hydrogen, unless coupled with carbon sequestration. It is estimated that carbon dioxide sequestration will increase costs by 20-30% (Hart *et al.*, 1999). The economics of SMR are considered in Section 11.2.1.

Typical plant sizes are:

- 500 – 3000 $Nm^3\ hr^{-1}$ for a small plant
- Up to 25000 $Nm^3\ hr^{-1}$ for a medium to large plant.

5.1.2 Partial Oxidation (POX) / Coal and Oil Gasification

POX and gasification are very similar so will be discussed in the same section. This process is becoming increasingly popular, and one of the oldest methods of producing hydrogen (Kruse *et al.*, 2002). The feedstock is usually heated to 1400°C in the presence of air or oxygen causing decomposition and producing hydrogen, carbon monoxide and residue (see Eqns. 4 to 6). This process is then followed by shift reaction (Eqn. 7) (Dutton, 2002).

This method of hydrogen production can use any form of hydrocarbon feedstock providing it can be compressed or pumped. It is common for coal to be ground and mixed with water to create a sludge/slurry before gasification using pure oxygen, the result is syngas, which needs to be quenched and scrubbed of soot. Eqn. 4 is an exothermic reaction which can be catalytic or non catalytic. It involves partial oxidation Eqns. 5 and 6 and shift conversion Eqn. 7 followed by cleaning of the hydrogen.

The generic reaction for any hydrocarbon undergoing POX/ Gasification reaction is:

$C_xH_y + 0.5xO_2 \rightarrow xCO + 0.5yH_2$ Eqn. 4

The reaction for natural gas:

$CH_4 + 0.5O_2 \rightarrow CO + 2H_2$ Eqn. 5

The reaction for coal:

$C + 0.5O_2 \rightarrow CO$ Eqn. 6

Partial Oxidation Shift Conversion:

$CO + H_2O \rightarrow CO_2 + H_2$ Eqn. 7

The conversion efficiencies in this system can reach 40% - 60% depending on the size and construction parameters of the plant

The drawback of POX is that it requires expensive pure oxygen. The conversion of the POX system is approximately 50% efficient in large production plants (Dutton, 2002).

Cost data for hydrogen from partial oxidation and gasification is given in Tables 11.1. and 11.3. To reduce emissions, CO_2 capture could be used, estimated to add 25 – 30% to the cost of production (Hart *et al.*, 1999). However for a CO_2 neutral process, biomass is a potential feedstock in the production of renewable hydrogen and this production route will be reviewed in Section 5.2.4.

5.1.3 Pyrolysis

This process was developed by Kvaerner in Sweden as the Kvaerner carbon black and hydrogen process using an industrial scale plasma reactor. Each of the processes for thermochemical production of hydrogen is similar. However, this is the only method that does not produce carbon dioxide providing the material is decomposed at high enough temperatures in the absence of oxygen. The added value to hydrogen produced is the carbon black. The carbon black can be sold to companies who use it in their products (e.g. paint, ink, rubber, tyre, batteries, dyes and plastics) making the overall process more economical (Kruse *et al.* 2002). Cost data for hydrogen from hydrocarbon pyrolysis is given in Table 11.4.

Example:
If methane were "cracked" in the presence of carbon soot or graphite (the catalyst) at high temperature, the resulting emissions and byproducts would be hydrogen and carbon black. This can be sequestered or sold to industry.
$CH_4 + C_X \rightarrow C_{1+X} + 2H_2$
(Lakeman and Browning, 2001 and Dutton, 2002)

5.1.4 Hydrogen as a by-product of the chemical industry

Today a vast quantity of hydrogen is produced annually from the chemical industry as a byproduct of its processes such as production of chlorine, acetylene, cyanide. However the purity of the products differ and can range between 60-95% pure (Zittel, 2002) . Due to lack of consumers much of the hydrogen is used in heating or burnt without use (Zittel, 2002). The chemical synthesis of chlorine is reviewed here as an example of the untapped resources available in the chemical industry.

Chlorine is an important product in the manufacture of modern products such as vinyl and pharmaceutical products. Chlorine is produced by the electrolysis of brine to create chlorine, caustic soda and hydrogen in a mercury fuel cell (World Chlorine Council, 2002). Currently worldwide 1 million tonnes of hydrogen are produced in this manner, of which 0.03 million tonnes are produced in Britain. However, the process does leave the hydrogen contaminated with caustic soda and mercury, which needs to be removed before use (Granite *et al.*, 2000). Despite this the hydrogen is at least 95% pure before being cleaned of impurities (Zittel, 2002). Once clean the hydrogen can achieve purities of 99.9%. The chlorine and hydrogen must be kept separate as both are highly explosive and approximately 15% of the hydrogen produced is vented. Cost data for hydrogen from the chemical industry are given in Section 11.2.1.11.

The reaction for the creation of chlorine:
$2NaCl + 2H_2O \rightarrow 2NaOH + Cl_2 + H_2$
(World Chlorine Council, 2002).

5.1.5 Water electrolysis

The electrolysis of water using any renewable energy that produces electricity (such as solar, wind or tidal) can be used to generate hydrogen sustainably (Pidmore, 2002). Electrolyser technology is well developed and works by disassociating water into diatomical molecules. Electrolysis is the cleanest reaction for producing hydrogen. Cost data for hydrogen from electrolysis plant are given in Table 11.7.

There are a range of electrolyser products on the market, of these the two that seem to be most promising are the liquid alkaline electrolyser and the Proton Exchange Membrane (PEM) electrolyser, both well proven devices. Alkaline electrolysers depend on the circulation of electrolyte solution, they work at low current densities (<0.4 A/cm) and have conversion efficiencies of 60-90%.The liquid alkaline electrolyser is the preferred electrolyser at this time especially for large-scale producers (as these have efficiencies in the top end of the efficiency range). The technology is easily scaled up and is easier to thermally manage due to the movement of the liquid in the cells (Newborough, 2004, Heinzman *et al*. 1999, Momirlan and Veziroglu, 2002 and Kruse *et al*., 2002). The disadvantage of the liquid electrolyte is that it must have a stable energy input. The input energy must stay above 20% of the total capacity of the system to avoid hydrogen bubbles forming in the electrolyte. Bubbles formed in this way could cause an explosive mixture. Whilst the proton exchange membrane is considered the long-term option, it is ideal for small to medium size applications such as home or vehicle use (Kruse *et al*., 2002). PEM electrolysers use precious metal catalysts (e.g. platinum) and a solid polymer electrolyte. The PEM electrolyser has higher current densities than the alkaline electrolyser (1-2 A/cm) and has conversion efficiencies of 50-90%. The advantage of the PEM over the alkaline electrolyser is that by having a solid electrolyte it lends itself to intermittent input energy, thus making it suitable for renewable energy inputs (such as wind and wave).

Research is still being carried out on other types of electrolyser such as the solid oxide and ITM Power Ltd's newly developed electrolyser. The solid oxide electrolyser uses a solid ceramic electrolyser (e.g. zirconia/ceria) and operates at high temperature (800-1000ºC) The operation at high temperatures allows lower electricity inputs. The ITM electrolyser uses isomers in the polymer electrolyte material. The electrolyte can be molded into any shape desired, and costs a fraction of the price of standard PEM electrolyser.

Work has been carried out by Dutton's group on the implementation of wind powered hydrogen production systems. Dutton *et al*. (2000) review the affect of fluctuating power supply on electrolyser operation. The group developed, optimised and demonstrated a wind–hydrogen production plant. Hysolar (Hydrogen from solar energy) have been working on electrolytic production of hydrogen since 1986 where they began the construction of a 350kW solar hydrogen demonstration plant in Saudi Arabia (ERU, 1995).

Water can be changed into hydrogen and oxygen using an electrolyser:

$H_2O \rightarrow H_2 + 0.5O_2$

Electrolysis is 50% - 90% efficient depending on technology implemented and operating conditions.

Work is being carried out to try to create a closed loop cycle as an energy storage/ generation system but the two reactions need different catalysts.

Research challenges include:
- elimination of exotic material on the electrodes
- production of electrodes with electrochemical stability
- decreased cost of production

5.2 Research production methods

5.2.1 Photoelectrolysis

The process splits water directly into hydrogen and oxygen using sunlight. The device uses multi-junctional cell technology (semiconductors) and photoconductive layers with different semiconductor band gaps in series. It is the cascade structure that minimises the surface area. It is very important that the devices are water tolerant as the device will be in direct contact with the water (Dutton, 2002). The resistance of the semiconductor is very dependant on temperature. The light harvesting system must generate sufficient internal voltage to decompose the water. Despite theoretical photo conversion efficiencies of 15% (Dutton, 2002), and the high efficiencies obtained in wet cells, the splitting of water has yet to be achieved using visible light. Photoelectrochemical cells also lead to degradation of the active photoelectrode.

Research challenges:
- increase cell lifetime
- creation of a stable cell in water

5.2.2 Photochemical

Photochemical production of hydrogen uses a sensitizer to affect the redox reactions (this increases the quantum yield per unit area). The sensitizer (a molecule or semiconductor) is excited by visible light and stimulates photochemical reactions yielding electrons for water decomposition. In most cases, a catalyst is needed and a polymer to impede precipitation. There is, however, a trade-off between the two as the polymer also impedes the catalytic reaction. The reaction rate varies dependant on the uneven distribution of the sunlight (Momirlan and Veziroglu, 2002); therefore the placement of such a device would be paramount. The majority of studies use sacrificial donors or acceptors and it is then possible to study the half reactions separately.

Recent work carried out in this field has been done on the photocatalytic splitting of water using a novel series of solid photocatalysts NiM_2O_6 (M = Nb, Ta). This work resulted in a new photocatalyst splitting water to generate hydrogen under visible light (Ye *et al.*, 2003). Zou *et al*. (2003) have been carrying out similar work using the photo catalyst BI_2MNbO_7 (M=Al^{3+}, Ga^{3+} and In^{3+}).

Research challenges:
- Improvement of efficiency
- Molecular absorber must become robust
- Increase of lifetime of cells
- Design of gas separation equipment

5.2.3 Biological production of hydrogen

The biological production of hydrogen can be split into two categories, photosynthetic and dark fermentation. Biological systems have the potential for low capital costs, providing the cells are viable for extended periods.

Photosynthesis

Photosynthetic H_2 production by green and blue-green algae *(Cyanobacteria)* involves water splitting (biophotolysis) to produce H_2 and O_2. Green algae are one of the most promising groups for hydrogen production through photosynthesis (Melis, 2002). Under certain conditions green algae contain an enzyme, hydrogenase, which catalyses the reduction of protons by electrons to form hydrogen. Hydrogen production is a wasteful process for these algae, but the role of the enzyme is in managing the dark to light transition that algae face daily. Hydrogenase in green algae is only synthesised (induced) after several hours of dark preincubation in anaerobic conditions (without oxygen). Hydrogenase contains iron and is very O_2 sensitive, so when after a short period in light O_2 is produced, hydrogen production rate decreases. Thus sustained H_2 production by green algae is a challenge, as biologically this system is not designed for continuous operation. To overcome this, two-stage processes are suggested, a photosynthetic CO_2 fixing stage generating O_2 followed by a dark anaerobic fermentative stage generating H_2, so-called "indirect biophotolysis".

A green algae that has been extensively investigated for hydrogen production is *Chlamydomonas reinhardtii*. Hydrogen production can be enhanced by growth with limited sulphur and in light/dark cycles to synchronise cell division (Kosourov *et al*., 2002 and Laurinavichene *et al*., 2002). The operating protocol needs specification and when making use of natural light the process is only operative during daylight hours. Culture contamination must also be avoided. Photosynthetic production of hydrogen can also use blue green algae (*Cyanobacteria*) or photosynthetic bacteria (e.g. *Rhodobacter sphaeroides*). These microorganisms produce H_2 using the enzyme nitrogenase, normally involved in N_2 fixation to NH_3. Blue-green algae produce O_2 in photosynthesis which inhibits nitrogenase. Photosynthetic bacteria do not carry out light driven water splitting, but use compounds more reduced than water. Thus they require organic compounds for example from biomass or organic effluents. Nitrogenase is less efficient at H_2 production than hydrogenase since it is energy requiring and has a turnover rate 1000x slower. H_2 production by nitrogenase is inhibited by the presence of ammonia and N_2 so cells can be starved of a N source. An example of work on hydrogen production by photosynthetic bacteria is that in the Netherlands of Janssen and Hoekema (2003).

Challenges for photosynthetic hydrogen production include the lack of information on photobioreactor technology. This is not a familiar technology, and realistic information on design parameters, construction and economics are scarce. The reactor must be enclosed to allow H_2 collection and must give good light penetration through water and the culture, since cells only a few cell layers in are light-starved. Increasing cell concentration for process intensification hinders light penetration.

Research challenges:
- Development of a cost-effective operating protocol for continuous production of hydrogen from green algae
- Development of cheap and efficient photobiorectors
- Production of a stable, sustainable photolysis system using isolated enzymes

Fermentation

Fermentation to produce hydrogen is a dark, anaerobic process, with process similarities to the well-known anaerobic digestion process and to fermentation in the rumen. Carbohydrate rich organic material is the preferred substrate, e.g. root crops, fodder grass or food industry co-products. The theoretical maximum hydrogen yield by fermentation is 4 moles hydrogen per mole of hexose sugar (e.g. glucose) fermented (see equation below) i.e. approximately 0.5m^3 hydrogen per kg glucose equivalent. Fermentation end products such as acetic and butyric acids result, which may be further fermented in the dark to methane by anaerobic digestion. These acids could also in principle be feedstock for a photosynthetic process using photosynthetic bacteria to produce hydrogen, with a theoretical maximum of 12 moles hydrogen per mole of glucose equivalent.

Fermentative bacteria producing hydrogen in the dark may be cultivated in pure culture or occur in uncharacterised mixed cultures selected from natural sources such as anaerobically digested sewage sludge or soil. Pure cultures of Clostridia, Enterobacter and Bacillus have been studied but their use would necessitate operation in sterile conditions, which is likely to make the process too costly. Pure cultures of extreme thermophiles such as *Caldicellulosirupter saccharolyticus* and *Thermotoga elfii* can be grown to produce hydrogen at temperatures of 65^{o}C or above, which reduces contamination from other species (van Niel *et al*., 2002 and Claassen, 2003). However this thermophilic process may be too energy demanding unless heat recovery in the overall process is efficient.

The fermentative process acts on carbohydrate rich organic material producing hydrogen, carbon dioxide and acid end-products, eg acetate:
$C_6H_{12}O_6 + 2H_2O \rightarrow 2CH_3COOH + 2CO_2 + 4H_2$

Work on fermentative hydrogen production from mixed cultures in non-sterile, continuous reactors at temperatures around 30^{o}C (mesophilic) has been carried out in East Asia and in Wales in the University of Glamorgan (Hawkes *et al*., 2002b, Hussy *et al.*, 2003). The bacteria are generally species of clostridia able to use a wide range of carbohydrate substrates, including cellulose. Hydrogen inhibits its production by hydrogenase enzymes for thermodynamic reasons, so procedures lowering the hydrogen concentration are favoured. The challenge is to gain good hydrogen yields and prevent shifts in microbial populations to bacteria consuming hydrogen rather than producing it. Once operating protocols have been established and optimised, operating costs are expected to resemble those for high-rate anaerobic digestion processes.

Research challenges:
- Development of stable systems with optimum hydrogen yields using mixed microflora and non-sterile feedstock in continuous operation
- To obtain data on hydrogen yields obtainable from biomass crops

5.2.4 Thermochemical production of hydrogen

Thermochemical methods use the same technology as that covered in Sections 5.1.2 and 5.1.3. However the following methods are research based as they relate to the use of renewable feedstocks, introduce a mixed feedstock and have different operating parameters. Thermochemical production of hydrogen using biomass can be split into three specific areas: Gasification, Supercritical Water Gasification and Pyrolysis. The following are outlines of the most recent studies undertaken:

Gasification

Currently research is ongoing in Germany (Institut für Technische Chemie 2003) on the gasification of wet biomass and organic waste in hot compressed water. The goal of the research is to develop a gasification process for sewage sludge and waste streams from the food industry to covert to high quality gas. Midilli *et al*. (2002) have produced hydrogen from sewage sludge by applying downdraft gasification techniques using a fixed bed gasifier. Cost data for hydrogen produced from biomass gasification is given in Table 11.5.

Pyrolysis

Iwasaki (2003) has produced in conjunction with NEDO's WE-NET a feasibility study for pyrolysis using woody biomass (rice hull, rice straw, forest biomass and waste cooking oil), whilst Abedi *et al*. (2001) have been researching pyrolysis of peanut shells and Caglar & Demirbas (2001) have investigated solar assisted separation generated by pyrolysis from tea waste. Cost data for hydrogen from biomass pyrolysis plant is given in Table 11.6.

Supercritical gasification of biomass

Supercritical gasification can directly deal with wet biomass and has very high gasification efficiencies at low temperatures. The cost of direct gasification of biomass can be as high as three times the price of SMR, the use of biological waste streams such as fruit shells and tea waste can bring down the hydrogen cost to make it cost competitive with standard SMR. Currently work is being carried out by Demirbas (2003) where fruit shells undergo super critical water extraction to create hydrogen, whereas fundamental design of the process is being carried out by Matsumura and Minowa (2003)

Un-mixed reforming of vegetable oil

Unmixed reforming operates in a bed containing a catalyst (e.g. Ni, Fe or Cu) and a CO_2 absorbent such as CaO, MgO or BaO. The reactions take place in two phases. The catalyst is oxidized to either NiO, FeO or CuO thus causing the reactor bed to heat. The second phase involves the addition of the fuel feed (in this case vegetable oil), the catalyst will then donate the oxygen creating CO, CO_2 and H_2. The adsorbent material will absorb the CO_2 and will regenerate during the first phase by thermal decomposing. This process has advantages in that it does not require heating (except in the start up) and there are separate CO_2 and H_2 flows which would facilitate the ease of carbon sequestration. The process does produce hydrogen intermittently but by running two systems this could be solved. This work is being carried out primarily in the University of Leeds by Ross *et al*. (2003) with the collaboration of Johnson Mathay (EHEC 2003).

Plasma reforming

Plasma reformers use a combination of vaporization and activation techniques (described in Section 5.1.1); the plasma exists in a very high energy state (high temperature). The advantage of this system over traditional methods of SMR, POX or coal gasification is that it yields a high power density, fast response time, has fuel flexibility, high conversion efficiencies and can operate in POX, SMR or pyrolysis configurations. However, the system does have a high energy consumption (Kruse *et al*., 2002).

Research challenges:

- Reduce energy consumption
- Higher hydrogen yields
- Reduce carbon dioxide and monoxide emissions
- Increase start up response times.

5.2.5 Hydrogen bromide electrolysis

The production of hydrogen through the electrolysis of hydrogen bromide requires half the voltage of that required to electrolyse water (Lakeman and Browning, 2001). The reaction to extract the hydrogen is also reversible. The splitting of hydrogen bromide can be promoted by heat and light

The hydrogen bromide can be regenerated by reaction with methane:
$2HBr \rightarrow H_2 + Br_2$
Further reaction with methane:
$CH_4 + 2Br_2 \rightarrow C + 4HBr$

(Lakeman and Browning, 2001 and Dutton, 2002)

The overall emissions and by-products are hydrogen and carbon black, which can be sold or sequestered. The regenerative fuel cell is being developed by Innogy Technology Ventures Ltd in the UK under the title Regenesys™. The system uses a bromide / bromine cathode; this could be adapted using a hydrogen anode (Lakeman and Browning, 2001).

5.2.6. Hydrogen from nuclear power

The economics of nuclear energy are dependent on maintaining a continuous base load; hydrogen effectively decouples the production and consumption of this energy (Forsberg, 2003). The nuclear heat is a cheaper commodity than the electricity making any process that substitutes heat for electricity more economically favourable (Forsberg, 2003). An advantage of nuclear energy is that it serves countries that do not have significant amounts of natural resources available.

There are 4 methods of hydrogen production using nuclear energy:

- Conventional electrolysis using nuclear generated electricity
- High temperature electrolysis using nuclear electricity and heat
- Steam methane reforming coupled with High Temperature engineering Test Reactor (HTTR)
- Thermo chemical cycles for water splitting
- Hybrid combining thermo chemical and electrolytic steps

Electrolysis techniques were explained in Section 5.1.5. In most industrial nations peak energy demand is twice that of minimum demand; the low cost electricity produced by the nuclear power stations could be used in an electrolyser to produce low cost hydrogen.

Coupling nuclear heat and electricity make high temperature electrolysis a very attractive and very efficient way to produce hydrogen over and above standard electrolysis. The higher temperature results in better chemical kinetics that increase efficiency. This hydrogen production technique requires that the electrolysis unit is co-located with the nuclear power plant (Ogawa, 2003). The advantage of this approach is that it builds on existing solid oxide fuel cell technology and at lower temperatures than the thermochemical cycles (Ryskamp, 2003).

SMR requires a high temperature input, as explained in Section 5.1.1. The Japanese Atomic Energy Research Institute (JAERI) have demonstrated that the electrical energy required for heating this process can be significantly reduced through addition of heat provided by a nuclear reactor. JAERI have demonstrated that SMR can be achieved using the heat from their High Temperature engineering Test Reactor (HTTR) (Ogawa, 2003).

Thermo chemical hydrogen production can take place through a range of processes, the most promising of these to date are the sulphuric acid process and the Br-Ca-Fe process. The sulphuric acid process is a high temperature low-pressure reaction (Eqn. 8), and requires a intermediary iodine sulphur process (Eqn. 9) and a final hydrogen producing stage as indicated by equation 10. The process is very efficient and potential one of the most cost effective ways of making hydrogen from nuclear power, but is limited by extreme operating conditions (Ryskamp, 2003).

The reaction that takes place is:

$H_2SO_4 \rightarrow H_2O + SO_2 + O_2$ (800ºC) Eqn. 8

$I_2 + SO_2 + 2\ H_2O \rightarrow 2HI + H_2SO_4$ (Low Temp) Eqn. 9

$2HI \rightarrow H_2 + I_2$ (Intermediate Temp) Eqn. 10

Research challenges:

- The thermo chemical processes need corrosion resistant materials

The Department of Energy (DOE) hopes to develop of a new series of nuclear power plants (Generation IV) that could play a part in their hydrogen future.

5.3 Carbon dioxide sequestration

During the transition to the hydrogen economy, it is inevitable that the production of hydrogen from fossil fuel will be a stepping-stone until renewable and sustainable hydrogen production becomes a reality. During this time, it will be necessary for the carbon dioxide emissions to be stored (sequestered).

Three large-scale methods presently being considered are:

- Storage in deep sea saline reservoirs
- The injection of carbon dioxide into hydrocarbon deposits to enhance oil recovery or production of coal bed methane
- Injections into deep oceans

When carbon dioxide is stored below 800m it becomes supercritical and therefore stores in a dense form. The injection of carbon dioxide into deep saline reservoirs would displace the water. The world's potential storage has been estimated at a thousand giga tonnes, this is enough area to sequester hundreds of years of carbon dioxide. This method is currently under trial in Norway, the carbon dioxide is being captured in conjunction with Sleipner field. This trial is being monitored under site conditions gaining data that can be used in future projects (Hart *et al.*, 1999).

Injection into hydrocarbon deposits to enhance oil extraction can be utilised when the existing oil pressure drops, the carbon dioxide can then be injected into the underground oil reservoir to increase in oil extraction. This can dramatically change the productivity of an oil field. The drawback is that the remaining wells will store the carbon dioxide for thousands of years; this will then need constant monitoring and management. In suitable conditions, carbon dioxide can be pumped into deep mine shafts where coal has become unminable, the carbon dioxide would be sequestered into the coal releasing the stored methane. The methane can then be harvested at the pithead and used to create energy and the resulting carbon dioxide could be sequestered back into the mine (Hart *et al*., 1999).

The injection of carbon dioxide into the deep ocean is still speculative, the idea being that the carbon dioxide would be injected at 3000m. This is an extreme depth; at this depth the carbon dioxide would create a lake in the sea bed, then form a layer of solid carbon dioxide hydride. The long-term effects of this method are unknown; environmental implications would have to be reviewed and a detailed analysis compiled before this is undertaken (Hart *et al.*, 1999).

6. Storage

Current hydrogen production is predominantly in the chemical and metal industries, which produce hydrogen on site and gaseous hydrogen for transport around the UK. Small amounts of liquid hydrogen are imported into Britain from Holland (POSTNOTE, 2002). Hydrogen can be stored in the liquid or gas phase though the physical properties of hydrogen can make storage difficult, but developments are ongoing to increase the efficiency of storage vessels.

As discussed earlier in Section 2.1, storage is one of the most challenging technical considerations of a move towards the hydrogen economy, this is due to hydrogen's low energy density. Storage vessels need to have both high gravimetric density and volumetric density. United States storage targets from the Department of Energy (US DoE, 2003c) aim to achieve a gravimetric density of 6 wt%, (where wt% is defined as the ratio of grams of hydrogen per gram of system weight and 1wt% = 186 Wh/kg) in order for the hydrogen to become economical for transport applications. The gravimetric density is important as it indicates how much energy can be stored within a system in comparison with the overall weight. See Appendix 1 for properties of hydrogen.

Hydrogen may be stored:
- In compressed gas bottles
- As a cryogenic liquid
- As a metal hydride
- In carbon structures
- Through chemical storage

To date no commercially produced storage has achieved the US targets, however bench scale research has reached 10 wt% (US DOE, 2003c). Research is needed in order to create an economical onboard hydrogen storage system for vehicles. The storage vessel must not only have good storage properties but also needs to fit into engine spaces in order to maximise space inside the vehicle. The cost of transportation is related to the storage density. Thus increasing storage density will reduce the cost of hydrogen by reducing distribution costs. Hydrogen storage economics are considered in Section 11.2.2.

6.1 Mature storage techniques

6.1.1. Compressed hydrogen

As hydrogen is one of the lightest elements its energy per unit volume is comparatively low, thus storing gaseous hydrogen in gas bottles requires high pressures. The weight ratio of hydrogen stored to the weight of container means that the cost of transportation is restrictively high. Compressor development is a requirement for the reduction of cost and minimisation of the ecological footprint from compressing gas to the required pressures. Currently compressed gas cylinders achieve 2.1 wt% (Browning, 2000) Much of the hydrogen produced today is at 5MPa (see Chapter 5) and most conventional cylinders demand higher pressures. The highest price cylinders in the market demand gas pressures of 6.7MPa and the compression process required to reach these pressures is very energy intensive.

Compressed gas cylinders are commercially the most available and utilised storage methods today. The majority of the hydrogen transported in the UK is carried in this way. Traditional compressed gas cylinders are made from steel and have a gravimetric density of ~1 wt% (186Wh/kg). Steel cylinders used for moderate storage requirements are heavy and bulky, while with large volumes greater than 14,000 Nm^3, spherical vessels are invariably used. Newer composite cylinders are made of aluminium wrapped in carbon fibre. These small cylinders store hydrogen at pressures in the region of 70 MPa and result in a gravimetric density of 12 wt% (US DoE, 2003c). Some more recent carbon fibre wrapped cylinders have achieved gravimetric densities of ~5 wt%, however they utilize higher pressures and require a more complex filling and empting coupling which is costly. Ultra high composite cylinders with gravimetric densities of ~10 wt% (1860 Wh/kg) have been developed but the higher density is only achieved by using higher-grade carbon fibre, which is difficult to make and is therefore costly. Cylinders at pressures of 69MPa require complex filling equipment and the associated increase in cost will then transfer to the purchaser or user of the equipment.

Research challenges:
- Creating a low cost pressure system
- Increasing the amount of hydrogen that can be stored

6.1.2. Liquid Hydrogen

Liquefaction is an energy intensive process, which occurs at a temperature of 20ºK at 0.1MPa and the energy required for liquefaction is 8.5kWh/kg. Liquid hydrogen contains three times the energy of petrol in mass terms, however the energy needed to store liquid hydrogen is equivalent to 25-30% of its energy content. The cryogenic Dewar vessel is the most commonly used storage vessel for liquid hydrogen and the largest of these is based at NASA.

Cryogenic liquid vessels require very efficient insulation in order to keep the hydrogen in the liquid phase. Usually the vessels are spherical in shape in order to minimise the surface area and consequently heat loss, while negatively affecting the installation space requirements. Insulation ancillary equipment and fixings also increase the volume and weight of the system. Tank sizes range from a few litres to 3,800 m^3 (the latter is used by NASA and is one of the largest in the world). The motor manufacturers BMW have used liquid hydrogen in their new hydrogen powered cars and estimate boil of rates of 1% per day for small tanks in transport vehicles.

Research challenges:
- Creating a low cost, energy efficient liquefaction process.

It has been suggested by Egan (2004) that super critical hydrogen storage could be a solution to the storage problem, this would involve combining the liquid hydrogen and compression technology to hold hydrogen in its super critical form. This technology has yet to be proven.

6.2. Research activities

Currently, hydrogen storage is seen as one of the critical enabling technology areas, which will require significant advances in order to facilitate the move to hydrogen as a fuel.

6.2.1. Metal hydrides

Metal hydrides offer an alternative to storage in cylinders or cryogenic vessels. The hydride allows the hydrogen to be stored in a solid form (Elam *et al.*, 2003). Certain metal alloys have the ability to store hydrogen under moderate pressure creating a hydride (Kruse *et al.*, 2002). Metal hydride storage systems can be categorised as high or low temperature systems and the gravimetric targets set by the US DoE, (2003c) for on-board applications, are 7 wt%. The reactions are reversible and take place at moderate temperatures and pressures, storing the hydrogen within the metal atomic structure. The metal matrix is made of granular particles that adsorb the hydrogen.

Hydrogen is released from the metal hydride by applying heat or moderate pressure and the reaction can be described by the following equation:
$M + xH_2 \rightarrow MH_{2x}$
Where M is the storage metal alloy and x is dependant on adsorbtivity

Conventional hydrides require a high temperature to liberate the hydrogen. This is not practical in vehicle applications (Elam *et al.*, 2003). Low temperature hydrides are also available but have a lower gravimetric density (3-5 wt%) and a higher weight than the conventional hydrides (US DoE, 2003c). Though there has been considerable work recently on metal hydrides, there are still many challenges to overcome as can be seen below.

Hydrides have good theoretical volumetric performance of 100 g/L (1860 Wh/l) but a poorer gravimetric performance of 1-2 wt%. Where weight is not a problem hydrides are a good storage method though the desorbtion is endothermic (requires heat) (Elam *et al.*, 2003). Metal hydrides are a safe storage method as hydrogen is stored at constant pressure and when the heat source is removed, the hydride ceases to expel hydrogen.

Examples of storage alloys are $TiFeH_2$ and $LaNi_5H_7$. There are numerous research studies aimed at improving the storage capacity in hydrides. These include the addition of lighter elements such as Al or Mg, however when incorporated the temperatures needed to disassociate the hydrogen are very high and so far these alloys are impractical for stationary or transport use. Complex metal hydrides can be created but require extreme conditions to reverse the reaction and are slow to do so (Maeland, 2003).

Texaco Ovonic has produced a commercially available hydrogen storage system that tailors metal hydrides over a range of temperature and pressure requirements. The relative density of this system can exceed that of liquid hydrogen (Texaco Ovonics, 2003). The system is very heavy which is a disadvantage for the transport industry.

Research challenges:
- Developing alloying techniques for low temperature hydrides
- Development of an alloy that has an increased gravimetric density
- Developing a light weight system

6.2.2 Novel hydrides

Hydrogen can be stored in a chemical form. Primary hydrides such as LiH, $LiBH_4$, $NaBH_4$ undergo a reaction with water (hydrolysis), which can be violent. The system may need a deactivation coating on the particle to avoid thermal runaway however it will then suffer from a slow response time. The chemical storage of hydrogen is not rechargeable and may be considered as a good secondary source of hydrogen (one use only). Hydrolysis hydrides have a theoretical gravimetric density of between 5-8.5 wt%.

There is a commercially available product based on sodium borohydride called Hydrogen on Demand™, which uses an aqueous sodium borohydride solution (derived from borax) (Millennium Cell, 2003). The by-products of the reaction, nitrogen and sodium metaborate, are environmentally benign and the gravimetric density of this storage method is of the order of 4.4 – 7.7wt%.

The hydrogen from the Hydrogen on Demand™ system is released by passing the solution over a catalyst. The hydrogen then converts to hydrogen and sodium metaborate:
$NaBH_4 + 2H_2O \rightarrow 4H_2 + NaBO_2$

Research challenges:
- Stabilising the reactions
- Better response and control

6.2.3 Carbon based storage

In recent years considerable research has been carried out on nano carbon structures for use in hydrogen storage. There are wide ranges of amorphous carbon based materials exhibiting a high degree of porosity. Carbon nano-fibers were developed by North-Eastern University (USA) and consist of stacked graphite plates. Nano-fibers are thin fibres (5-100 nm diameter and 5-100 μm length) with the potential to store 50 wt% (9300 Wh/kg) at room temperature and high pressure but this work has since been discarded (now ~1wt%). The carbon fibres are grown over metal catalysts in a hydrocarbon gas. The best bi- and tri- metal catalysts for this process are Fe, Ni, and Cu.

Carbon nano-tubes can be categorised as single wall nano-tubes (SWNT) or multi wall nano-tubes (MWNT). SWNTs consists of one or more seamless cylindrical shells of graphitic sheet. MWNTs by contrast, are made up of a few tens of cylindrical graphitic sheets (Valoen, 2001). Activated carbon is a highly disorganized and porous, three dimensional set of graphite planes that vary in size.

MWNT tubes can theoretically store up to 10 wt% of hydrogen but again require either high pressure >10MPa or low temperatures of at least -100ºC. Experimental results reported for carbon nanotubes vary widely. Sarkar and Banerjee (2004) believe this is due to the improper characterization of the nanotubes by researchers. Sarker and Banerjee hope to remove the ambiguity of results by developing a new system of characterization that will allow researchers to clearly identify the factors that affect hydrogen storage.

A sample of nano-fibres was tested by Browning (2000) who reported that it had a maximum of 6.5 wt% adsorption. This was expected to improve with increased purity of the fibres. This type of storage system is still in its developmental stage and has yet to prove itself as a commercially viable option. In a recent report on hydrogen storage conducted by Bernard and Chahine (2004) it was concluded that although SWNT and MWNT have a higher hydrogen storage capacity, activated carbon was a better storage medium due to its higher surface area. This was confirmed by Zhou *et al.*, (2004) whose research compared hydrogen take up in MWNT and superactivated carbon; they demonstrated that the activated carbon held 3.6-5.1 times greater amounts of hydrogen than the MWNT's.

Research challenges:
- Large-scale production of purified nano tubes and activated carbon

6.2.4. Hydrogen storage through ammonia dissociation

Ammonia is a widely used chemical; it is non-flammable and international handling procedures are in place. This makes ammonia a good storage vehicle for hydrogen as it eliminates the problem of storing and distributing gaseous or liquefied hydrogen (Faleschini *et al.*, 2003). The ammonia can be shipped using existing methods safely and can then be converted to hydrogen on board vehicles or in filling stations so that the hydrogen can be distributed.

Hydrogen is released from ammonia by 'cracking', which requires the application of temperature and/or pressure in the presence of a catalyst which will separate ammonia into hydrogen and nitrogen:
$2NH_3 \rightarrow 3H_2 + N_2$

The catalyst chosen affects conversion from ammonia to hydrogen and it has also been found that pre heating the ammonia improves the efficiency of the cracking reaction.

One drawback to using ammonia as a storage device is that some fuel cells are sensitive to ammonia (Faleschini *et al.*, 2003). The hydrogen would need, therefore, to be very pure with any traces of ammonia removed.

7. Distribution and Infrastructure

7.1 Long distance distribution using storage mechanisms

The technical aspects of storage systems were covered in Chapter 6, however in this chapter the storage capacity of vessels and their appropriateness for distributing large quantities of hydrogen are considered.

Standard compression cylinders do not hold very much hydrogen in comparison with the overall weight of the cylinder. It has been estimated that high pressure cylinders at a pressure of 40MPa hold approximately 1.8kg. Although it is possible to load many of these smaller cylinders on to a vehicle a compressed hydrogen tube trailer holds one load equal to approximately 460kg at pressures of 20.60MPa (Howes, 2002 and Amos, 1998).

Liquid hydrogen vessels are typically spherical in shape to reduce the surface area and need heavy insulation. Even with very efficient insulation, boil off will occur and it is estimated to be around 0.3% per day on long hauls (Dutton, 2002). The maximum amount of liquid hydrogen transported in one container is normally 360-430kg (Howes, 2002, figures derived from Amos, 1998).

Liquid hydrogen has a higher gravimetric density than compressed gas and therefore liquid hydrogen can be transported more economically over longer distances. Today all of the UK's liquid hydrogen is imported.

The transportation of hydrogen using metal hydrides would be an advantage over compressed or liquefied hydrogen as solid storage allows a high storage density without the high pressure or dangers of a liquid hydrogen spill. Metal hydrides are however very heavy and very expensive, precluding them as a viable large-scale storage method at present. Research work is ongoing into other storage materials such as light metal hydrides, polymers and micro, meso and nano-porous carbons.

7.2 Modes of transportation for hydrogen

Current hydrogen distribution modes in the UK are given in Table 11.11. The amount of hydrogen needed to supply the hydrogen economy will, with current distribution mechanisms, require hundreds of trucks carrying multiple cylinders or hundreds of tube trailers to travel the roads daily. This would increase the traffic flow nationally. The environmental impact of distribution via road or rail needs to be considered and emissions of distribution vehicles will need to be factored in the early stages of the transition, as they may not be running on hydrogen. With increased traffic movement the chances of road accidents increase and development of emergency procedures and standards needs to go hand in hand with widespread use of the roads as distribution networks for hydrogen.

Other modes of transport need to be considered. There are already examples of transportation of hydrogen on ships; the Euro-Quebec team exported hydrogen from Canada to Germany via ship, and each ship contained three cryogenic containers (Lakeman and Browning, 2001). The advantage of transportation by ship is that environmental damage is avoided in case of an accident, as unlike oil a hydrogen spill would evaporate and dissipate with no environmental damage. If a combination of distribution networks were used it could ease the pressure on any one mode and hopefully reduce the chances of a major accident.

Research challenges identified by the DTI (2002b) in the Sustainable Energy Route Map – Hydrogen, are the development of:

- Safe refuelling technology
- Codes and standards relating to the transport use of hydrogen
- Low cost compression and liquefaction

7.3 Pipeline

There are already hydrogen pipelines in the UK, based around production plants and heavy industry. Within the UK there are large network pipelines in Teesside and in Wales there are pipelines in Port Talbot. The hydrogen pipeline works in a similar manner to natural gas pipelines. However, due to the physical properties of hydrogen natural gas pipelines cannot be used directly to transport pure hydrogen. As explained by Eliasson and Bossel, (2000) the natural gas pipeline network would need to be upgraded in order to accommodate hydrogen. Hydrogen can result in fracturing of pipelines as it causes the embrittlement of steel and since it is a very small molecule is easily diffusible so could escape through the existing pipes (Howes, 2002 derived from Padro & Putch, 1999). However, hydrogen in mixtures similar to town gas could be used in the interim. Currently pipelines run typically at pressures of 1-3MPa and flow rates of 310-8900kg/h (Amos, 1998)

7.4 Grid transmission

Hydrogen can be generated locally using renewable energy sources; the hydrogen could act as a buffer overcoming the intermittency synonymous with renewable electricity production (DTI, 2002b). The hydrogen can be stored and reconverted into electricity, which could be distributed via the national grid. The location of the renewable energy technology must be considered, as only in areas where grid connections were strong would this method of transmission be suitable. Another factor that could influence this distribution method would be that 7.6% of energy losses occur during transmission and distribution on the national grid (DTI, 2002a).

7.5 Infrastructure

Today hydrogen is mainly distributed via road in compressed gas cylinders. However, this distribution network is only used to supply industry. If hydrogen is to be used as an everyday fuel consideration must be given to the feasibility of developing a distribution network capable of moving the volumes of hydrogen that will be needed.

The distribution network appropriate to Wales will depend on a number of factors, some of which will include:

- Centralised or decentralised hydrogen production
- Speed of transition to the hydrogen economy
- Transport infrastructure
- Geographical location
- Cost of transportation
- End application of the hydrogen
- Storage mechanism

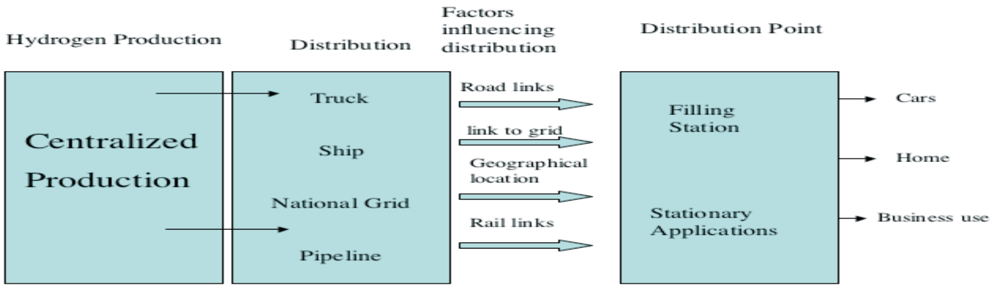


Figure 7.1. Centralised production infrastructure

These factors will determine the area covered by each distribution network.

Centralised production is usually based on a large production plant (see Figure 7.1.). The plant distributes its hydrogen by road, rail or sea to distribution points or large scale end users, alternatively it could convert the hydrogen to electricity and distribute via the national grid. Centralised production benefits from economies of scale and would suit areas with a good transport infrastructure to aid distribution to fuelling stations, stationary applications or large-scale end users.

In areas where some of the influencing factors are missing i.e. poor road or rail links, or there is a need for reinforcing the grid, a decentralized hydrogen production facility may be more appropriate. Decentralised hydrogen production systems rely on small individual hydrogen production facilities being on-site or near to the demand (see Figure 7.2.). This type of system could be utilized in small rural communities providing they had enough natural resources to produce hydrogen.

Using this type of system a small community could become self-sustaining and the need for large-scale distribution and storage may become redundant. This type of infrastructure would be easier to install than larger scale projects and is flexible as additional units can be added over time as the community grows

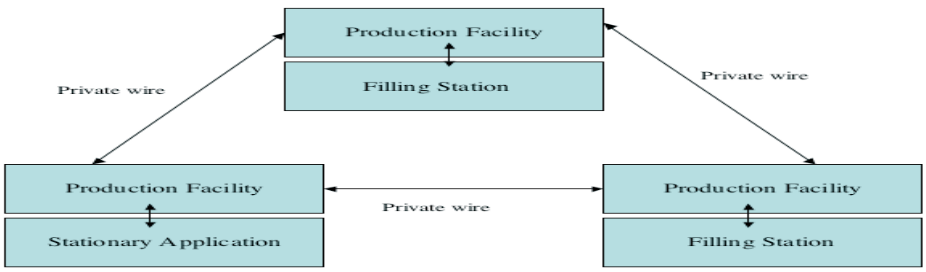


Figure 7.2 Distributed hydrogen infrastructure

7.6 Infrastructure mechanisms

The mechanism for development of the infrastructure can be a chicken and egg problem, as infrastructure will not be developed until there is a demand for product and the product will not be developed until there is an infrastructure in place (Kruse *et al*., 2002). It needs governmental strategy to make appreciable moves forward in this area.

Developing an infrastructure over a long period with minimum disruption could be done by encouraging fleet vehicles such as taxis, buses, council vehicles, mail delivery and milk floats and tankers to convert to hydrogen.

Their geographical area is limited by specified routes or patches and they would therefore be the ideal vehicles to begin the move towards the hydrogen economy. The establishment of an infrastructure could be begin with small filling stations based at fleet depots such as the successful facility based at Munich Airport. As the hydrogen economy develops the filling stations can expand and begin selling hydrogen to the general public. In time, as hydrogen use becomes widespread, the network of fleet depots will service an increasing number of vehicles and develop into a national network of hydrogen filling stations. This option relies on a slow transition to hydrogen; this route could make the transition to hydrogen slower than necessary. Car developers tend not to like this route as it would slow the market for their hydrogen cars.

The alternative is to develop a national program to develop and establish infrastructure. This route would be required if a quick transition to the hydrogen economy was needed. However, the implementation of such a scheme would cause large scale disruption and would be exceedingly expensive and logistically impractical (Kruse *et al*., 2002 and Pidmore and Bristow, 2002).

It may be possible to combine these two extremes; if development of fleet infrastructure were combined with government backed upgrading of infrastructure to hydrogen compatible systems the transition to the hydrogen economy could be developed sooner.

8. Uses for Hydrogen

Hydrogen offers the potential for pollution free transport; hydrogen can be used in Internal Combustion Engines (ICE) and Fuel Cell Vehicles (FCV). It can be an effective means to store energy from intermittent renewable sources such as wind farms and tidal energy. Used in combined heat and power units it can provide heating and electricity for home and business use.

However, the hydrogen economy is not a new idea. Hydrogen was identified by Henry Cavendish in 1766 and the first fuel cell was created by William Grove in 1839. Town gas, which constituted up to 50% hydrogen, was until the 1950's used in homes around the UK. It was used successfully for many years and was not considered hazardous (Hart *et al.,* 1999). Today's uses of hydrogen (Figure 8.1) are based on industrial use, with artificial fertiliser and the petroleum industries being the heaviest users (Kruse *et al.*, 2002). In relation to this use the number of stationary and transportation demonstration projects being carried out is small.

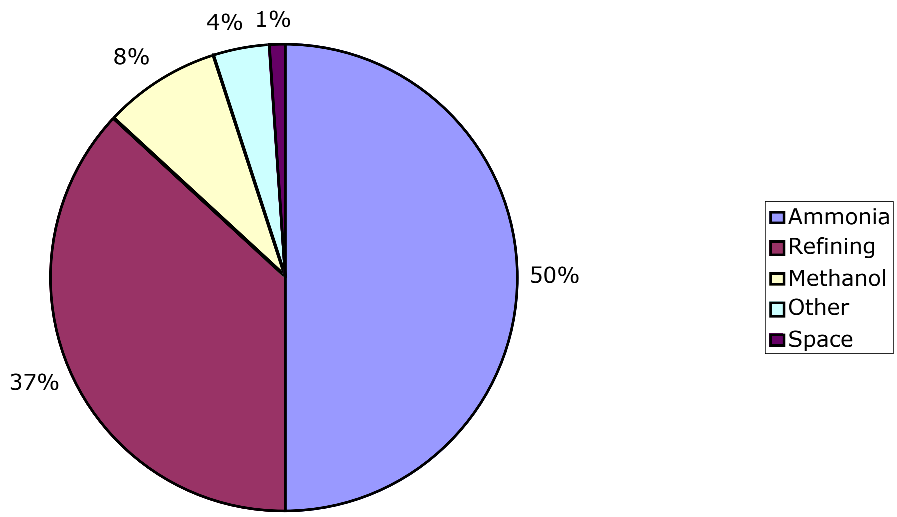


Figure 8.1. Today's use of hydrogen.

8.1 Utilisation Technologies

8.1.1 The Fuel Cell

Fuel cells (and electrolysers which bring about the reverse reaction) are principally characterised by the electrolyte they use. In a fuel cell, hydrogen is combined with oxygen without combustion and is not limited by the Carnot cycle (Lakeman and Browning, 2001). Theoretically, the fuel cell can convert 83% of the energy into electricity (Kruse *et al.*, 2002) but this is not achieved in practice due to the resistive losses in the fuel cell stack (Lakeman and Browning, 2001).

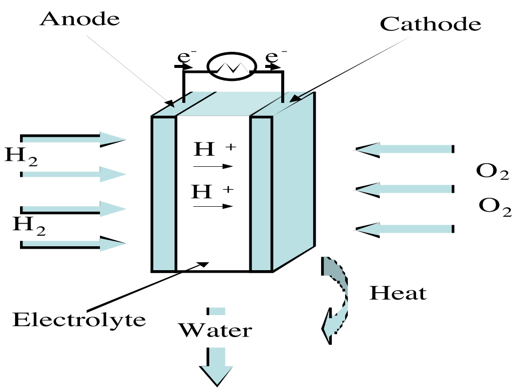


Figure 8.2 Diagram of Fuel Cell

A fuel cell (see Figure 8.2) is comprised of:

Anode	negatively charged electrode
Cathode	positively charged electrode
Electrolyte	conducts charged ions (protons), transports dissolved reactants to the electrodes
Catalyst	facilitates the reaction

The fuel cell works by ionising the hydrogen at the anode. The hydrogen ions then travel through the electrolyte to combine with the oxygen at the cathode to create water. The by products of this reaction are heat and electricity. One major target is to reduce the cost of the fuel cell to make it competitive with existing electricity generating technology (Lakeman and Browning, 2001).

The seven most widely used fuel cells are: Phosphoric Acid fuel cell (PAFC); Proton Exchange Membrane fuel cell (PEM); Molten Carbon fuel cell (MCFC); Solid Oxide fuel cell (SOFC); Alkaline fuel cell (AFC); Direct Methanol fuel cell (DMFC) and the regenerative fuel cell. Table 8.1 gives typical uses and operating temperature range of these full cells.

Table 8.1 Fuel cell uses and operating temperatures

Fuel Cell Type	Uses	Operating Temperature °C
Alkaline	Space and Transport	50-200
Proton Exchange Membrane	Transport and Mobile Equipment	80-200
Direct Methanol	Space, Transport, Small CHP and Mobile Equipment	50-80
Phosphoric Acid	CHP and Power Plant	190-210
Molten Carbonate	CHP and Power Plant	600-650
Solid Oxide	CHP and Power Plant	600-1000

Taken from Kruse *et al.*, (2002)

The phosphoric acid fuel cell (PAFC) uses an acidic electrolyte, the electrolyte consists of a thin film of phosphoric acid held in place by a fluorocarbon bonded silicon carbide matrix. The catalyst is usually a precious metal such as platinum. The PAFC, the most commercially developed fuel cell, is usually associated with energy outputs above 200kW and is already used for stationary applications in hospitals, nursing homes, hotels and schools for back up power generation (Heinzman *et al.*, 1999, Newsholm, 2003). Woking Borough Council is the first council to commercially use a stationary phosphoric acid fuel cell in the UK. The phosphoric acid fuel cell has a low efficiency (35-45%) and is tolerant to carbon dioxide impurities (Kruse *et al.*, 2002).

The alkaline fuel cell (AFC) was used on the Apollo flights and NASA space shuttles; it uses an aqueous potassium hydroxide as an electrolyte and uses non precious metals as catalysts. The AFC is being tipped as the most likely fuel cell to be used in the advent of a hydrogen based economy; this is due to efficiencies of 70% and ease of scalability. However, the liquid electrolyte is very corrosive. The fuel cell is also very sensitive to carbon dioxide; carbon dioxide impurities impair the efficiency of the fuel cell (Newsholm 2003, Kruse *et al.*, 2002). Until recently, these fuel cells have been very expensive. However, fuel cell manufacturers ENECO have recently been working successfully on reducing these costs.

The Proton Exchange Membrane (PEM) fuel cell has been developed since 1959; it consists of a fluorocarbon polymer that will allow the passage of protons from the anode to the cathode. These fuel cells like the phosphoric acid cell are tolerant to carbon dioxide, but are carbon monoxide sensitive; the carbon monoxide reduces efficiency of the cell. PEM's have high power densities, the ability to vary output, quick start up times and an ability to operate at relatively low temperatures (80ºC). This makes them ideally suited for small to medium sized applications and vehicle applications. They are however very expensive and difficult to manufacture. For more information on fuel cell costs see Section 11.2.4.

The solid oxide fuel cell (SOFC) is a high temperature cell (1000ºC) where the electrolyte is made from hard non-porous ceramic and has a cheaper catalyst than the PEM or the PAFC. SOFC's are very resistive to poisoning and can be fed fossil fuel directly where it will be internally reformed; the maximum efficiency of this process is 60%. However, there are difficulties when operating at high temperatures particularly with the stability of materials.

Molten Carbon fuel cells use a molten metal carbonate suspended in a porous ceramic matrix as an electrolyte, and non precious metals catalysts. This fuel cell can directly use fossil fuels where internal reforming to hydrogen takes place. This high temperature fuel cell (650ºC) is not easily damaged by impurities, The electrolyte is however highly corrosive, which leads to low durability of these systems.

A significant amount of research is currently being undertaken to develop the regenerative fuel cell. The regenerative fuel cell is advantageous compared with other fuel cells in that it in principle can create and use hydrogen in a closed loop cycle. Only one cell would be needed instead of a separate electrolyser and fuel cell, making the cell more attractive by reducing the amount of material used and reducing costs. However, in a regenerative fuel cell the catalysts required for the fuel cell and electrolyser functions cannot yet be optimised to the same efficiency as individual fuel cell or electrolyser units.

Research challenges:

- Development of cost-effective fuel cells at a range of scales
- Research on environmental impact of platinum needed for fuel cells and sustainable fuel cells.

8.1.2 Biological fuel cell

Biological fuel cells are able to use several (normally organic) substrates as a fuel, and some, discussed here, use hydrogen. Biological fuel cells use enzymes such as hydrogenase to oxidize hydrogen and produce a current. The catalyst in the biological fuel cell is the enzyme, therefore precious metals (such as platinum) are not needed (Halme *et al*., 2000). Enzymes can be immobilized on sustainable produced solid surfaces (e.g. carbon). Work is being carried out on the use of heterogeneous catalysts by Lamle *et al.* (2003), and on inorganic artificial catalysts based on biological modles by Prof C J Pickett, Department of Biological Chemistry, John Innes Centre, Norwich, UK. If biological fuel cells using hydrogen to produce electricity could be made viable, the materials for their construction could be sustainable and environmentally benign.

8.1.3 The Internal Combustion Engine

Petrol engines have been converted to use hydrogen since the 1930's when Rolf Erren developed the Erren Engine. His methods were also used during the 1970 oil crisis to modify cars to run on hydrogen (Kruse *et al.*, 2002). Hydrogen internal combustion engines are 20% more efficient than petrol engines, but like all heat engines they are limited by the efficiency of the Carnot cycle. The hydrogen internal combustion engine suffers knock, this is caused by auto ignition of un-burnt fuel in the "end gas region"; this can be overcome by spark timing but compression rate and intake temperature have the most effect (Li and Karim, 2004). Most of the research that has been carried out aims to modify existing petrol engines but up to 15% hydrogen can be added without the need for any adjustments (Kruse *et al.*, 2002). The use of hydrogen in an internal combustion engine does not provide a completely emission free propulsion system, as the burning of hydrogen in air will produce some NOx. Work is being carried out to identify ways of reducing the NOx emissions from engines.

8.1.4 Turbines

Hydrogen is similar to conventional fuel when used in a turbine or jet engine. However, the temperature can be increased when using hydrogen; and this will lead to an increase in overall efficiency (Lakeman and Browning, 2001). The advantage is the reduction of greenhouse gases with a small amount of NOx being the only pollutant (if pure hydrogen is burnt in air). Several coal gasification plants have gas combustion chambers that burn syngas (hydrogen based gas, see Section 5.1.2.). Syngas is a by-product of coal gasification hence the burning of syngas will produce carbon dioxide emissions contributing to the greenhouse effect. Turbine technology is currently cheaper than fuel cells and may be used as a transition technology (Kruse *et al.,* 2002).

8.2 End Uses

Hydrogen has an important role in both transport and stationary applications, especially when the hydrogen is derived from renewable sources. We can see from Figure 8.3 how the mix of energy end-uses in the UK is distributed. In the following section, we will show how hydrogen can help to displace fossil fuel in the predominant end uses of transport and household, and also investigate the role of hydrogen in energy balancing renewable energy.

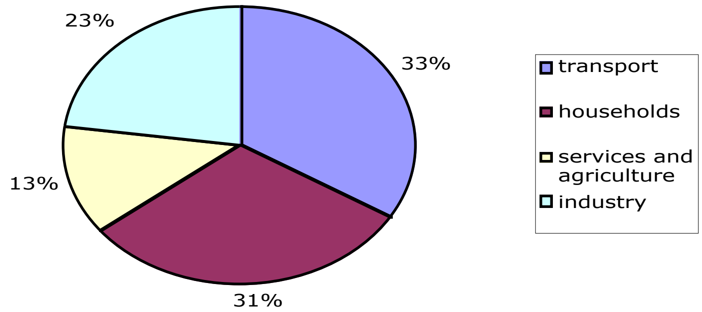


Figure 8.3 Energy use in the UK (derived from DTI, 2004)

Transport

As we can see from Figure 8.3. the largest energy use sector is transport. Transport has been the single largest user of energy in the UK for the last 17 years. Energy demand has increased 92% between 1970 and 2002 (DTI, 2004) and up to 98% of this is petroleum based. The overwhelming majority of all journeys in the UK made by road vehicles are made by cars (Foley, 2001). There is growing dependence on the car and thus dependence on fossil fuel. The environmental effects of road transport can increase climate change; the green house gases that occur in vehicle emissions are carbon dioxide and nitrous oxide. In Wales road transport is the single largest source of greenhouse emissions after power generation and the iron and steel industry. Road transport contributes 12% of overall CO_2 emissions in Wales (4.7% UK emissions). Hydrogen vehicles are seen as a cleaner means of transport (Heinzman *et al.*, 1999, Foley 2001), by improving air quality in highly populated urban areas. If based on a fuel cell, an important ancillary benefit is that transport noise could be much reduced.

Eight major car manufactures are currently developing prototype hydrogen cars, (for example Ford, DaimlerChrysler, BMW) (Chapman, 2002). Ford, Honda, Toyota and DaimlerChrysler are among the car manufacturers that have developed a range of fuel cell run cars (Hydrogen Fuel Cell Letter, 2002). Currently the fuel cell is expensive and bulky for private cars so in the near term ICE may be used as a transition technology until the fuel cell becomes competitively priced. BMW have developed a combined hydrogen/petrol IC engine that allows the driver to fill up on either hydrogen or petrol. This would be useful during the transition to a hydrogen economy (Pidmore and Bristow, 2002). Heffel (2002) has been investigating ways of reducing NOx emissions by changing the operating parameters of the ICE engine. Fleet cars are likely to be the first cars to be converted to hydrogen as they, like buses, operate within confined locations and can be serviced by small hydrogen filling stations owned by the fleet owners.

Hybrid vehicles can utilise the maximum amount of energy from the hydrogen through combining fuel cell and combustion technology. The fuel cell can utilise ~60% of the energy while the rest is lost as heat. If the exhaust gas is then used in a turbine it can increase the efficiency of the system to a maximum of 80% (see Section 6.2.1).

Buses, unlike cars, are built to order, allowing manufacturing operations to be easily optimised. The majority of hydrogen buses that have been demonstrated (see for example the CUTE project, Section 4.2.1) have used compressed gas, which has been stored on the roof. The commercial availability of hydrogen buses is expected in the next year. As buses follow a known route and travel specified distances the infrastructure would be relatively simple. Oslo is expecting to have 125 buses on the roads by 2010 (Kruse *et al.*, 2002).

Stationary

Stationary fuel cell systems can be used to provide heat and power for small to medium sized buildings. A system can be built to service anything from a small house to community buildings. PEM fuel cells, PA fuel cells and SO fuel cells are particularly suitable for small-scale residential heating schemes. The advantages of these systems are that they are quiet, excess heat can be used in heating and hot water production for surrounding buildings and there is no need to reinforce the grid. Hydrogen technologies are ideal for rural areas as hydrogen that is produced and stored locally can be used to power communities where grid connection is poor or needs replacing. These fuel cell systems can also be used for back up in emergencies, when loss of power can endanger lives (Kruse *et al.*, 2002). Smallscale applications may be excessively expensive at present, but may be economically feasible in areas (particularly rural) where existing energy is already expensive.

The stationary application of hydrogen is an area of much research. Kazim and Veziroglu (2002) recently carried out mathematical modelling to identify the role of PEM fuel cells in the diversification of electricity production in the United Arab Emirates. They concluded that the transition would ease pressure on natural resources and provide economic savings. The advantage of this type of modelling is that the programme can be adapted for countries that have similar economic and energy situations.

In recent years micro fuel cells have been developed as replacement for batteries in cell phones, laptops and video cameras. The fuel cells are designed to last ~5 years

Energy Balancing

Hydrogen can be used in conjunction with renewable energy technologies to increase the attractiveness of renewable energy under NETA. In the longer term this may be important to minimise frequency and voltage disturbances with higher proportions of RE in the overall electricity supply system. Consideration must be given to cost e.g. does the cost of the electrolysis, storage and re-conversion justify the predictability and thus the economic return associated with it through the NETA agreement (DTI, 2002b).There are short-term benefits by including hydrogen as a balancing mechanism within the current electricity trading arrangements The hydrogen can be used as a buffer between the renewable energy source and the grid thereby overcoming the intermittency that is synonymous with renewable energy (DTI, 2002b) . The advantage of using hydrogen in a renewable energy system is that the full potential of the technology can be harnessed, and the predictability overcomes the need for a fossil fuel powered baseline on the national grid. A number of hydrogen/renewable energy systems have been tested; the Pheobus project utilised photovoltaic/hydrogen in a system that run for 8 years. Wind/hydrogen systems have successfully been tested in Germany, Norway and Argentina (Kruse *et al.*, 2002).

9. Safety Standards

Today hydrogen is classed as an industrial gas. The term "industrial gases" refers to gases such as acetylene, argon, ammonia, carbon dioxide, chlorine, hydrogen, oxygen, nitrogen, etc., used in a wide range of applications Consequently the current regulations make the use of hydrogen as an energy vector difficult.

"Hydrogen technologies should provide at least the same level of safety, reliability and comfort as today's fossil fuel energy carriers" EHEC , 2003

9.1. Introduction to chemical hazards

The types of hazards associated with hydrogen are physiological (such as frostbite, respiratory ailment and asphyxiation), flammable/explosive atmospheres (chemical) and mechanical (e.g. embrittlment), as discussed in NASA, (1997).

9.1.1. Mechanical Effects

Hydrogen has a very low diffusion co-efficient that enables it to permeate through materials and seals that would stop most gases. Specific flanges and seals need to be used

Hydrogen has an embrittling effect in metals and non-metals causing fractures, cracks and deterioration in the mechanical properties of metals. Hydrogen embrittlment is affected by a number of variables including: *Hydrogen: concentration, pressure, temperature, purity, impurity and moisture content. Metal: composition, tensile strength, microstructure, grain size and heat treatment history.*

There are three types of hydrogen embrittlement: Environmental hydrogen embrittlement, internal hydrogen embrittlement and hydrogen reaction embrittlement (see Table 9.1).

Table 9.1 Causes and consequences of hydrogen embrittlement

Type of embrittlement	Cause	Consequence		Temperature
Environmental hydrogen embrittlement	Plastically deformed in gaseous hydrogen environment	Increased surface cracks, losses in ductility, decreases fracture stress	Cracks start at surface	200-300ºK
Internal hydrogen embrittlement	Caused by absorption of hydrogen	Premature fractures in metals, little or no warning	Cracks start internally	200-300ºK
Hydrogen reaction embrittlement	Absorbed hydrogen chemically combines	Forms brittle hydride	Forms brittle hydride	above room temperature

(Derived from NASA, 1997)

Face centre cubic metals are very resistant to embrittlement (with the exception of nickel). Metals used for hydrogen applications are copper aluminum alloys and austenic stainless steel; mild steel should not be used in pipes. Normal carbon steel is used in gaseous hydrogen applications but not at low temperature (~20ºK); steel becomes more susceptible to embrittlement with higher purities of hydrogen. The adverse effects of hydrogen increase with alloy strength and/or tensile stress levels.

9.1.2. Physiological Effects

Hydrogen is classified as non-toxic and is not listed as a carcinogen but is an asphyxiant although hydrogen has no threshold limit value.

Hydrogen has potential effects that may include:
possible eye and skin irritation, low hazard of ingestion for usual industrial use, but inhalation may cause respiratory tract irritation, low doses may have a narcotic effect, and higher doses may cause asphyxiation and death (Fisher Scientific, 2003). The reasons for hydrogen-caused injuries are given in Table 9.2.

Table 9.2 Reasons for hydrogen-caused injuries

Injury	Reason
Asphyxiation	This can occur when a person enters a region with high hydrogen concentrations
Rupture	This can be caused by a blast wave of detonation or explosion
Frostbite	Caused when skin is in prolonged contact with liquid hydrogen
Burns	Caused by fire, explosion or detonation

Derived from the guidelines in NASA (1997)

Liquid hydrogen could come into contact with the skin during leaks or spills, which are most likely to occur through mechanical failure (such as brittle failure, deformed seals and gaskets, vessel misalignment, or failure of flanges).

9.2. Specific Combustion Hazards

The primary hazard is ignition and flammability; implementation of safety precautions and the application of safety standards reduce these risks.

9.2.1. Fire Hazards

When flammable materials are present, there is always a risk of fire and hydrogen is no exception. A fire is a non-explosion fuel-oxygen combustion event. One of the differences between a hydrogen fire and conventional fossil fuel fire is that it is not always possible to tell if a hydrogen fire is extinguished. An example of a hydrogen fire was shown in a presentation by the Health and Safety Laboratory (HSL) (Butler, 2004). The heat signature of the fire was compared to the visual signs of fire demonstrating that due to the nearly invisible flame, hydrogen fires are difficult to detect. A simple method to detect fires is by throwing particulates such as dirt in the area of the suspected fire or placing a brush in the flame; this will create a visual sign of fire as the particles/bristles fluoresce. High tech methods as implemented by fire brigades involve the use of heat detectors or ultra violet detectors.

Hydrogen can be ignited by very low energy (1mJ). Static discharge can be created through the leaking of a hydrogen pipe; the hydrogen passing the pipe creates a build up of charge and holds enough energy to ignite hydrogen. Hydrogen has a very fast travelling flame and burns with a low radiative heat so that only the area in close proximity to the flame will be hot.

9.2.2. Explosion Hazard (deflagration)

Hydrogen is a highly flammable gas with a large explosive range (4-74% vol). It is also possible for flammable vapours to travel back from an ignition source to the source/point of the leak and cause a flash back. The ignition energy needed for 4%v/v upwards is 1mJ. Deflagration can cause injury and property damage. The features of hydrogen explosions are reviewed in Table 9.3.

Hydrogen is particularly difficult to detect due to the absence of visual or odour properties. Hydrogen is light and disperses very quickly into the atmosphere and normally away from the area of hazard. The buoyancy of hydrogen reduces the risk of explosive atmospheres forming in a well-ventilated area. In a confined space, such as a garage, the build up of hydrogen would not be noticed due to its physical properties. An overlooked leak could allow the hydrogen to increase in concentrations leading to the creation of an explosive atmosphere. There is currently a great deal of work being carried out to create cheap hydrogen detectors as reported by Lakeman and Browning (2001). An alternative solution avoiding the build up of an explosive atmosphere is the integration of venting in the roofs of garages etc. Allow the hydrogen to escape (DTI 2002b). Students at Penn State University are working to enable hydrogen to comply with US government mandates by giving hydrogen an odor (Penn State, 2002).

Table 9.3. Features of hydrogen explosions

Time scale	Slow
Energy output	Low
Combustion mixture	Premixed
Lower explosion limit	4%v/v
Higher explosion limit	74%v/v
Energy ignition	1mJ
Theoretical overpressure	0.8MPa (8 atmospheres)

Derived from Cadwalader and Herring (1999)

9.2.3. Detonation hazard

A detonation is a combustion event, where the combustion wave front is supersonic in the un-reacted medium. Detonation limits are between 18-59%v/v of hydrogen in air and ignition energy is in the range of 10kJ. A detonation event can cause injury leading to death and serious property damage to buildings and exposed equipment. Detonations cause more damage and are more dangerous than ordinary explosions (deflagrations), as the damage is caused over a much larger area. It is possible to cause deflagration to change to detonation when there is a high concentration of hydrogen in the air (>18.3%) and a combustion wave pressure reflection that will increase the speed above 350m/s. Features of hydrogen detonations are given in Table 9.4.

Table 9.4. Features of hydrogen detonation

Time scale	Fast
Energy output	Large
Combustion mixture	Premixed
Lower detonation limit	18.3%v/v
Higher detonation limit	59%v/v
Energy ignition	10kJ
Theoretical overpressure	2.44Mpa (14.5 atmospheres)

Derived from Cadwalader and Herring (1999)

9.3. Comparison of hydrogen with other fuels

The alternatives to hydrogen that are currently available include: methane, propane, methanol, gasoline and diesel (see Table 9.5). In an open space the buoyancy of hydrogen/air mixtures means they disperse quicker than with natural gas/air. However, in confined areas there is a significant risk of explosion specifically where there is unprotected electrical equipment. The National Hydrogen Association (NHA) considers hydrogen less dangerous than propane and more dangerous than natural gas in relation to the minimum flammability range. Hydrogen also has an auto ignition temperature of 585°C, higher than both propane and natural gas.

Table 9.5. Comparison of the specific properties of selected fuels.

Fuel	Min Flammability Range	Max Flammability Range	Auto-ignition temperature ˚C
Hydrogen	4%	74%	585
Methane	5.50%	15%	540
Propane	2.20%	9.60%	490
Methanol	6%	36.50%	385
Gasoline	1%	7.60%	230
Diesel	0.60%	5.50%	

College of the Desert 2001

As explained in Section 9.2 the combustion hazards of hydrogen have been well documented allowing the comparison with other alternative fuels. In comparison with gasoline hydrogen offers some attractive features, as the diffusion coefficient of hydrogen is so high any hydrogen leak would disperse very quickly. Hydrogen has a lower theoretical explosive energy and higher detonation limits in air and lower flame temperature than petrol. However, the convenience of having a liquid fuel has to date led to a customer preference for petrol. The nearest similar fuel is natural gas which like gasoline has lower limits of detonation, higher theoretical explosive energy and a lower diffusion coefficient. It can be seen in Table 9.6. that the differences between natural gas and hydrogen are smaller than those between gasoline and hydrogen.

Table 9.6. Comparisons of detonation and explosion ranges of specific fuels

	H_2	Natural Gas	Gasoline
LHV	120MJ/kg	38-47MJ/kg	43MJ/kg
Phase	Gas	Gas	Liquid
Toxic effect	Non –toxic, asphyxiant	Non –toxic, asphyxiates	Poisonous, irritant to lungs, stomach and skin
Flame Temperature (°C)	2045	1875	2200
Limits of Detonation in Air (Vol. %)	13-65	6.3-13.5	1.1-3.3
Theoretical Explosive Energy (kgTNT/m^3 gas)	2.02	7.03	44.22
Diffusion Coefficient in Air (cm^2/s)	0.61	0.16	0.05

9.4. Standards and Regulations

Codes and standards need to be implemented in order to develop the hydrogen economy quickly. Standardized fittings are essential if the freedom to fill up at any fuelling station is to be maintained. International standardization of coupling will be paramount to facilitate trade in vehicles and equipment (Ohi, 2002).

The differences between regulations and standards:

- Regulations - are compelling; they are expressed as laws and are initiated by political bodies. Regulations relate to applications but not materials.
- Standards - are not legal requirement; they support free exchange of goods and are made by interested parties such as trade bodies. Standards are not mandatory, but give to products manufactured according to such 'harmonized' standards a 'presumption of conformity' to the essential legal requirements in the directives.

To review each country's safety standards requirement would be an epic task. A hydrogen vehicle has to comply with existing laws and legislation in order for it to be approved and it is impossible to meet every country's requirements with one vehicle design. However, many of the laws and legislations are outdated and do not address the challenges of a hydrogen fuelled vehicle. Within Europe, a vehicle needs to comply with 47 different directives in order to achieve approval (EIHP, 2003a). Due to the absence of standardized reference fuel or engine power testing, the hydrogen vehicle cannot comply with the directives relating to emissions, fuel consumption and engine power. There are also specific hydrogen safety issues that are not covered by these directives, such as standards relating to safety of on-board storage systems (EIHP, 2003a).

The development of global safety regulations and standards are an essential element of developing a hydrogen economy. Standardisation allows a platform of commonality, which reduces trade friction, lowers cost, speeds product development and helps corporations be more flexible in meeting customers' needs.

There are a number of organizations developing safety standards in response to the growing interest in hydrogen-fuelled vehicles. Some of the groups working on safety standards include The International Standards

Organization (ISO), The Economic Commission for Europe (ECE) and the US Department of Energy. This legal framework for the ISO standards is provided by the World Trade Organisation (WTO) as the member countries must accept products that meet an agreed safety level. These rules have been set in an effort to eliminate discrimination; the product would meet these levels if it complied with either IEC or ISO standards.

The UK Health and Safety Laboratory (HSL) are currently developing working groups to identify current legislation and standards.

Synopsis of standards and regulation bodies

The following section will introduce a selection of standards organisations and regulation bodies and the present information on recent guidance and regulation. For a Glossary see Appendix 3.

Comité Europeén de Normalisation (CEN)

CEN is a formal process to produce standards, shared principally between 22 national members and the experts assembled from each country. These members vote for and implement European standards. CEN works closely with the European Committee for Electrotechnical Standardization (CENELEC), the European Telecommunications Standards Institute (ETSI), and the International Organization for Standardization (ISO). It also has close liaisons with European trade and professional organizations.

CE marking - The ce mark is the official marking required by the European Community for all electric- and electronic equipment that will be sold, or put into service for the first time, anywhere in the European Community. It proves that the product fulfils all essential safety and environmental requirements as they are defined in the European directives. Committees in the member states contribute and finally vote for (or against) the resulting standards.

International Standards Organization (ISO)

Within the ISO the Technical Committee 197 (see Table 9.7) is directly responsible for the development of hydrogen specific safety standards.

Table 9.7. ISO TC 197 Working group topics

WG	Topic
1	Liquid hydrogen – land vehicle fuel tanks
2	Tank containers for multi modal transportation of liquid hydrogen
3	Hydrogen fuel – Product specification
4	Airport hydrogen fuelling facility
5	Gaseous hydrogen blends and hydrogen fuels – Service stations and filling connectors
6	Gaseous hydrogen and hydrogen blends- land vehicle fuel tanks
7	Basic considerations for the safety of hydrogen systems
8	Hydrogen generators using water electrolysis process
9	Hydrogen generation using fuel processing technologies
10	Transportable gas storage devices – hydrogen absorbed in reversible metal hydrides

Working Groups are currently developing a number of hydrogen specific standards. Only five standard have been published, see Table 9.8 for current status of ISO standards. However, it is worth noting that the UK is not participating actively in the creation of the standards (ISO, 2003). Standards such as the ASTM, DIN, CEN and ISO are not legal requirements; standards only achieve a legal status if there is a reference to the standard in a legal requirement.

Table 9.8. Status of ISO standards

ISO	Title	Stage	Ref*
13985	Liquid hydrogen – land vehicle fuel tank	Draft International Standard	[a]
13984	Liquid hydrogen -- Land vehicle fuelling system interface	Published 1999	[c]
14687	Hydrogen fuel –product specification	Published 1999, cor- 2001	[c]
13986	Tank container for multimodal transportation of liquid hydrogen		[a]
15594	Airport hydrogen fuelling facility operations	Published 2004	[b]
15866	Gaseous hydrogen and hydrogen blends – service stations	Committee Draft	[b]
15869	Gaseous hydrogen and hydrogen blends – land vehicle fuel tanks	Committee Draft	[a]
15916	Basic considerations for the safety of hydrogen systems	Published 2004	[b]
16110	Hydrogen generators using fuel processing technology	Committee Draft	[c]
16111	Transportable gas storage devices – hydrogen absorbed in metal hydrides	Committee Draft	[c]
17268	Gaseous hydrogen land vehicle fuel connections	Working Draft	[b]
22734	Hydrogen generators using water electrolysis process	Committee Draft	[c]

*Derived from: [a] Bose and Gingras, 2000 [b] ISO website (ISO, 2004), [c] Dey, 2003

International Electrotechnical Commission (IEC)

The International Electrotechnical Commission (IEC) is the leading global organization that prepares and publishes international standards for all electrical, electronic and related technologies. These serve as a basis for national standardization and as references when drafting international tenders and contracts. The IEC set up the first committee to begin standardization of fuel cells – Technical Committee 105. IEC/TC 105 developed safety standards for the emerging fuel cell market. One of the most important tasks of IEC/TC 105 is to design standards that do not inhibit further development. Working groups are listed in Table 9.9 and the status of IEC standards in Table 9.10. The IEC/TC 105 works closely with ISO.TC 197.

Table 9.9. IEC TC 105 Working group topics

WG	Topic
1	Terminology
2	Fuel cell modules
3	Stationary fuel cell power plants- Safety
4	Performance of fuel cell power plants
5	Stationary fuel cell power plants – installation
6	Fuel cell systems for propulsion and auxiliary power units (APU)
7	Portable fuel cell appliances – safety and performance requirements

Table 9.10. Status of IEC standards

Project code	Title	Stage
IEC 62282-1 TS Ed. 1.0	Fuel cell technologies - Part 1: Terminology	Draft approved for Committee Draft with Vote
IEC 62282-2 Ed. 1.0	Fuel cell technologies - Part 2: Fuel cell modules	Approved for FDIS circulation
IEC 62282-3-1 Ed. 1.0	Fuel cell technologies - Part 3-1: Stationary fuel cell power plants - Safety	Approved New Work
IEC 62282-3-2 Ed. 1.0	Fuel cell technologies - Part 3-2 : Stationary fuel cell power plants - Test methods for the performance	Draft circulated as Committee Draft with Vote
IEC 62282-3-3 Ed. 1.0	Fuel cell technologies - Part 3-3: Stationary fuel cell power plants - Installation	Approved New Work
IEC 62282-4 Ed. 1.0	Fuel cell technologies - Part 4: Fuel cell system for propulsion and auxiliary power units (APU)	Approved New Work
IEC 62282-5 Ed. 1.0	Fuel cell technologies - Part 5: Portable fuel cell appliances - Safety and performance requirements	Approved New Work
PNW 105-61 Ed. 1.0	Micro Fuel Cell Power Systems – Safety	Proposed New Work

(EHEC, 2003)

European Integrated Hydrogen Project (EIHP).

The EIHP has been created to amalgamate and harmonise the necessary European legislation for the use of hydrogen in vehicles. The EIHP regulations are unique in that once the European Economic Commission (CEN) approves the drafts, the regulations will replace national vehicle standards in Europe.

In Europe, the EU directives and the European Community and ECE regulations of the Economic Commission for Europe are responsible for harmonizing legal requirements (EIHP, 2003c). The ECE is a United Nations organization, consisting of a consortium of countries and is free for the accession countries. Members include the European Union, the United States of America, Australia and Japan (EIHP, 2003c).

In order to facilitate the approval of hydrogen vehicles the ECE created the European Integrated Hydrogen Project (EIHP). The aim of the EIHP is to harmonize the necessary European legislation for the use of hydrogen in vehicles. Phase 1 of the EIHP attempted to find a suitable platform for a pan-European harmonization of infrastructure components, however this failed to be identified. Phase 2 of the EIHP project aims to monitor drafting of standards for harmonization which define refueling and inspection procedures and develops standards for public garages and tunnels. The organization has now developed concepts for safety and standardization of vehicles and is working towards harmonizing regulations (EIHP, 2003f).

To date the EIHP has drafted two regulations, one relating to the use of liquid hydrogen, which includes:

I. Specific components of motor vehicles using liquid hydrogen
II. Vehicles with regards to the installation of specific components for the use of liquid hydrogen

and another relating to the use of compressed gaseous hydrogen, which includes:

I. Specific components of motor vehicles using compressed gaseous hydrogen
II. Vehicles with regard to the installation of specific components for the use of compressed gaseous hydrogen. (EIHP, 2003b)

The EIHP also intends to develop codes of practice for hydrogen refueling stations, standardization of interfaces involved in refueling, standardization of on board storage pressure for compressed gaseous hydrogen and further development of world wide harmonized and accepted regulations. The EIHP regulations are unique in that once the European Economic Commission (CEN) approves the drafts, the regulations will replace national vehicle standards (in Europe). As CEN is an arm of the United Nations, they also have the ability to request all United Nations members to adopt the regulations (NHA, 2002b).

The first steps to developing globally harmonized international standards for fuel cell vehicles occurred in January 2002 when experts from the US, Japan, Germany met with representatives from ISO TC 22 SC21 (electric powered road vehicles) to work on the development of globally harmonized international standards. The development of fully harmonized standards will allow free trade throughout the world. However, it is expected that to develop these standards and gain global consensus will take many years; it is not expected that any global standards will emerge before 2010.

The Vienna Agreement

"The Vienna Agreement is a technical co-operation agreement between ISO and CEN and was created to avoid duplication of standards between ISO and CEN and IEC and CENELEC. This agreement was conducted by ISO and CEN on May 17th, 1991, establishing the mutual technical cooperation in standards development. The agreement defines the joint development of standards, and has permitted the development of DIS (Drafts for International Standards) by CEN. The cooperation in technical committees is promoted by allocating a leading role to either ISO or CEN for each Working Group." (Hido, 2003)

Specific UK Regulations:
The safe handling of hydrogen is paramount for the safe implementation of a hydrogen economy. In the UK the Health and Safety Commission (HSC) and the Health and Safety Executive (HSE) are responsible for the regulation of almost all the risks to health and safety arising from work activity in Britain. Their mission is to protect people's health and safety by ensuring risks in the changing workplace are properly controlled.

The two main examples of regulations relating to the workplace are:

The Health and Safety at Work Regulations 1999, which require employers to identify significant risk presented in the workplace, and to carry out appropriate risk assessment and appropriate measures to reduce the risk as much as is reasonably practicable.

The Dangerous Substances and Explosive Atmospheres Regulation 2002 which classes any fuel that is flammable and presents a significant risk of fire and explosion hazard as a dangerous substance under the Dangerous Substances and Explosive Atmospheres Regulation 2002 (HSE, 2002), the DSEAR Regulations. Where these substances are present these regulations introduce new duties.

The HSE work with various international bodies on occupational health and safety law (OHS). In the European Union, these bodies include the following:

Directorates General of the Commission, European Agency for Safety and Health at Work, Eurostat and the European Committee for Standardisation. The HSE are responsible for negotiating and implementing specific Directives, Standards and Conventions, via domestic legislation

Before developing any hydrogen project in the UK, consultation with the Health and Safety Executive and planning officers in the region are essential in order to comply with all current health and safety legislation.

Risk assessment - a systematic approach to identify and assess potential hazards – implementing measures and controls to minimise risk focused on the most important risk factors. Risk assessment brings cost savings and lower risks from accidents and damage. Risk assessment allows the systematic and safety conscious operation of hydrogen systems.

Hydrogen in the home - All hydrogen gas appliances that are used in a domestic context must be fitted by a CORGI registered fitter under the Gas Safety (installation and use) Regulations 1998 (HSC, 1998).

The DTI are responsible for the design of domestic fuel cells. Once the hydrogen is used in the home with the product being heat the device comes under the Gas Appliance Directive (GAD) (HSE, 2003). If the primary output is electricity then the application does not fall under GAD.

Industrial Safety Codes

Hydrogen has been used in industry for decades during which time safety codes and standards have been developed. These safety standards have allowed the safe use of hydrogen and each one of the large gas manufacturers produces its own supplementary standards. The standards are predominantly concerned with the industrial application of hydrogen. The industrial gas companies work closely with the Health and Safety Executive and British Standards to develop workable hydrogen regulations.

The European Industrial Gases Association (EIGA) - is a technically oriented organisation representing the vast majority of European and a number of non-European companies producing and distributing industrial gases. Most national industrial gases associations are also associated to EIGA. To carry out its work EIGA is in frequent touch with a considerable number of European and International Standardisation and Regulatory Organisations and Authorities as well as a number of trade and industrial organisations.

The British Compressed Gas Association (BCGA) - is the British trade association representing companies in the industrial gases industry that manufacture and distribute gases, manufacture cylinders to contain them or equipment to use them. It is associated to EIGA. EIGA industrial standards being taken up by the HSE are shown in Table 9.11. Its members supply gases and equipment to the electronics, food, medical and scientific sectors. BCGA has substantial representation on the committees of BSI, CEN, and ISO in order to contribute to standards, which will be beneficial in the fields of safety and commerce. In technical and safety matters the member companies co-operate closely with each other and with the authorities to achieve the highest level of safety and environmental care in the handling of industrial gases, which are characterised by demanding physical and chemical properties.

British Standards - are the world's leading provider of standards covering everything from protection of intellectual property to technical specifications. British Standards provides UK industry and other stakeholders with their major access to and influence on standardization, both in the European arena (with CEN, CENELEC and ETSI) and internationally (with ISO and IEC).

Industrial standards are developed by The British Compressed Gas Association (BCGA) and The European Industrial Gases Association (EIGA). Industrial gas companies also develop their own standards which tend to draw on the BCGA and the EIGA standards. The industrial gas companies work closely with the Health and Safety Executive and British Standards to develop workable hydrogen regulations.

Table 9.11. EIGA industrial standards being taken up by the HSE

Type of exposure	Distance from hydrogen source (m)
Open flame, ignition source including unclassified electrical equipment	5
Site boundary areas where people congregate, such as car parks	8
Building, wood frame construction	8
Wall openings in offices or workshops (installation shall not be directly below opening)	5
Bulk flammable liquids or LPG above ground	8
Bulk flammable liquids or LPG under ground	5
Flammable gas cylinder storage other than hydrogen	5
Oxygen cylinder storage	5
Liquid oxygen storage	8
Liquid nitrogen or argon storage	5
Stored combustible material e.g. timber	8
Air compressor and ventilator intakes (installation shall not be directly below such intakes)	8
Activity other than that directly related to the hydrogen installation	5

(HSE, 2003)

Regulations being developed

Regulations and standards differ from country to country, below some examples are shown of examples of regulations and standards from the US, Japan and Canada.

US

The US is reliant on standards as opposed to regulation. There are thousands of state and local code bodies, who use and modify ICC and NFPA codes. America has over 270 standard development organizations. There is currently no development of ICE standards,

The US Department of Energy are working with:

- The National Hydrogen Association (NHA),
- National Renewables Energy Laboratory,
- National Fire Protection Agency (NFPA),
- The Compressed Gas Association (CGA),
- The Instrument Society of America (ISA),
- and the Society of Automotive Engineers (US DOE, 2003d)

Examples of standards in the US include the ASME boiler pressure vessel code, the leading guide for containment of hydrogen in pressurized systems. In most jurisdictions in North America, it has been adopted into regulations governing pressurized systems. Other codes include – FAR and transport of dangerous goods for interstate and inter-provincial transport & IMDG for international marine transport. The most commonly required standard is National Fire Protection Agency Standard NFPA50A+B for the use of gaseous and liquid hydrogen (respectively) at consumer sites. Electrical devices (in the presence of H_2) are covered by US national building code. See Appendix 2 for an extended list of US hydrogen code developing bodies.

The Partnership for Advancing the Transition to Hydrogen (PATH)
This organisation has partner members which include Japan, US and Canada. The PATH sees the development of a global community of interest in hydrogen that works to implement a hydrogen energy future through providing a forum for sharing information, relating relevant experiences, and collaborating in activities, which facilitate the technical and financial implementation of that future.

Japan
The Japanese government have set a target to put into place their entire safety standards and regulations within the next 5 years. JEVA and JASIC address transport and comment on EIHP and SAE output. The National Fire Service address hydrogen infrastructure and the JIS is being developed for fuelling stations in Japan and there are 8 laws that cover the development of hydrogen technology in Japan – for the use of hydrogen outside the national law the government can pass guidelines.

Canada
The standards council of Canada has appointed 4 standard development organizations, including BNQ (who develop H_2 technology standards) and CSA (who develop fuel cell standards). Canada relies on the international community for fuel and fuel cell standards for stationary applications. Canada has hydrogen standards for rail and tanker. Portable applications come under IEC 105 and TC 197. Infrastructure standards are limited to CGA, CEC and NFPA.

9.5. Safety Research

In the absence of historic data and experience, systematic forecasts revealing the hazards must be used to compensate (Swain *et al*. 2002). Research has been carried out over the last 30 years into the safety implications of hydrogen, particularly in simulations that explore the pattern of escape of hydrogen from containers. The simulations can then predict the pattern of hydrogen accumulation within the surrounding spaces. The HSL are actively engaging in developing and corroborating modelling activities and 'real life' simulations of hydrogen leaks and fires.

Many studies have focused on predicting the behavior of hydrogen in rooms; this is due to the need to predict and evaluate the most appropriate safety measures needed to implement the hydrogen economy. Certain aspects of hydrogen safety are known for leaks in enclosed spaces (Swain, *et al.* 2002) i.e. in non ventilated rooms the total volume rather than flow rate affects the level of risk of explosion, This is due to the concentration after a significant release. It can create over pressure and is a greater risk than that posed by a burning jet, whose flame size depends on the hydrogen flow rate. The magnitude of overpressure is a function of gas motion in enclosed spaces. The risk of combustion exists between the total volume of 4.1% and 75% and continues until ventilation or combustion. For leaks in un-enclosed spaces the strongest risk factor is from the flow rate as opposed to the volume escape. The risk of large overpressure caused by the hydrogen/air mixture is small.

However, for hydrogen releases in partially ventilated areas both volume release and flow rate pose a risk and then the geometry of the room affects the accumulation of hydrogen. These attributes have recently been the focus of much research, with models and simulations being carried out. Work by Rehm and Wang (2002) focused on developing a modelling system to simulate the accident related behaviour in safety enclosures. Puzach (2002) has developed a three dimensional mathematical model to simulate heat and mass transfer in non-uniform hydrogen-air mixtures during continual release in a room. The study investigated the affects of mechanical ventilation systems on the hydrogen/air mixtures. It was concluded that burning of non-uniform hydrogen/air mixtures near the floor can lead to the formation of explosive atmospheres away from the hydrogen source. In addition mechanical ventilation was more effective than natural ventilation only in the initial states, the subsequent effect of mechanical ventilation was weak. However, blowing inert gas can change the height of the explosive mixture.

The uses of simulations are important in order to improve safety; this is done through the collection of data to inform policy makers. The testing of simulations with experimental data is equally important (as with the results from Puzach, 2002) and essential to give confidence to the results obtained by the simulation. Other simulations have determined the optimum sensor height for locations within a building with varying degrees of ventilation.

In a recent experiment, a fuel leak was simulated to directly compare petrol and hydrogen cars. The cars were simultaneously ignited and within seconds both cars were alight. The petrol car was engulfed in flames within a minute and continued burning leaving the windows melted and a charred mass. The hydrogen car's fire caused no damage to the interior of the car and maximum temperature inside the car reached 67°C. The quick dispersal of hydrogen caused the fuel to be exhausted and after 100 seconds the fire went out (Swain, 2001)

10. Policy

There is increasing recognition from governments internationally that energy policy is about more than securing enough energy at the right price for the country. An overwhelming amount of evidence has raised considerable awareness of the consequence of human energy consumption on the global condition. Climate change through greenhouse gas emissions and the impact on human health and social well being from air pollutants are now shaping government thinking to a large extent. This has resulted in the emergence of international agreements and a series of national policies to act on these issues.

Many advanced industrial nations have been built on the back of relatively cheap and plentiful energy supplies. However, the oil crisis of the 1970s and a more recent realisation that the bulk of the limited remaining supplies of oil and gas are in regions that are politically unstable have prompted governments to rethink energy supply provision. Securing supplies of energy for long-term prosperity of a nation has become an increasingly critical aspect of energy policy. These factors are also creating the first signs of recognition that breaking an energy paradigm based on fossil fuel dependency may have economic advantages. Governments are gradually starting to appreciate the benefit of promotion of new industries to meet the demand for cleaner energy.

Sustainable hydrogen energy is a logical conclusion to a number of these issues, with the potential to eliminate greenhouse gas emissions, remove the problem of local and trans-boundary pollutants and provide a secure indigenous energy resource that is more evenly distributed among all regions and countries of the world. Countries are moving at a different pace towards this realization. However, the emergence of many national hydrogen energy policies and national and international hydrogen agreements and development programmes indicates a rapidly growing momentum towards the hydrogen economy. This framework document can be seen as an initial outline of the path that Wales can follow to become part of this international advance towards the hydrogen economy.

10.1 Historical Perspective on Hydrogen Energy Policy

Governmental interest in the concept of a hydrogen economy is not new. Indeed initial policy interest in using hydrogen as an energy transport medium has origins in Europe in the early part of the twentieth century, particularly in Germany in the 1930's as a means of achieving energy self-sufficiency (Bockris, 2002). This included a number of successful vehicle trials using hydrogen. During the Second World War, work continued in Germany on hydrogen as a transport fuel and fears of oil supply restriction led the Australian government to consider industrial hydrogen energy (Dunn, 2002). US military work on hydrogen during the war years eventually led to the use of hydrogen in the US space programme (Williams, 1980).

Post-war, the availability of cheap oil and the predominance of oil technology suppressed any further significant interest until the oil crisis of 1973. Shortly prior to this, a small number of dispersed scientists and practitioners had simultaneously started to re-examine the possibilities of hydrogen energy as a response to dwindling fossil fuel resources and also due to environmental concerns (Bockris, 2002). The need for management of oil supply security and a desire for energy policy co-operation led to the creation of the International Energy Agency in 1974 as an autonomous agency linked with the Organisation for Economic Co-operation and Development (OECD). The initiation of the IEA hydrogen programme in 1977 has led to a sustained programme of research and development into many areas of hydrogen as an energy carrier. Despite this international interest demonstrated by the IEA, a combination of the continued availability of cheap oil and nuclear energy growth stalled the wider acceptance of hydrogen energy with most governments, until relatively recently.

10.2 Geopolitical Drivers to Hydrogen Energy Policy

There are a number of shared political drivers leading to the promotion of hydrogen energy. Whilst they are common in global terms, there is a significant difference of stated emphasis in different countries. Each of these themes is mentioned here and discussed in greater depth in the sections that follow.

Climate Change

For many countries, the impact of CO_2 emissions from fossil fuels on the global climate is the most significant environmental driver. To address this, many countries have initiated preferential policies for introduction of renewable energy. However, there is also a growing realisation that intermittency of many renewable energy sources could lead to supply and demand problems once there is a greater proportion of renewable in the energy mix. To overcome this many governments are starting to comprehend that sustainably produced hydrogen is a means to eliminate greenhouse CO_2 and to overcome the discontinuous nature of many renewable energy sources.

In particular, this has emphasis in the EU where there is growing governmental acceptance from member states that hydrogen could have a important role in achieving removal of net carbon emissions from the energy system.

Security of Supply

The recurring theme of security of energy supply is a major driver to the hydrogen economy for most industrialized nations, particularly in the USA and Japan, but increasingly in Europe in the wake of the Iraq war and in a climate of international terrorism. In the case of the USA, recent high levels of activity in the field of hydrogen energy are given major impetus by the US administration’s desire for domestic resource production and freedom from dependency on imported energy (Abraham, 2003). In Japan’s case, a strong desire to overcome its existing reliance on imported energy is an important motivator.

Supply of Affordable Energy

Over the last century, all industrialised economies have been dependant on the availability of cheap oil and gas as the basis of their economic strength. All sectors, particularly transport have benefited from the relatively inexpensive and continuous supply of fossil fuel products. However, the combination of increasing worldwide energy demand and the concentration of the bulk of the remaining oil and gas supply in politically unstable regions provides increasing upwards pressure on oil and gas prices. The ability to produce hydrogen from a range of readily available sources, particularly water using renewable energy provides freedom from increasing oil and gas prices.

Local Atmospheric Pollution

Rarely the major driver, this is nonetheless an important concern for many countries, particularly those with large urban populations. The World Health Organisation (WHO, 2000a) estimate that globally 3 million people a year die as a result of air pollution, the primary cause of this pollution being industry and vehicles. Many of the harmful pollutants released from current fossil fuel combustion can be reduced or completely removed by the use of hydrogen as the energy medium.

Promotion and development of indigenous hydrogen industry

Whilst this may be seen as a consequence of a wider push towards hydrogen energy, national advantage through nurturing indigenous hydrogen energy related industry is an increasingly important driver. This aspect is particularly prevalent in the automotive sector, but also in the wider energy sector. Whilst this is rarely seen as the most prominent driver, this is a common and growing theme, particularly in the USA, Canada, Germany, Japan and now more recently in the UK.

10.3 Geopolitical Barriers to Hydrogen Energy

Clearly, as well as drivers to the hydrogen economy, there are also some barriers to achieving the transition. These barriers are discussed below.

Influence of Fossil Fuels

Despite numerous warnings about the depletion of the world's fossil fuel resources and restricted sources of supply, oil based transport fuels and increasingly gas for electricity are overwhelmingly dominant due to their convenience and relative low cost. Individual government positions vary, but oil, gas and coal continue to dominate international energy supply. Despite recent energy policy objectives to reduce fossil fuel dependency in many countries, respective government transport and energy policies continue to prolong the dominant use of carbon-based energy, especially oil based fuels for transport. Whilst some might expect the major oil companies to be protective of this dominant position, all have considerable hydrogen energy programmes which envisage an eventual transition away from fossil based energy. The progressive tension of increased demand and diminishing resource will continue to erode this barrier to the introduction of hydrogen energy.

Infrastructure Investment Costs

The significant anticipated investment in developing a hydrogen supply infrastructure remains a major barrier. Indeed this is at the root of hydrogen's "chicken and egg" dilemma (US DoE, 2002a); without a suitable infrastructure, mass production of hydrogen applications will not take place; without the substantial demand that mass production would provide, there is little incentive to invest in the infrastructure. Despite this dilemma, the governments of most industrialised countries are now investing effort and money in examining the prospects for a hydrogen energy infrastructure. In addition, manufacturers in the nascent hydrogen energy industry (particularly car manufacturers) lobby for state investment in developing infrastructure.

Technical Barriers

The majority of governments have historically viewed a number of these technical barriers, such as CO_2 sequestration, hydrogen storage efficiency or fuel cell viability as being set too high. In the 1980s, the view was often expressed that hydrogen would only become important in energy terms as a means to upgrade heavier fossil fuels such as coal and residual oil or substitute natural gas (ETSU, 1983) The last decade has seen a progressive shift in this view from the majority of industrialized nations, to confront these technical barriers through investment in research development and demonstration.

Variable Acceptance of Drivers

As demonstrated below, there is different emphasis on and acceptance of the drivers to a hydrogen economy. For example, the EU and its constituent members have arrived at a general acceptance of the impact of CO_2 as a greenhouse gas and have put in place policies aimed at significantly reducing carbon emissions, including mandatory targets for high emitters (European Commission, 2003a). Publicly, the US government is not fully convinced of all of the scientific arguments linking CO_2 and climate change (US DoE, 2003e). They argue that only through sustained economic growth will countries be in a position to invest in the technological developments required to mitigate and prevent climate change. Hence the US administration has put in place policies that link carbon emissions to economic growth and have only put in place voluntary CO_2 emissions schemes. Nonetheless, the USA has implemented a major hydrogen and fuel cell vehicle research, development and demonstration programme. As stated earlier, the USA's hydrogen energy programme is guided primarily by a desire to reduce energy import dependency. Whilst this is a concern in the EU, it has lesser influence. The result of following a hydrogen energy policy driven predominantly by security of supply concerns may be a reduced environmental benefit through the early introduction of hydrogen technology that is too dependent on CO_2 emitting processes. Eyre *et al*. (2002) are concerned that such a "dash for hydrogen" may be less environmentally beneficial than the development of improved energy efficiency through, for example, hybrid vehicles, followed by a later introduction of sustainable hydrogen to the energy system.

10.4 Global Climate Change Politics

"Some of the effects of climate change are by now inevitable and, indeed, we may already be seeing - in the increased incidence of drought, floods and extreme weather events that many regions are experiencing - some of the devastation that lies ahead,"

Kofi Annan, President, United Nations March 19, 2004

10.4.1 International Recognition of Climate Change

"An increasing body of observations gives a collective picture of a warming world and other changes in the climate system." Third Assessment Report of Working Group I of the Intergovernmental Panel on Climate Change (IPCC, 2001a)

Since the industrial revolution, global society has become increasingly dependant on fossil fuels to meet our needs, to the point where some 85% of our global energy demand is met from fossil fuels (Baptiste and Ducroux, 2003). Whilst this has brought great convenience to our lives, it also brings an unwanted legacy.

The Intergovernmental Panel on Climate Change (IPCC) working groups have now collated overwhelming confirmation that anthropogenic emissions have led to an increase in global temperature and hence to climate change. The third Assessment Report of Working Group I of the IPCC indicates that the release of greenhouse gases, most notably CO_2 from the burning of fossil fuels, has contributed to the global average surface temperature increasing by approximately 0.6°C during the 20th century, the largest global temperature increase during one century throughout the previous 1000 years. The 1990s was the warmest decade since records were started in 1861 and the current decade is set to be warmer still. The scientific consensus is that this warming trend will continue and is likely to accelerate if we fail to act by dramatically reducing the quantity of CO_2 emitted. Changes are taking place to physical and biological systems that may be irreversible. The physical impact of this warming include:

- Approximately 10% decrease in global snow cover since the late 1960s
- Widespread retreat of mountain glaciers in non-polar regions
- Significant decrease in the amount of sea-ice since the 1950s
- Global average sea levels have risen between 0.1 and 0.2 metres during the 20th century
- Global ocean heat content increased since observations were started in the 1950s

(IPCC 2001a)

Potentially, adverse human impact will be felt through increased incidence of flooding and intensity of droughts. The consequence is that an estimated 150 million people will be environmental refugees by 2050 (Myers, 1993).

Whilst it is the industrialised nations of the world that have contributed most to this phenomenon, the irony is that the adverse effects will be greatest on those who have contributed least. Those with least resources will have the least capacity to adapt to the consequences of climate change and are therefore the most vulnerable to its impact.

10.4.2 International Agreements on Climate Change

Climate change is a global phenomenon and one that requires global as well as local action. The international policy response to the challenge of global climate change has been inconsistent. As indicated, some governments have fully accepted the evidence and have been willing to put renewable energy programmes in place. Others have been more reticent in realizing their international obligations, only recently taking a positive approach on reducing greenhouse gas emissions. In 1990 the UN General Assembly established the International Negotiating Committee (INC) to negotiate the terms of a framework convention on climate change, which produced the UN Framework Convention on Climate Change (UNFCCC 2002a) in New York in May 1992, which in turn was opened for signature at the Rio Earth summit of the following month. The Convention entered into force in March 1994.

In December 1997 the Kyoto conference of the parties adopted the Kyoto protocol, elaborating on the UNFCCC. (UNFCCC, 2002b) At the end of October 2004, 84 Parties have signed and 126 Parties have ratified, accepted, acceded or approved of the Kyoto Protocol. These countries represent 44.2% of global CO_2 emissions. The EU, responsible for 14% of global CO_2 emissions, has approved the protocol and all member states have ratified. The majority of the other signatories have now acceded, approved, accepted or ratified the protocol or have indicated an intention to do so (as in the case of the Russian Federation). Among notable exceptions to this list of countries are Australia, Indonesia, and most importantly United States of America. At the heart of the Kyoto protocol are the legally binding emissions targets, the subject of intense negotiation during and since the Kyoto meeting. In the Bonn meeting of 2001, a series of compromises to the original targets were made, resulting in a greater level of acceptance amongst wavering governments. However, as is now well known, these compromises were not enough to convince the USA to ratify the treaty.

10.4.3 European Union, Climate Change and Renewable Energy

In international terms, the EU as a whole has adopted a positive attitude to renewable energy with 14% of gross electricity consumption and 6% gross energy consumption coming from renewable sources. Building on the community strategy and action plan "Energy for the future: renewable sources of energy" of 1997, the 2001 EU directive on the promotion of green electricity (from renewable sources) provides a framework to increase the amount of energy from renewables in Europe to 22% of gross electricity consumption by 2010 and gross energy consumption to 12%.

Supported by EU policy, the last decade has seen a dramatic (2000%) growth in wind energy. However, the overall European energy demand is so large that this has only marginally improved the total percentage of renewables in the primary energy mix.

As Figure 10.1 and Figure 10.2 show, there is a significant variability in the proportion of renewable energy production in the total energy provision of each of the European member states.

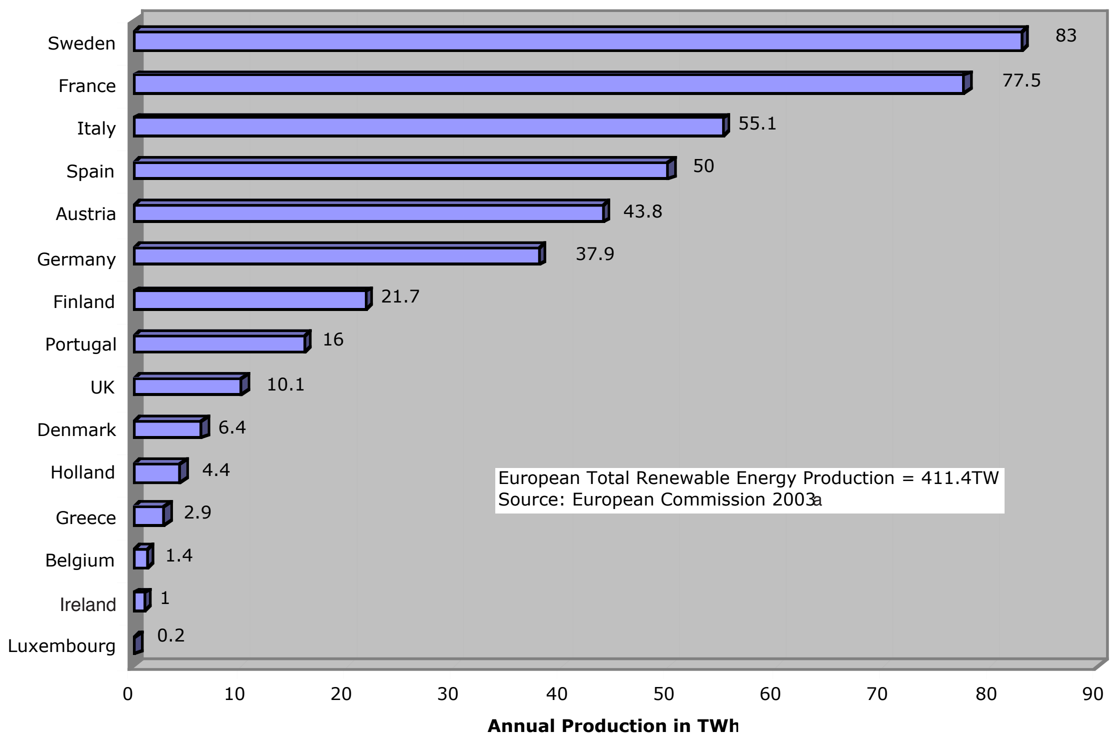


Figure 10.1 Total renewable energy production for European member states for 2001, (European Commission, 2003a).

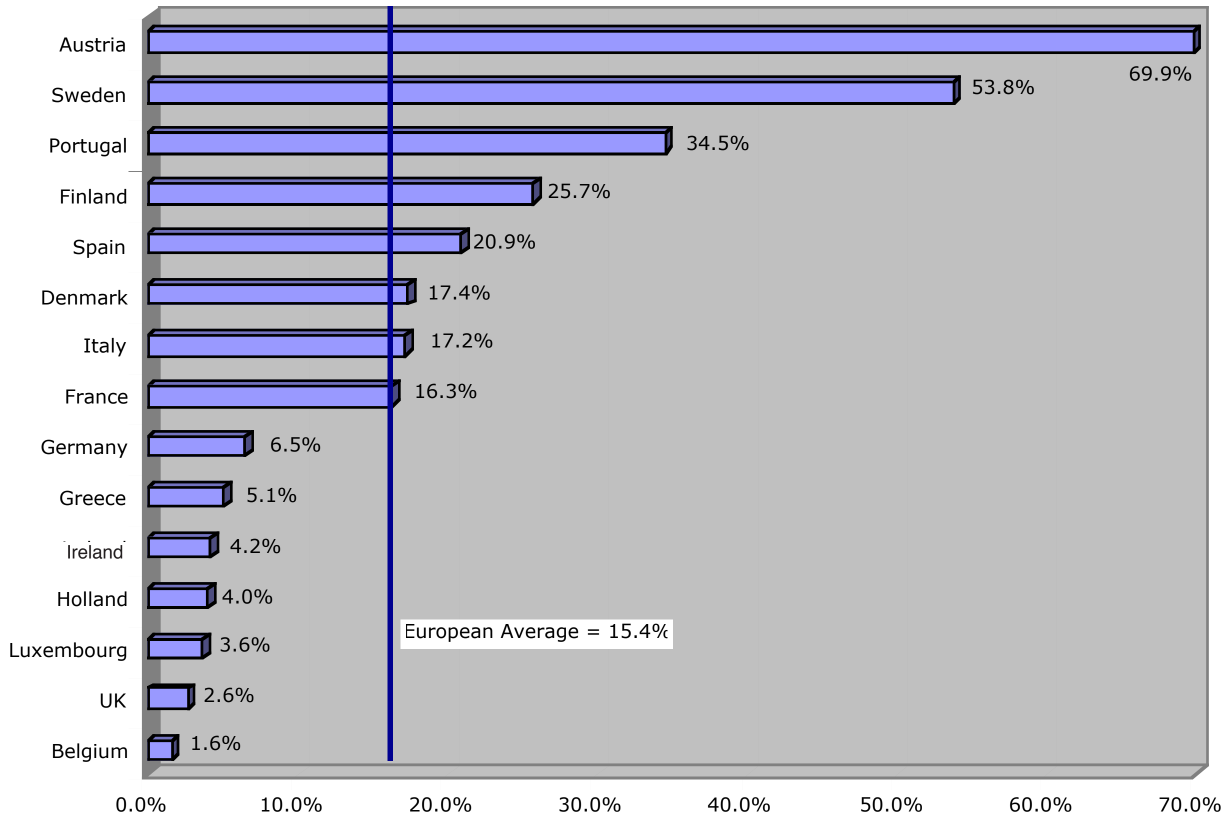


Figure10.2 Share of renewable energy in total consumption % for European member states. (Source: European Commission 2003a)

10.4.4 UK Climate Change Policy Measures

The most definitive statement on UK climate change policy is the recently issued Energy White Paper "Our Energy future – creating a low carbon economy" published in February 2003 (DTI 2003a). A significant part of this policy document is devoted to climate change and the UK's strategic responses. Essentially, the White Paper agrees with the views put forward by the IPCC third assessment report (IPCC, 2001a) on the causes and impacts of climate change and relates the impacts globally and to the UK. It also puts forward an initial (and rising) estimated cost of £70/tC (in range £35 - £140) for the damage cost of carbon emissions (without considering the cost of climate related catastrophes).

Actions to limit emissions highlighted in the White Paper include:

- Ratification of the Kyoto protocol with an emissions reduction target of 12.5% below 1990 levels by 2008-2012 *and* a national target of 20% reduction by 2010 (see section 10.4.7.2)
- Recognising that unilateral action is meaningless, a concerted campaign to establish a consensus for change and firm commitments to reduce global emissions
- Acceptance of the Royal Commission on Environmental Pollution's (RCEP's) recommendation of continual progress towards a long term goal of reduction in carbon dioxide emissions of some 60% from current levels by about 2050 (RCEP, 2000)
- A target of 110-120 MtC total greenhouse gas emissions by 2020 through efficiency programmes in households, industry, commerce and the public sector, transport, increasing renewable energy and through European carbon trading.

- Taking steps to improve the resource productivity of the UK economy – producing more with less pollution, further demonstrating the decoupling of emissions and economic output.

The implementation of the White Paper is being taken forward via the Sustainable Energy Policy Network (SEPN) a cross governmental body which includes a non-governmental Sustainable Energy Policy Advisory Board. In April 2004, as part of the work of SEPN, a report was published entitled 'Creating a Low Carbon Economy - First Annual Report on Implementation of the Energy White Paper', outlining the UK's actions and performance against the White Paper, (DTI, 2004b).

Climate Change Levy

The climate change levy, introduced in April 2001, applies a levy on each kWh of electricity, natural gas, coal or LPG consumed by most businesses and public sector organisations (oil is not included as it already attracts duty). Some nominated energy intensive industries can obtain 80% discounts, but only with climate change agreements and legally binding ten-year energy reduction programmes.

The impact of the climate change levy is that the affected organisations seek energy efficiency improvements and in some cases move to exempted forms of energy such as renewables, or good quality CHP. A substantial amount of the money collected is used for energy efficiency research and capital grants for energy saving equipment.

A criticism of the effectiveness in reducing CO_2 via the climate change levy is that the exemptions let the major CO_2 emitters go without significant economic penalty and that the levy is not applied to domestic users, who account for significant amounts of emitted CO_2 (FOE, 2001). At the same time business, particularly energy intensive areas like the chemical industry, has criticised the levy for damaging the competitiveness of UK industry against international competition (CIA, 2004).

Sustainably produced hydrogen qualifies as being exempt from climate change levy, although natural gas or LPG used to produce hydrogen via steam reforming would normally attract climate change levy. This provides an incentive to produce hydrogen sustainably, or to use hydrogen in conjunction with intermittent renewable energy.

Renewables Obligation

The Renewables Obligation is a pivotal mechanism for supporting the growth of renewable energy in the UK (Connor 2003). Introduced in April 2002, the Renewables Obligation requires electricity suppliers in England and Wales to obtain a specified and increasing proportion of the electricity that they trade from renewable sources. Eligible generators receive Renewable Obligation Certificates (ROCs) for each MWh of renewable electricity that they generate, which can then be sold to suppliers. Suppliers can present these certificates to cover the required percentage of their output and satisfy their obligation. If they cannot supply enough certificates to cover their obligation, they can pay a buy-out price to cover the shortfall. The buy-out price for the third year of the Renewables Obligation is set at £31.39 per MWh until 31st March 2005 when it is likely to be increased by approximately 3%.

The proceeds from any buy-out payments are returned to suppliers in proportion to the number of certificates that they present, thus supporting the renewables industry. It is estimated that this support and exemption from

Climate Change Levy will be worth around £1 billion a year to the UK renewable energy industry (DTI 2003a). Subject to any future repeal, the UK government plans to maintain support through the Renewables Obligation until 2027. The initial obligation stretched to 11.4% of total UK electricity production by 2011/12. This has been reviewed and extended to 15.4% by 2015/16 (Figure 10.3).

Despite being the most significant aspect of policy for the promotion of renewable energy, the impact of the renewables obligation on hydrogen energy may be seen as neutral. In the short term, the renewables obligation provides little incentive as certificates can be obtained through introduction of un-buffered intermittent renewables, such as wind, wave, tidal or solar energy. Alternatively, landfill gas, sewage gas, biomass and energy crops are also eligible and it is entirely conceivable hydrogen can be produced from these schemes as an intermediate in the production of electricity. As indicated elsewhere in this report, as the percentage of electricity generated from intermittent renewable sources increases, there is an increased need to incorporate effective energy storage, potentially in the form of hydrogen. In addition local infrastructure conditions may also promote the inclusion of hydrogen as a buffer to an intermittent renewable energy source.

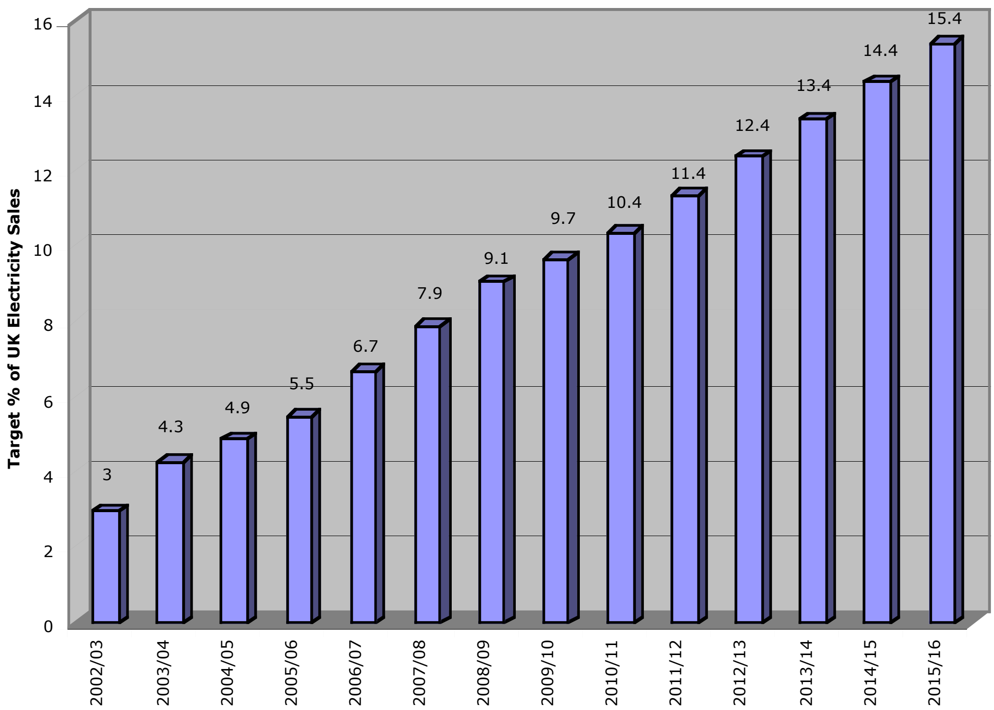


Figure 10.3 Mandated build up of renewable energy until 2016 from the Renewables Obligation

Utilities Act 2000 and New Electricity Trading Arrangements (NETA) and the British Electricity Trading and Transmission Arrangements (BETTA)

The Utilities Act of 2000 introduced a framework for increased competition in the UK energy markets and for energy efficiency targets and imposes the objective of improving electricity and gas consumer protection. The legislation also gave rise to the Renewables Obligation. The Act imposed the separation of supply and distribution through new licensing arrangements, hence stimulating a more open market for energy.

Introduced in March 2001, NETA put in place a market-based trading mechanism for electricity, which abolished the Electricity Pool Purchase Price and the Non-Fossil Fuel Obligations (NFFO). The main objectives of NETA are to encourage competition and provide a mechanism to balance supply and demand in the transmission system.

Unfortunately, NETA has had a negative impact on the less polluting energy technologies, CHP and renewables. The problems caused by NETA for suppliers in these sectors are:

- Difficulties experienced by typically small generators to cope with the administrative demands of the balancing mechanism
- Difficulties of prediction of supply capability, particularly with intermittent renewables

The consequence is that the CHP and renewables generators are disproportionately penalised for not supplying the energy predicted. As a result of these difficulties, the balancing mechanism has been amended to operate more effectively and more amendments are proposed to better reflect cost impact of balancing to small generators (DTI, 2003c). However, NETA in its current format does little to further the stated policy commitment to promote renewable energy.

The British Electricity Trading and Transmission Arrangements (BETTA) are due for implementation in April 2005 and seek to unify the electricity trading arrangements, which exist for England and Wales, and for Scotland. Although specific consultation has taken place to address the issues of small generators, there are only marginal additional benefits for small renewable generators.

Clearly it is possible for renewable electricity supplies to become more reliable through the addition of hydrogen energy storage (Dutton, 2002). The current economics of this option are the only stumbling block as the cost benefits of improved predictability of supply would be offset by the additional cost of installing and operating the hydrogen equipment.

10.4.5 Climate Change Policy in Wales

"The National Assembly for Wales is committed to playing its part in developing and delivering a climate change programme which meets the Kyoto target and moves the UK towards its domestic goal of a 20% reduction in carbon dioxide emissions by 2010"
Welsh Assembly Government Website - *Accessed 5th November 2004*

Under Section 121 of the Government of Wales Act 1998, the National Assembly for Wales has a duty to promote sustainable development. It is therefore appropriate that the Assembly should have an active policy on reducing the impact of climate change through the use of renewable energy.

“Sustainable development is not an option that will go away – sustainable development is the only way forward”
Rhodri Morgan AM First Minister for Wales

The predicted effects of climate change on Wales (NAfW, 2000b) is that there will be:

- An average temperature rise of between 1.1^{o}C and 2.9^{o}C by 2080
- More frequent storms and potential flooding
- A rise in sea level
- Increased rainfall and greater inflow to estuaries and the sea
- Wetter winters drier summers

These climatic changes could have a significant impact on the natural environment in Wales, land stability, tourism, farming, industry and the general population, not least through increased insurance costs. This is without considering the impact of carbon emissions from Wales on other, more vulnerable countries.

The Welsh Assembly Government has recognised the critical need for action on climate change in its Review of Energy Policy in Wales (NafW, 2003b). It is no accident that in its first report of this energy policy review, the Economic Development Committee considered renewable energy in Wales. In arriving at their conclusions, the committee accepted the scientific consensus that global warming is occurring, largely due to the release of carbon dioxide resulting from the use of fossil fuels. They concluded that to overcome this both energy efficiency and renewable energy would have to be pursued with vigor.

The committee's recommendations from the report (following full public consultation) can be summarized as follows:

Recommendation 1
- Recognizes the need to move towards a zero carbon economy over the next 20-50 years
- Seeks to develop its indigenous renewable resources to reduce carbon emissions
- Promotes renewable energy to enhance industrial rural and commercial opportunities without prejudicing tourism or areas of environmental significance

Recommendation 2
- Sets a benchmark for production of electricity from renewable sources of 4 TWh per year by 2010, made up of roughly equal parts of on shore wind, off shore wind and other sources

Recommendation 3
- The National Assembly aims to become a 100% user of renewable energy
- Urges other agencies and public bodies to take similar steps and support projects for technologies that exploit local opportunities or unique resources.

Recommendation 4
- Aims to support resolution of the difficulties of achieving connections for renewable generators.

Recommendation 5
- Aims to clarify and streamline the planning process for renewable energy developments while not diluting in any way the proper democratic control of such decisions
- Seeks an extension of its powers with regard to the approval of power generation facilities
- Seeks mechanisms to provide local communities with immediate and tangible benefits from renewable energy developments

Recommendation 6
- Seeks to make Wales a showcase of sustainable economic development through clean energy technologies, through increased innovation, research and development, building on Wales' manufacturing strengths.
- Identifies the energy sector as being of high growth potential in Wales
- Seeks to encourage skills development and private sector investment in the energy sector in Wales

In support of Assembly policy, the Welsh Development Agency has produced an Energy Policy in August 2003 (WDA, 2003). The policy considers both supply and demand side aspects of energy supply in Wales and recognises the transition to an energy supply in Wales that introduces proportionately more renewable energy from now until 2020.

WDA Energy Policy and Hydrogen
Whilst the policy does not mention hydrogen directly, the Agency has identified scope for action in the following areas in section 5.2 of the policy:
Transport – Signpost the potential linkages that exist between future energy technologies and the development of new technology for vehicles and transport.
Industrial Processes – Promote and signpost the development of new low carbon technology.

10.4.6 UK & Wales Climate Change Policy and Implementation of Hydrogen Energy

It is feasible that the UK Kyoto commitment (12.5%) and the larger national reduction target of 20% reduction on 1990 levels by 2012 can be achieved without widespread implementation of hydrogen energy. Taking a realistic view, the timescale for these targets is too short for hydrogen energy to have any significant impact. However, there is broad agreement that to avoid significant adverse effects from global warming a long-term programme of continuous and radical CO_2 emissions reduction is needed. The Royal Commission on Environmental Pollution's (RCEP's) recommendation is that the UK should put itself on a path towards a reduction in carbon dioxide emissions of some 60% from current levels by about 2050. The IPCC suggests that if we act to stabilise global CO_2 concentrations at 1000ppm, global temperatures will rise by over 4°C by 2200. Even if dramatic action is taken and CO_2 emissions drastically reduced to stabilise global concentrations at 450ppm, global temperatures will still rise by over 2°C. (Figure 10.4) To achieve this significant reduction in carbon emissions and to continue to achieve economic growth and social well-being, there needs to be a step change in energy provision. Sustainable hydrogen energy is such a step change and recognised as the the most promising candidate to allow these long-term targets to be met (DTI, 2003a).

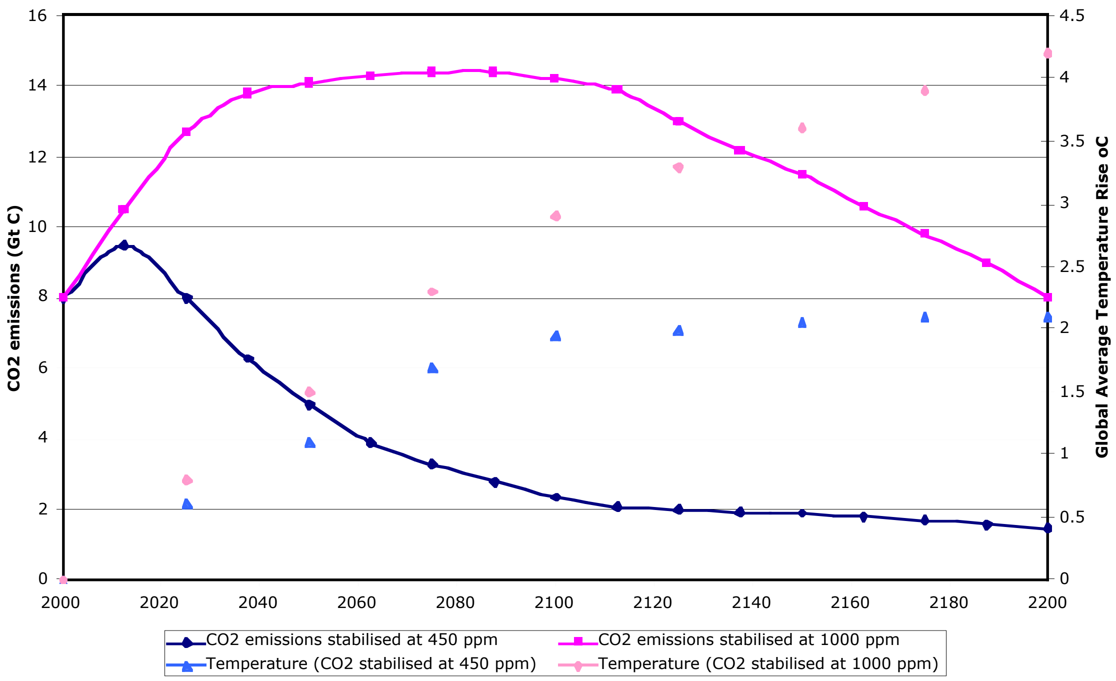


Figure 10.4 IPCC projections for global CO_2 emissions and corresponding global temperature rise

In Wales, a 4TWh target of renewably generated electricity by 2010 could similarly be met without the added benefit of hydrogen energy. However, the aspirational target of 20% by 2020 and the further move towards a zero carbon economy will realistically require the adoption of hydrogen as an increasingly significant part of the Welsh energy profile.

10.4.7 Emissions Trading

Following the introduction of air pollution emissions trading schemes, particularly in the United States, there has been a realisation that emissions trading is a mechanism that is especially suited to reducing emissions of greenhouse gases. The following sections describe the approaches to emissions trading adopted in the UK, in Europe and globally through the mechanisms of the Kyoto protocol.

UK Emissions Trading Scheme

The UK Emissions Trading Scheme (ETS) began in March 2002 and was the first national greenhouse gas emissions trading scheme. The underlying principle of emissions trading is that through a market mechanism, emission reductions happen where the cost of making the reduction is lowest. As a result the overall (national) costs of emission reduction are kept to a minimum. Organisations that take part in the scheme are given an allowance for greenhouse gas emissions in terms of carbon dioxide equivalent (CO_2e). They can achieve their allowance in a number of ways:

- Alter their processes or production to meet the targeted reduction in emissions
- Make alterations that reduce their greenhouse gas emissions by greater than their allocated amount, leaving a surplus allowance that can be traded
- Continue to emit greenhouse gases in excess of their allowance and purchase allowances from the market

Thus, targets set at a national level can continually reduce the overall level of emissions, whilst individual firms are given the flexibility to trade to meet their allocation or make the required process changes. In general, organisations will chose to do this by whichever method is the least expensive. This should mean that the overall cost to the country is minimised for achieving the required emissions reduction. To date 11.88million tonnes of CO_2e emissions have been reduced by organisations taking place in the UK greenhouse gas emissions trading scheme. The UK ETS is one of the major mechanisms to ensure that the UK Kyoto targets are achieved.

EU Emissions Trading Scheme

The EU ETS will start on January 1st 2005. The same rationale applies to the EU ETS as outlined for the UK ETS. Rather than being a voluntary scheme, organisations carrying out prescribed activities above nominated threshold values will be included. These so called Schedule 1 activities include for example, combustion plant over an aggregate 20MW thermal input, steel production over 2.5 tonnes per hour, paper mill above 20 tonnes per day production capacity. Operators of prescribed Schedule 1 processes will require a greenhouse gas emissions permit and will be subject to the rules of the EU ETS.

As part of the EU emissions trading scheme each member state has to propose a total number of greenhouse gas allowances to be allocated to their country's industry, which in turn must be approved by the European Commission. In April 2004 the UK government estimated the total amount of CO_2 emissions from UK industry for the period 2005-7 would be 52.1 million tonnes. However, in October 2004 the government have adjusted this figure upwards to 56.1 million tonnes, some 7.6% higher than originally estimated. In announcing this effective relaxation of emissions targets Secretary of State for the Environment, Margaret Beckett, stated:

"In making this allocation, we are balancing the need to protect the competitive position of UK industry while moving us beyond our Kyoto Protocol commitment towards our tougher national goal." (DEFRA, 2004b)

Kyoto protocol and emissions trading

As well as country-wide or global-region schemes, organisations in Kyoto participating countries can also take advantage of international emissions trading. Emission credits can be gained by countries by reducing greenhouse gas emissions and through the introduction of "carbon sinks", including forestation. Countries that still exceed their Kyoto emissions targets will be allowed to purchase credits from countries that have credits to spare. In addition, developing nations can be assisted in emissions reductions programmes by developed nations, in return for emissions credits. Japan and the EU countries have pledged a fund of $410m p.a. between 2005-2008 for this purpose.

Countries rejecting the Kyoto protocol are not able to take place in international greenhouse gas emissions trading. Whilst this does not undermine the scheme, the exclusion of the largest single CO_2e emitter is unfortunate.

Emissions trading and the Hydrogen Economy

In principle, the imperative to reduce CO_2 emissions is a positive driver towards hydrogen energy schemes. Zero emission renewable hydrogen energy schemes replacing heavily emitting standard processes would benefit from the maximum level of CO_2e credit. Conversely, the relatively high current cost of hydrogen energy equipment means that cheaper, less CO_2 effective schemes are more likely to be considered, particularly whilst the value of CO_2e credits remains relatively low. As the "low-fruit" of cheaper emissions reductions opportunities are exhausted and the value of CO_2e credits increases, then there may be greater incentive to explore hydrogen energy options. Nonetheless, emissions trading can be of real benefit to new hydrogen energy projects now.

10.5 Security of Energy Supply

10.5.1 Worldwide Concerns

In addition to the environmental imperative to shift to a hydrogen economy, there is an increasing need in terms of security of supply. Whilst precise figures vary, most experts predict that the global demand for energy will rise significantly over the next 50 or 60 years, primarily through demand from developing countries. The IPCC median scenario for global energy use suggested a fourfold increase in primary energy demand between 1990 and 2100. At the same time reserves of oil and gas are being depleted, particularly in the industrialised western democracies. Expert predictions vary, but most agree that oil resources are finite and are facing depletion some time in the next 40-70 years. Between now and then, there will be increased competition for the diminishing amounts of oil to be found. With the majority of the remaining reserve in the Middle-East, we face the potential of a future dependant on oil imports from countries that are "currently perceived as relatively unstable" (DTI 2003). Gas supply may last a little longer, but again, reserves are finite and the major longer-term reserves will be in the Middle-East and Russia (BP, 2004).

So as well as any concerns about climate change, simple supply and demand economics indicate that our current dependence on oil based products is going to have to change in many of the world's largest economies. Many of the governments of these countries are realising that hydrogen, especially hydrogen produced from sustainable indigenous resource, provides a realistic alternative, for stationary applications and particularly for transport applications. Hydrogen provides an effective bridge between renewable energy production and the growing needs of the transport sector.

Amongst concerns from other countries, security of supply has also become a significant driver towards the establishment of a hydrogen economy in the USA. Active in the area for some time, the US Department of Energy's Hydrogen, Fuel Cells & Infrastructure Technologies Program has been given significant new impetus by a realisation of increased dependency on imported energy, especially from the Middle-East and as part of a heightened sense of homeland security following the events of September 11th 2001 and the war in Iraq.

10.5.2 EU Security of Supply Policy

As long ago as December 1968, there was an EEC council directive imposing an obligation on member states to maintain specified minimum stocks of crude oil and petroleum products. These measures were updated in 1998 (Council Of The European Union, 1998). Growing concerns regarding the security of energy supply in Europe have led to the construction of policy documents outlining a European strategy for the security of energy supply, natural gas and petroleum products, although these measures have yet to be adopted.

Under the title “Intelligent energy for Europe”(EIE) the EU has put forward proposals for 2003-2006 with the objective of reducing the EU's dependency on external supply of energy (estimated at 70% by 2030). At the same time the policy attempts to reinforce the fight against climate change by combating the increase in CO_2 emissions in the energy sector, particularly in transport.

Within an overall energy security framework, the policy is broadly supportive of the move to a sustainable hydrogen energy future, free from the excessive burden of imported energy. However, it is unlikely that EIE will lead directly to any hydrogen energy schemes within the 2006 timeframe.

10.5.3 UK Policy on Security of Energy Supply

Over recent decades, the UK has enjoyed plentiful supplies of North-Sea oil and gas. Consumer price reductions from successful liberalisation of energy markets had also contributed to a sense of confidence about energy supplies. However, recent national and international developments have increased the awareness of and level of attention to security of energy supply in the UK. Volatile prices in international oil and gas markets, continued political tensions in the Middle-East, recent blackouts in America, London and Italy, the shock from the impact of September 11th 2001 and the UK fuel protests of September 2000 have all had an impact on raising the profile of energy security.

Following the opportune discovery and extraction of oil from the North Sea in the early 1970s, the UK became a net energy exporter and achieved an oil trade surplus for the first time in 1980, which has been maintained ever since. However, it is likely that the UK will become a net importer of gas by 2006 and of oil by 2010 (DTI 2003a). Forecasts are that by 2020, three quarters of the UK's primary energy consumption will be imported. Whilst the government's energy white paper points out that most advanced industrial economies are already significantly dependant on imported energy, energy import dependency becomes a more significant driver behind the national energy security policy.

In the UK, as in most western industrial economies, there is a fundamental desire for reliable energy supplies at predictable prices delivered through the market in UK energy policy (DTI, 2003a). Reliability in the short term, resilient to changes in supply and demand, is one aspect of the UK policy. Longer term, the need to maintain an adequate diversity of supply, free from disruptive external influence, is also a critical factor. Whilst most of the initial emphasis in UK energy security policy is based on a series of measures for improving the security of supply of existing fossil fuels (particularly natural gas), there is a clear longer term policy emerging that reduces this dependency through renewable energy and indigenous energy. Within the energy security policy framework in *Our energy future – creating a low carbon economy* (DTI, 2003a) hydrogen produced from a wide range of sources is seen as having significant potential for enhancing energy security.

Natural Gas Dependency

The Energy Review published in February 2002 by the Performance and Innovation Unit (now part of the Government's Strategy Unit) indicated that the UK is likely to become significantly dependant on imported gas for a significant portion of its energy demand. Their conclusion, echoed in the government's Energy White Paper (DTI 2003a) was that this increased dependence was not a pressing problem. This conclusion must be seen in a short- to medium-term context, particularly given the UK's impending dependency on imported gas and the location of the remaining natural gas reserves. The trend towards natural gas is being supported by efforts to achieve security through promotion of competition and international market liberalisation. In addition the need to achieve a diversity of suppliers is being followed by seeking international agreement and through market led pursuit of commercial security.

The increasing dominance of natural gas for the UK's energy provision raises the possibility of the introduction of hydrogen energy through steam methane reforming, either regionally in large-scale reformers, or locally in district schemes, on the forecourt or on-board vehicles. These possibilities have been considered as part of a longer-term carbon reduction policy by the DTI (DTI, 2003a).

Threats to Supply Continuity

Risk of disruption and threats to the UK's energy system integrity are also covered in the Energy Policy *Our energy future – creating a low carbon economy*. Measures include contingency plans against threats from terrorism, civil actions, and abnormal weather. Part of this contingency is the promotion of diversity of sources, fuel types and trading routes to avoid over reliance and hence vulnerability. There is, however, an anticipation of potential price shocks from geo-political disruption or infrastructure damage. Renewable energy promotion in the UK and internationally is suggested to overcome this potential risk, giving an increased possibility for hydrogen as an energy store to buffer intermittent renewables.

10.5.4 Security of Energy Supply Policy in Wales

In Wales, as in the rest of the UK, there is general acceptance that energy policy must encompass security of energy supply in addition to the economic, environmental and social goals of sustainable development. In the context of renewable energy, the recent final report on renewable energy in Wales stated:

"The National Assembly should seek to promote a vision for renewable energy in Wales that emphasizes safe, clean and secure energy supplies and contributes positively to reducing global warming." (NAfW, 2003a)

Comprehensive statistics on overall patterns of energy consumption in Wales have been difficult to determine as they are typically subsumed within overall UK figures. However, The Energy White Paper (DTI, 2003a) indicated the importance of local and regional decision-making for energy policy in delivering a number of national energy policy objectives. As a result, regional figures are now starting to be published. Figure 10.5 shows published electricity and gas consumption figures for the four years to 1998 and for 2001-2002 (NAfW, 2002b), (DTI, 2003d).

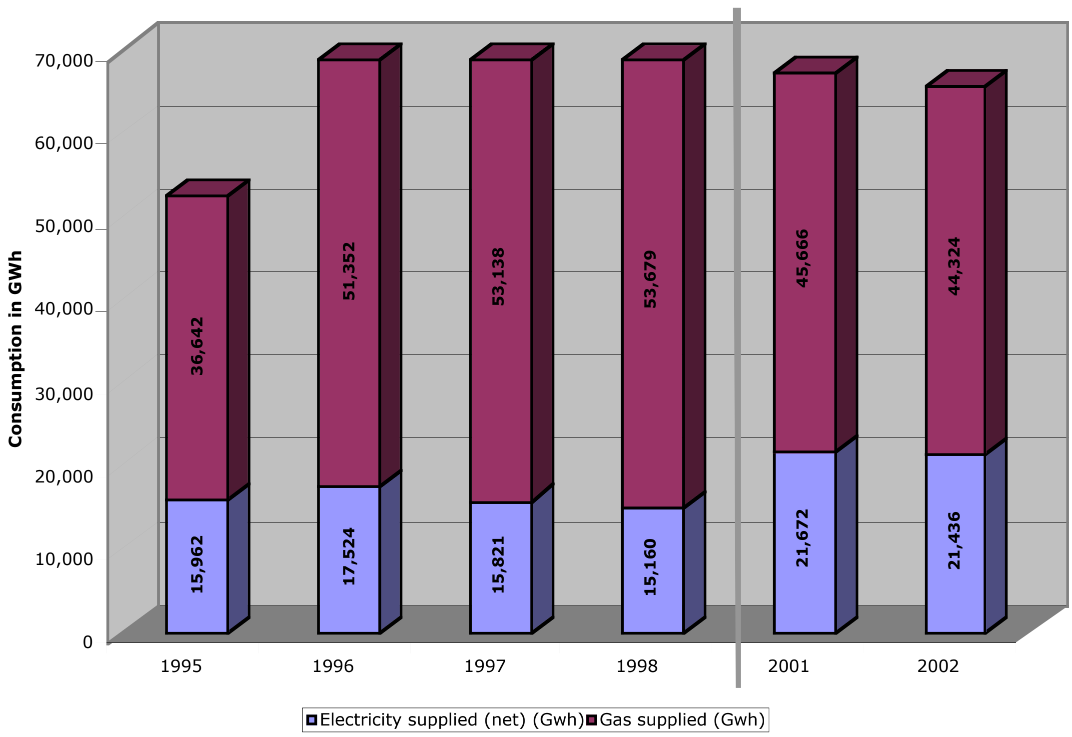


Figure 10.5 Electricity and gas consumption in Wales 1995-1998 and 2001-2002

Wales is currently well endowed with electricity generating capacity, in greater proportion per capita than the UK as a whole, although the proportion of this capacity from renewable sources is small, especially when compared with the rest of Europe. Figure 10.6 shows the excess of production over demand in Wales for 2001 and 2002. It also shows that demand for electricity dropped marginally in 2002, yet the total electricity produced (and exported) increased.

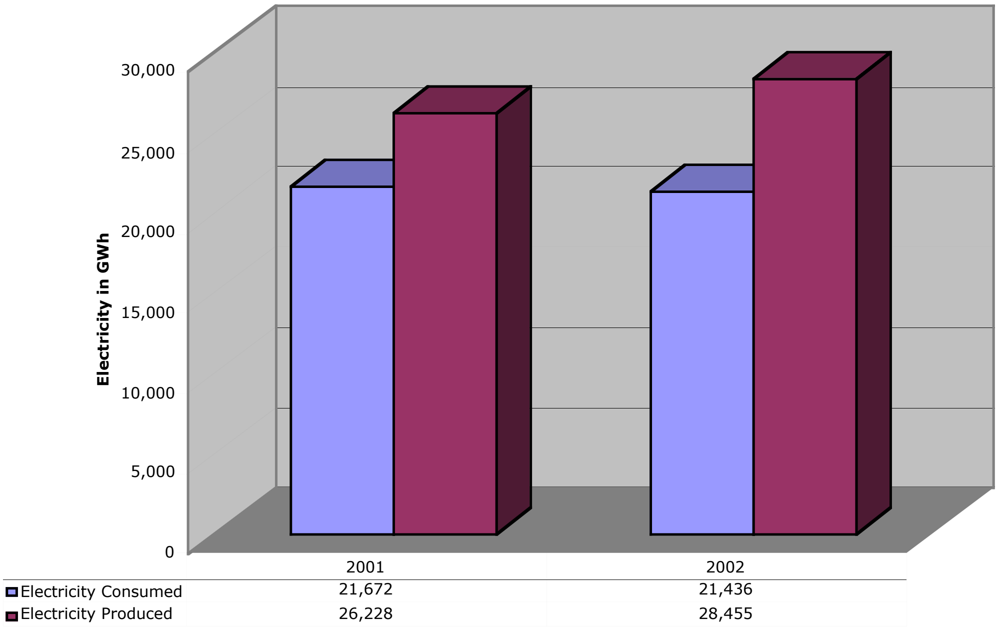


Figure 10.6 Wales Electricity Supply and Demand 2001-2002

Table 10.1 shows the total installed electricity production from power facilities of all types in Wales and the proportion of the overall electricity mix in Wales provided by each generating method. Although the total amount of renewable electricity generation grew by nearly 11% (76 GWh), the percentage contribution of renewables remained static at 2.4%.

Table 10.1 Total Electricity Generation in Wales by Production Method 2001-2002 (DTI, 2003d)

	Generation of Electricity in Wales in GWh	
Fuel Source	**2001**	**2002**
Coal	8,598 (29.2%)	7132 (22.7%)
Oil	69 (0.2%)	54 (0.2%)
Gas (CCGT & CHP)	14,604 (49.6%)	13101 (40.5%)
Renewable	709 (2.4%)	785 (2.4%)
Pumped storage	1,836 (6.2%)	2,030 (6.3%)
Nuclear	3,045 (10.4%)	8,676 (26.9%)
Other Thermal	549 (1.9%)	512 (1.6%)
TOTAL	29,429	32,311

It should be noted that the installed capacity of renewable electricity generation in Wales is significantly more than the total electricity produced. However, installed capacity must be used with caution due to the availability and loading of the source. Wales's nuclear source at Wylfa may produce approximately 88% of installed capacity, although this can fall dramatically during planned maintenance shutdowns (as illustrated in the difference in Nuclear production in Wales between 2001 and 2002 in Table 10.1). The % of installed capacity typically produced is around 80% for coal or gas fired power stations, usually 21% for the pumped storage facility at Dinorwig, whilst intermittent renewable sources produce 30-35% of capacity on average. However, the recent review of renewable energy in Wales (NAfW, 2002a) indicated that over half of the generating capacity in England

and Wales would need to be replaced over the next 20 years. This includes the 1.0GW nuclear plant at Wylfa that has a licence to run up until 2004, but is unlikely to be replaced with nuclear capacity in line with UK government policy. Given the Welsh Assembly Government's commitment to developing the renewable energy supply and renewable energy industry in Wales, a significant amount of the replacement to decommissioned power stations will be in the form of renewable energy. This adds to the diversity and potentially security of supply and favours the eventual development of a hydrogen economy.

Unsurprisingly, the majority of electricity use in Wales is used by the main centres of population along the southern M4 corridor and to a lesser extent along the northern strip. Recent installation and commissioning of the 500MW Gas CHP power station in Baglan goes some way to improving the balance between generating capacity and demand in Wales. However, the energy infrastructure in the west of Wales is more constrained. There are currently no major natural gas import facilities in Wales, Burton Point in north Wales accounting for less than 1% of natural gas supplies. Barrow (12% of UK gas supplies) is the only one of the six current major natural gas terminals that is on the western side of the UK. This may change following the granting of planning permission in Pembrokeshire to construct a Liquefied Natural Gas (LNG) import and storage facility. Initial proposals for the terminal were to handle up to 6 billion cubic metres per year of natural gas, which is approximately 5% of the natural gas demand expected in the United Kingdom at the end of this decade. This proposal has since been upgraded.

In the short to medium term the impact of this upgraded infrastructure will be to improve the supply position for natural gas. It also provides the possibility for provision of larger steam methane reformer based hydrogen production in Wales. The output could be used by the West Wales refining industry in the preparation of cleaner fuels, but could also allow development of a hydrogen energy supply hub.

10.6 Air Quality Policy

"An estimated 3 million people die each year because of air pollution. . . this figure represents about 5% of the total deaths that occur annually in the world" (WHO, 2000b)

Major health and environmental problems result from air pollution. We have discussed global climate change from emissions of greenhouse gases like CO_2 and methane and its impacts. Other air pollutants, predominantly the result of human activity, have just as destructive an effect. In this case the effect is directly felt by humans, prompting ill health and, as the statistic from the World Health Organisation shows, a devastating number of premature deaths. A sad fact is that the vulnerable in our society are the ones that suffer from poor air quality the most. The young and the elderly, particularly city dwellers are the most likely to suffer adverse health impact from air pollution. Poor air quality is an indicator of social deprivation and improvement in air quality is one of the major goals of sustainable development. More than just affecting human health directly, air pollution is also responsible for contamination of water sources, and harm to animal and plant life.

Air pollution is often a local issue, with emission from traffic and industry causing high concentrations of harmful pollutants such as NO_2 and particulates. It can also be an international issue, with emissions of SO_2 or ozone travelling significant distances and causing transboundary issues.

The role of hydrogen in overcoming the problems posed by a number of the most common pollutants is outlined in Table 10.2 below:

Table 10.2 Common air pollutants, their health impact and the role of hydrogen in overcoming these impacts

Pollutant	Health Impact	Role of hydrogen in overcoming
Nitrogen dioxide and other oxides of nitrogen (NOx)	Cause of asthma and respiratory diseases. Excess concentrations linked to a significant increase in death in children under 5 years old	Nitrogen dioxide is an unwanted combustion product, particularly from vehicle engines or industrial combustion processes. Hydrogen vehicles, particularly fuel cell vehicles, can effectively eliminate vehicle NO_2 emissions. Hydrogen internal combustion engines have also been shown to significantly reduce NO_2 emission. Similarly NOx emissions from combustion-based power stations can be displaced by implementation of replacement hydrogen based systems.
Particulates (particularly below 10μm or PM_{10})	High levels of particulate matter (indoor or outdoor) can cause acute respiratory infections and significantly reduce life expectancy	Numerous industrial processes and diesel engines are significant sources of particulates. Replacement of diesel engined trucks and buses with fuel cell vehicles will eliminate much of the particulate pollution in cities, especially if linked to integrated transport policy, that promote the use of (fuel cell) buses
Sulphur dioxide and other oxides of Sulphur (SOx)	Causes local and transboundary acidification ("acid rain") and a potential cause of asthma	High sulphur content in fossil based vehicle fuels is a significant source of sulphur dioxide. Initially, hydrogen has a significant role to play in the reduction of the sulphur content in these fuels, through hydrodesulphurisation in the refinery. Longer term the replacement of petrol by hydrogen eliminates the problem. Hydrogen power installations can also remove SOx problems, caused particularly by coal fired power stations.
Carbon monoxide	Toxic, causing formation of carboxyhaemoglobin in the blood (oxygen starving)	Carbon monoxide is a product of incomplete combustion of hydrocarbons, in industrial combustion processes and internal combustion engines. Again replacement of hydrocarbon fuelled internal combustion engines with hydrogen fuel cell vehicles will practically eliminate CO vehicle emissions
Most of the positive impact is related to hydrogen fuel cell vehicles replacing hydrocarbon internal combustion engines, and the potential to progressively replace power generating capacity with renewable / hydrogen systems. There is also potential to use the oxygen from electrolytically produced hydrogen to enhance combustion processes and reduce industrial air pollutants.		

The significant reduction in air pollution resulting from the adoption of hydrogen fuelled fuel cell vehicles is one significant advantage over the use of (heavier) bio-fuels in internal combustion engines.

10.6.1 International Policy on Air Pollution

The 1979 Geneva Convention on Long-range Transboundary Air Pollution and its eight specific protocols form one of the fundamental international agreements on atmospheric pollution. It has formed the basis for a significant amount of international environmental law. The recognition that emissions from one country could have a detrimental impact on another is at the root of the convention, in particular the role of sulphur emissions from Western Europe travelling thousands of miles and causing acidification of Scandinavian lakes.

The Convention entered into force in 1983 and outlines the international cooperation required for air pollution abatement and sets out a structure for air pollution policy and research. As well as sulphur emissions (in the form of SO_2) the subsequent protocols have introduced international agreements on volatile organic compounds, persistent organic pollutants, nitrogen oxides, heavy metals and ground level ozone. A total of 49 countries have accepted or ratified the convention, including the UK, all EC member states (including May 2004 entrants) and the USA.

As indicated above, the implementation of sustainable hydrogen energy for transport and as a replacement to hydrocarbons in power generation can have a significant impact on reducing concentrations of some of these pollutants.

10.6.2 European Air Quality Legislation

A large number of European legislative instruments exist to control air pollution in member states, including controls on motor vehicle emissions, fuel quality, and fuel economy of new vehicles, industrial combustion, and air quality management. The legislation is too numerous to detail here, but if required can be researched on the European Union's Europa web site. *(http://europa.eu.int/scadplus/leg/en/s15004.htm)*

Clearly, none of this legislation mandates the transition to hydrogen vehicles or hydrogen energy schemes. However, the general principle of the legislation is to improve the quality of air through reduction and removal of air borne pollutants. Correctly implemented, a hydrogen energy economy can achieve these aims.

10.6.3 UK (and Welsh) Policy on Air Pollution

"Clean air is an essential ingredient of a good quality of life. People have a right to expect that the air that they breathe will not harm them" (DETR, 2000)

In January 2000 the UK parliament presented the air quality strategy for England, Scotland, Wales and Northern Ireland "Working Together for Clean Air" (DETR, 2000). The policy, laid before the Westminster parliament, Scottish parliament, National Assembly for Wales and Northern Ireland Assembly outlines the overall and updated UK strategy to respond to the issue of air pollution.

Despite evidence that air pollution has significantly reduced in the UK in recent years, the adverse effects on health and environment are still significant. Up to 24,000 people are estimated to die prematurely in the UK each year due to air pollution.

Visible smog is less of an issue in the UK than some countries. Although visible smog has not been completely eliminated in all areas, the replacement of uncontained wood and coal burning in homes has dramatically improved this aspect. However, the common pollutants of current concern are not visible. In particular, the rapid and continuing growth in road transport led to a significant increase in vehicle pollution in the 1980s. Improved regulation of vehicle emissions and vehicle testing has improved the situation, but vehicle emissions are still the most significant cause of air pollution in the cities and towns of the UK.

The 2000 Air Quality Strategy tightens the limits on five of the seven common pollutants, namely: benzene, 1,3-butadiene, carbon monoxide, lead, and nitrogen dioxide. The target for sulphur dioxide was maintained at the European limit value. The PM_{10} target was actually relaxed to agreed European limit values, as the earlier target was felt to be unachievable.

Policy instruments to meet the targets set out in the strategy include improved vehicle emissions monitoring. The UK policy document, A new deal for transport: a better deal (DfT, 1998) and corresponding policy statements from the Welsh Assembly Government, outline measures to lessen congestion, improve public transport use and hence reduce pollution levels.

The Department for Transport strategy document "Powering Future Vehicles Strategy"(DfT, 2002) outlines a vision of transition to lower pollution transport, particularly for carbon reduction, but also to reduce air pollutants. The strategy includes a commitment to accelerate the shift towards technologies such as hydrogen fuel cell vehicles, albeit beyond 2010.

The air quality strategy reaffirms responsibilities for air quality monitoring and improvements. Local authorities have responsibility for achieving air quality with pollution concentrations below the prescribed limits for the seven pollutants listed above. Due to the transboundary nature of ozone pollution, this is not a local authority responsibility. As well as local air quality strategies, local authorities also have responsibility for land use planning and local transport plans, which can have a positive impact on air quality. Within these powers, forward-looking local authorities are looking to implement demonstration hydrogen transport schemes as a forerunner to low and zero carbon transport. Similarly national support for implementation of hydrogen transport can signal intentions on air quality in preparation for wide-scale implementation. Hopefully, good intentions will be matched by actions over the next few years.

Industrial sources of air pollution are again monitored by the local authorities and by the Environment Agency. Specific industrial operations coming under the Integrated Pollution Control (IPC) and now Integrated Pollution Prevention and Control (IPPC) regulations, have a responsibility to implement best available technologies not entailing excessive cost (BATNEEC) to ensure pollutants are kept within agreed plant limits and are responsible for self-monitoring and emissions reporting. It is worth noting that existing steam methane reforming hydrogen plants (without CO_2 sequestration) are emitters of CO_2, NO_x and CO. Typically these plants came under the IPC regulations and are coming under IPPC.

10.7 Promotion and development of indigenous hydrogen industry

Over the last decade there have been a growing number of national hydrogen energy programmes in many countries. The majority of these are studies on the various aspects of hydrogen energy, but increasingly there are national support programmes, aimed at stimulating and developing hydrogen energy related industries. The most noteworthy national programmes to date have been the WE-NET project in Japan and the US Department of

Energy's national hydrogen programme. Iceland has also embarked on an ambitious national programme and significant state supported programmes in Canada and Germany are in progress. In addition, there are smaller scale initiatives in a number of other countries.

State sponsored, international collaboration on hydrogen energy is also increasing. The International Energy Agency has a collaborative programme on hydrogen and there have been collaborative projects between Germany and Saudi Arabia, and Canada and Europe amongst others. In some countries, state support has been reduced and largely given way to private industry investment, for demonstration projects and the like, in stark contrast to the substantial state funding now established in the USA.

10.7.1 International Collaboration

International Partnership For The Hydrogen Economy

The International Partnership For The Hydrogen Economy (IPHE) was created in November 2003 at the instigation of Spencer Abraham, Secretary of Energy of the United States of America. The IPHE is intended to facilitate international co-operation on hydrogen and fuel cell research, development, demonstration and commercial utilisation. With the aim of enhancing energy security and environmental protection the IPHE also acts as an international forum for the development of common codes and standards and policy advancement to accelerate the cost-effective transition to a global hydrogen economy. At the time of writing the IPHE membership included representation from Australia, Brazil, Canada, China, France, Germany, Iceland, India, Italy, Japan, Norway, Republic of Korea, Russian Federation, United Kingdom and United States. In addition to individual member states, the European Commission is also represented on the IPHE. The IPHE has been set up to promote bilateral and multilateral collaboration on hydrogen and fuel cell technologies and to encourage the implementation of large-scale, long term public-private cooperation to advance hydrogen and fuel cell technology.

In addition to the IPHE there are numerous bilateral agreements between countries, particularly on co-operation in research towards the hydrogen economy. For example, there is such an agreement in place between the UK and USA on hydrogen energy research as part of a wider bilateral arrangement on energy research in general.

International Energy Association (IEA)

As reported earlier, The IEA's hydrogen implementing agreement was established in 1977. The wide-ranging programme involves the collaborative research on all aspects of hydrogen technology.

Enhanced Oil Recovery and Hydrogen

One potentially useful approach is the subject of an IEA implementing agreement, namely enhanced oil recovery (EOR). The technique is also highlighted in the UK Energy White Paper as having the potential to maximise the potential benefit from the UK's existing oil and gas reserves as a measure to reduce import dependency. EOR through carbon dioxide capture and storage has the potential to achieve this policy aim. Measures to support demonstration projects are indicated in the policy, which raises the possibility of off-shore hydrogen production and in-situ carbon dioxide sequestration to achieve a triple goal of enhanced recovery of oil and gas reserves, capture of the carbon from these fossil fuels and the provision of a zero carbon energy system on-shore.

EOR is a reality. Over 80 EOR schemes have been contributing to oil production since 1972 (either water flood or CO_2 injection). Experience in the Permian Basin suggests 0.5 tonne CO_2 injection is required per barrel of oil (IEA

2002), so significant quantities of CO_2 will be required if EOR is to have a major global impact. An additional relevant possibility is integrated coal gasification combined cycle power plants (IGCCs). Two schemes at Onllwyn in Neath-Port Talbot and at Hatfield near Doncaster are currently being developed, but are stalled in the planning process. Plants such as these produce significant quantities of CO_2 that can be used for EOR or need to be captured, but pertinently also produce major quantities of hydrogen. The hydrogen could be used to enhance on-site power production, but can also be used as a source of hydrogen for production scale hydrogen energy projects. The possibilities are being actively investigated by the regional development organizations.

10.7.2 European Activities

The European Union has become increasingly active in its support for hydrogen energy programmes. In October 2002 the European Commission launched the High Level Group on Hydrogen and Fuel Cells, an assembly of 19 important European stakeholders drawn from related industrial organizations. The aim of the High Level Group was to create an integrated vision of the role that hydrogen and fuel cells can play in a sustainable energy future for Europe and to determine the requirements for global leadership in the field in the next 20-30 years. The High Level Group was set up due to a desire to accelerate development towards sustainable energy future with hydrogen and electricity as interchangeable energy carriers, reducing greenhouse gas emissions and reducing dependency on fossil fuels. The group was also set up following a recognition that Europe lagged behind the world leaders USA and Japan in efforts to develop a hydrogen economy and that reversing this trend could lead to increased competitiveness for European industry.

In June 2003 the High Level Group published their final report “Hydrogen Energy and Fuel Cells: A Vision of Our Future”. This report captures a collective vision (if such a thing exists from such a diverse group) of a future hydrogen economy for Europe and a range of measures that Europe can undertake to achieve this vision. Five specific actions are outlined as follows:

1. A political framework, particularly in energy and transport that creates the conditions that enables new technologies to enter the market.
2. Initiation of a European strategic research agenda to guide community and national research programmes.
3. Introduction of a European deployment strategy to move from prototype to demonstration to commercialization. The idea of major scale “lighthouse projects” to integrate stationary power and transport systems on a pan European basis.
4. Creation of a European roadmap, setting targets and decision points for research, demonstration, investment and commercialization.
5. Formation of a European Hydrogen and Fuel Cell Technology Partnership to provide advice, stimulate activities and monitoring activities.

European Hydrogen and Fuel Cell Technology Platform

Created in September 2003 as a result of the report of the European High Level Group the European Hydrogen and Fuel Cell Technology Platform (HFP) was set up by the European Commission to “facilitate and accelerate the development and deployment of cost-competitive, world class European hydrogen and fuel cell based energy systems and component technologies for applications in transport, stationary and portable power.”(European HFP, 2003). The platform consists of individuals representing the academic and scientific community, industry, finance and public authorities and is steered by a high level advisory council established in December 2003.

One key role of the platform, together with the European Commission, is to co-ordinate research, development and deployment programmes and initiatives at a European and local level. Following recommendation by the advisory council, co-operation has been established between EU member states on the co-ordination of national research activities in this field. It is intended that the HFP will encourage deployment opportunities for and investment in hydrogen and fuel cell developments towards a European hydrogen economy. The HFP is structured as indicated in Figure 10.7 and participants meet regularly to ensure shared ownership and to establish a European momentum towards the hydrogen economy.

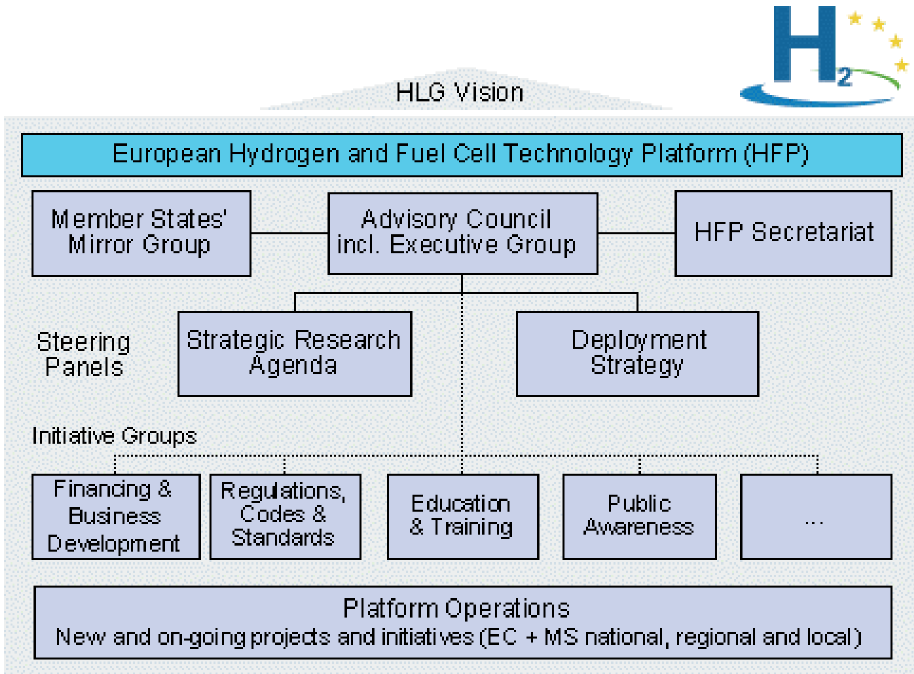


Figure 10.7 Structure of the European hydrogen and fuel cell technology platform (HFP)

The HFP, through steering panels, is now in the process of developing a hydrogen and fuel cell Strategic Research Agenda and a Deployment Strategy addressing the issues required to bring hydrogen and fuel cells to the market place. The full Strategic Research Agenda is due for delivery to the Advisory Council in September 2005. The Deployment Strategy steering panel has the task of identifying short to medium term applications and "lighthouse" projects as a basis for the feasibility of building selected regional hydrogen economies, linking to the future European hydrogen economy.

European Framework Programme

The European Framework Programme is intended to strengthen the scientific and technological base of industry and hence encourage its international competitiveness. It does this within the context of support of other EU policies. Funding for hydrogen and fuel cell related projects has grown from 8 million for the Second Framework Programme (1988-1992) to more than €130 million in the Fifth Framework Programme (1999-2002), where 25 projects related to hydrogen and fuel cells were sponsored. In the first call of the Sixth Framework Programme (FP6) a further 9 hydrogen projects have either been granted or are in contract negotiation with an estimated EC budget of €60million. A further 6 fuel cell projects are at the same stage with an estimated EC funding of €30million. Over the duration of each framework programme, the segregation into separate calls (four in the case of FP6) allows prioritisation of the research and demonstration aspects from call to call. For the duration of

FP6 (2003-2006), the hydrogen and fuel cell related research, development and demonstration budget is anticipated to be €250million from the EC, matched with equivalent industry funds.

European Growth agenda – The "Quick Start Initiative"

In November 2003 the EU launched the hydrogen and fuel cell "Quick Start" initiative as part of the overall "European Growth Initiative" to accelerate the transition from a fossil fuel based economy to one based on hydrogen. The €250million of EC funding earmarked for hydrogen and fuel cells under the sixth framework programme represents the initial phase of the "Quick Start" initiative. The aim of this initiative is to set up a number of public/ private partnerships linking major research and important demonstration projects for hydrogen systems and facilities. The aim is also to involve the European Investment Bank and member states in these partnerships in order to leverage project finance, with the anticipated budget split on a 40/60 public/ private share basis.

Two specific ten-year partnerships are envisaged in three phases between 2004 and 2015. Firstly, the co-ordination of advanced research and development leading to the establishment of an industrial scale demonstration plant producing hydrogen and electricity from fossil fuels that separates and safely stores the CO_2 generated by the process. This project has an anticipated budget of €1.3billion and is known by the term HYPROTECH.

The second partnership is a major project aimed at aligning research and technological development towards exploring the feasibility of "hydrogen energy communities" or the "hydrogen village". The project will encompass a holistic approach including technical, safety and economic aspects. The aim is to install both centralised and decentralised hydrogen production and distribution infrastructures and to have both autonomous and grid-connected hydrogen power systems. Each hydrogen energy community will include an extensive number of hydrogen powered vehicles and the accompanying fuelling infrastructure. The intention is to investigate different production pathways, including renewable energy sources. This initiative has the name HYCOM and has an anticipated budget of €1.5 billion.

European targets for hydrogen transport fuel introduction

The European Commission has indicated a target of 20% substitution of diesel and petroleum for transport with alternative fuels by 2020 in its White Paper on a common transport policy (European Commission 2001b). Later in 2001 this target has been separated into indicative values for Biofuels, Natural Gas and Hydrogen (European Commission 2001c). The communication from the Commission suggests an "Optimistic development scenario" which targets hydrogen as 2% of the total European transport fuel mix by 2015 and 5% by 2020 (see Table 10.3). Although the hydrogen targets are an aspiration rather than fixed, they represent a realistic, if challenging goal in the short to medium term.

Table 10.3 European Commission Optimistic Development Scenario for the introduction of hydrogen and other alternative fuels.

Year	Biofuel	Natural Gas	Hydrogen	Total% of overall fuel mix
2005	2	-	-	2
2010	6	2	-	8
2015	(7)	5	2	14
2020	(8)	10	5	(23)

10.7.3 National programmes

USA

Announced in January 2003, the US Hydrogen Fuel Initiative is an ambitious programme seeking to develop hydrogen, fuel cell and infrastructure technologies for America. The total budget for the programme is $1.2billion over 5 years, with $159k appropriated through the initiative for R&D in 2004 and $227k requested for 2005. The programme aims to work in partnership with the private sector (typically on a 50% match funding basis) to address the research, development, demonstration and commercialisation activities required to bring a hydrogen economy to fruition in the USA, thus reducing dependency on imported oil and as a contributor to the US clean air and climate change strategies.

In January 2002 US Energy Secretary Spencer Abraham launched the FreedomCAR initiative, a partnership with the US automotive industry to expand research required to produce practical and affordable hydrogen fuel cell vehicles. FreedomCAR also encompasses enabling technologies such as lightweight materials and batteries, as well as hydrogen and hydrogen mixture internal combustion engines. The budget for FreedomCAR is $500million over five years.

Both of these initiatives recognize that the success or failure of the transition to a hydrogen economy will depend on consumers accepting and converting to the technology in sufficient number. These two initiatives are intended to research and demonstrate the most promising technologies to improve the business case for the more significant investment in the hydrogen economy (Chalk, 2003). This investment is intended to provide enough research and development stimulus to allow the US to make a decision on progressing to commercialisation by 2015.

In February 2002, the US Department of Energy published *A National Vision of America's Transition to a Hydrogen Economy – to 2030 and Beyond*, outlining the future goal of a secure and clean energy future based on hydrogen.

In November 2002, this vision document was been complemented by the publishing of the US *National Hydrogen Energy Roadmap*. The Roadmap is essentially a plan for action in several subject areas; Production, Delivery, Storage, Conversion, Applications, Education and Outreach, and Codes and Standards.

In February 2004 the US DoE have further updated their approach by publishing the *Hydrogen Posture Plan: an Integrated Research, Development and Demonstration Plan*. This describes how the DoE intends to integrate its hydrogen R&D activities into a focused Hydrogen Program.

The California Fuel Cell Partnership is another example of state / industry collaboration to develop hydrogen, particularly for transport applications.

Japan

The Japanese WE-NET (World Energy Network) Project was set up in 1993 under the umbrella of the "New Sunshine Programme" of the Japanese Agency of Industrial Science and Technology, part of the Ministry of International Trade and Industry. The objective of the New Sunshine Programme is to develop innovative technologies to allow sustainable growth whilst solving energy and environmental issues (Mitsugi *et al.,* 1998, Toshiaki, 2003). WE-NET's ambitious aim is to "construct a worldwide energy network for effective supply, transportation and utilisation of renewable energy using hydrogen."

WE-NET has three phases. Phase 1 ran from 1993-1998 and was concerned with research, mainly analysing the possibilities for production, storage, transportation and utilisation of hydrogen. Phase 2 ran from 1999-2002 and addressed the development of production, storage, transportation and utilisation technologies in Japan. Complementary to the first two phases of WE-NET, there has also been significant state sponsored Research and Development of Polymer Electrolyte Fuel Cell Systems (Toshiaki, 2003). Work has also included research and development of large-scale hydrogen liquefaction plant, an ocean-going liquid hydrogen tanker, a programme to investigate hydrogen absorbing alloys and research into a 500 MW hydrogen-burning turbine, including materials of construction and potential combustion cycles. The third phase of WE-NET, running from 2003-2020, carries the title "Development for Safety Use and Infrastructure of H_2" and addresses the implementation of the hydrogen energy infrastructure and technologies. The New Sunshine Programme as a whole is supported by $11billion, $2billion of which is allocated to the WE-NET project.

A number of factors drive the Japanese programme. Most significant is the security of energy supply issue. Japan currently has a negligible proportion of indigenously produced energy, so is keen on developing a future that is less dependant on imports. Urban air quality and long-term promotion of Japan's auto industry are also significant factors. CO_2 emissions reduction is important to Japan, but potentially less so than other factors.

Canada

Canada supports a large hydrogen and fuel cell support programme through the Canadian National Hydrogen Research and Development programme and Canadian Transportation Fuel Cell Alliance. Canada has also produced a roadmap document entitled “Canadian Fuel Cell Commercialisation Roadmap” (Industry Canada, 2003) which puts forward a development plan for the fuel cell industry and promotes Canadian manufacturers involved in the fuel cell industry. The remote nature of some populated parts of Canada make it an ideal location for hydrogen technologies to compete economically with alternative energy sources.

Germany

Germany’s main driving force towards a hydrogen energy future is environmental, but also with a strong desire to promote indigenous industry. There has been a long history of German state support for hydrogen energy. The German Federal Ministry for Education and Research (BMBF) and the German Federal Ministry for Economics and Technology have funded research and development, and have engaged and promoted indigenous industry to collaborate on high profile demonstration projects since the 1980s. This level of state support has reduced significantly during the 1990s in all areas, with the exception of fuel cell research and development. At the start of the decade, German federal funding for hydrogen energy research and development ran at approximately 17 million DM per annum (Hyweb, 1998). By 1999, this level of state support had dropped to 1 million DM. During the same decade, German state support for fuel cell research and development rose from less than 1 million DM in 1990 to a peak of nearly 18 million DM in 1995. This had dropped to 14 million DM by 1999, of which 10 million DM went to PEM and SOFC research in equal measure.

Support for hydrogen energy projects has been particularly strong in Bavaria, home of the Munich Airport hydrogen fuelling station, including hydrogen fuelled airport buses and airport ground support vehicles. This is also the hub of BMW's long established hydrogen vehicle development programme. Significant other collaborative demonstration projects have received state sponsorship in (e.g. in Berlin and Hamburg).

Concerns have been expressed in Germany, as in the UK, that a fast track pursuit of hydrogen for transport, using hydrogen from fossil fuels, would prove less effective than systematic replacement of the hydrocarbon electricity production plant with renewables (Eisenbeiss, 2003). However, the Transport Energy Strategy (TES) a consortium of 8 major auto and fuel companies has convened in Germany to present an industry consensus on alternative fuels to reduce transport CO_2 impact. Hydrogen is emerging as the clear favourite from the TES group.

The BMBF has reached a conclusion that there is little prospect for the widespread introduction of hydrogen energy until the significant economic hurdles are overcome. Whilst some state support will continue, this will mostly be targeted at Fuel Cell research and development. BMBF funding criteria favour those fuel cell technologies that have a high potential for innovation and can help with the development of competitive advantage for German companies.

Iceland

Iceland, with a population approximately one tenth that of Wales, is pursuing a policy of turning the country into the world's first hydrogen economy. Built on a strong existing renewable energy resource, the state has encouraged private industry to invest in an infrastructure in Iceland (Arnason and Sigfusson, 2000). Primarily this is through the creation of the consortium Icelandic New Energy, including Norsk Hydro, Shell, Daimler Chrysler and Vistorka (Eco Energy). Vistorka is part public and part privately owned. The vision is seen in five phases:

i. PEM fuel cell bus demonstration in Reykjavik (up to 3 buses)
ii. Replacement of the Reykjavik bus fleet with PEM fuel cell
iii. Introduction of methanol powered PEM cars and public transport
iv. Shipping vessel demonstration
v. Replacement of Icelandic fishing fleet with PEM fuel cell powered vessels

The Ecological City Transport System (ECTOS) is the first substantial demonstration project in Iceland. The first stage of the project consists of the building of a fuelling station producing and compressing hydrogen via electrolysers, fed by hydro- and geothermal electricity. The hydrogen will be compressed to 350bar for storage on-board three fuel cell buses. Alongside the technical implementation, a number of socio-economic and environmental studies are taking place in preparation for the roll out of further hydrogen applications and the eventual 'hydrogenisation' of the Icelandic economy. (Maack and Skulason, 2000), (Skulason and Peterson, 2003).

Italy

The Italian National Hydrogen Programme is supported by the Ministry for Research and the Ministry for Environment. With a budget of €89 million over three years, the programme is considering the development of hydrogen production from renewable sources or from fossil fuels together with CO_2 sequestration in geological formations and development of related technologies. Also included is research into hydrogen/CO_2 separation and the development of hydrogen storage systems. The programme also looks at the development of technologies, components and systems for hydrogen transport and distributed energy generation (Vellone, 2003).

Other Countries

State sponsored hydrogen energy programmes also exist, for example, in Denmark (Sorenson and Sorenson, 2000) Brazil (De Sousa, 2000), Norway and Sweden. Significant research and development continues in a number of other countries with a degree of state sponsorship.

10.7.4 UK Activities

"The ability of hydrogen to replace fossil fuels, especially in transport, will also transform our energy system - and offers a vision of a transport system that is completely clean - with no exhaust emissions."
Tony Blair London, 24 February 2003

In the UK the Department of Trade and Industry (DTI) has been considering the role of hydrogen in the UK economy for some time. Despite a large number of active research programmes in the UK, government promotion of hydrogen energy has been limited until relatively recently. Although there was no commitment to a future hydrogen strategy and no indicated targets, the 2003 energy White Paper “Our energy future - creating a low carbon economy”, was the first significant UK government document that identified the major part that hydrogen can play in the future energy strategy of the UK. The policy document indicates that hydrogen is likely to play a key role in future transport technologies. Initial government support comes via:

- Exemption of hydrogen from road fuel duty
- Enhanced capital allowances with 100% first year write down for hydrogen infrastructure projects
- Support for further fuel cell research
- Giving priority to hydrogen projects in the Carbon Trust’s Innovation Programme
- Funding the London fuel cell bus trial, starting in 2003 and supporting the BP hydrogen fuelling station that runs parallel to the project
- Further support for fuel cell vehicles is promised in the policy
- Support for demonstration projects is also promised, together with regional organisations, particularly for hydrogen production and carbon abatement technologies

With this energy policy white paper as the basis the DTI is currently in the process of developing a strategic framework for hydrogen energy in the UK. The intention is to assess sources of competitive advantage for the UK in the transition to a hydrogen economy and how the transition meets with the strategic priorities of the nation. Finally the review will assess the best ways for this transition to take place and provide a framework for hydrogen economy development in the UK. It must be stressed that at present UK policy towards hydrogen is presented in terms of a possible, rather than probable, alternative.

In addition to the support promised for hydrogen energy development in the energy White Paper, the DTI and Carbon Trust have published a Fuel Cell Commercial Review (Chase *et al.*, 2003), which assesses the potential for the development of the UK fuel cell industry. The report indicates that the industry potential to become a significant world player can be realised through investment now.

A new industry network “Fuel Cells UK” was launched in 2003 to facilitate collaboration and to develop a vision for the future of the UK fuel cell industry. The aim is to develop a fuel cell research programme funded jointly by EPSRC, DTI and the Carbon Trust. Help is also indicated for UK organizations seeking international collaboration, through the EUREKA programme.

The EPSRC funded SUPERGEN programme contains a substantial sustainable hydrogen research programme. The UK Sustainable Hydrogen Energy Consortium (UKSHEC) working on this project comprises 10 UK Universities. The University of Glamorgan is responsible for the hydrogen production research content, whilst others are researching novel hydrogen storage and socio-economic aspects of a sustainable hydrogen economy.

International cooperation is also promised following a research and development agreement between the UK and the US. In 2003 a Memorandum of Understanding (MOU) was signed between the US Department of Energy and the Department of Trade and Industry that will allow cooperation in several broad areas of energy research and development.

10.7.5 Hydrogen Activities in Wales

"The Welsh Assembly Government will promote development that meets the needs of the present without compromising the ability of future generations to meet their own needs."
National Assembly for Wales

The overriding purpose of this document is to create a framework for the transition to a hydrogen economy in Wales and to indicate how Wales can gain a competitive advantage through this transition process. This report forms part of the project “A Sustainable Energy Supply for Wales: Towards the Hydrogen Economy” which has, in part, been supported by the National Assembly for Wales. This demonstrates, at least, a desire to explore the possibilities arising from the transition to a hydrogen economy. The Vision of a hydrogen economy in Wales presented in Chapter 2 of this report provides an initial blue print for Wales to make the transition to hydrogen and, as with any plan, should be regularly reviewed and reframed to reflect current circumstances.

Wales’ strong commitment to sustainability through Section 121 of the Government of Wales Act gives clear guidance that the transition to a hydrogen economy in Wales must recognise the social and environmental impact of introducing new technologies, as well as the economic considerations. This emphasis suggests that Wales should vigorously pursue a version of the hydrogen economy that stresses the importance of renewable sources of hydrogen energy.

As stated in Section 3.6, Wales is already active in hydrogen and in pursuit of the hydrogen economy. Wales has a cluster of seven active hydrogen production plants along the M4 corridor in South Wales, which also represents the main population centre of the country. Although the capacity of these plants is limited, the available volume and their geographic spread could provide the potential for an early hydrogen vehicle-refuelling infrastructure. This cluster is not matched elsewhere in the UK, at least in number. As a result there is also a body of hydrogen expertise already in Wales.

The Hydrogen Valley initiative (H2V) led by the Welsh Development Agency (WDA) brings together a broad coalition from industry, government and academics in support of the development of hydrogen energy applications. H2V has emerged from the WDA's automotive strategy and their Accelerate Wales supply chain development initiative. As a result there is particular emphasis on the transport sector and the promotion of hydrogen transport and fuel cell industries, and to establish markets at home and abroad.

Hydrogen Valley's Vision:
To achieve a zero emission energy based economy supported by sustainable business community through the exploitation of leading edge technologies and stimulation of emerging niche markets.

The strategic objective of H2V is the delivery of technology, research and marketing projects focused on meeting this vision. In turn the strategic goals developed by the H2V partners are defined as follows:

- Production and supply of low cost hydrogen
- To promote the credibility and viability of hydrogen economy
- Development of zero emission integrated transport networks
- Development of a low carbon centre of excellence in South Wales
- Identification and acquisition of support funding
- Development and mass production of Alkaline fuel cells (AFC)
- Identification and enrolment of complementary partners
- Development and manufacture of electric/hybrid vehicles

The Hydrogen Valley Initiative and the University of Glamorgan led "Cymru H_2 Wales" project have worked very closely together to move towards these goals and to identify and initiate projects aligned with the strategy. As a number of these projects are in the process of securing funding, they have not been separately identified here. However, the range of projects instigated in Wales is broad and includes renewable hydrogen production from wind and solar PV, bio-hydrogen through fermentation, hydrogen transport applications based on internal combustion and fuel cell drives, stationary fuel cells for heat and power. Hydrogen transport projects investigated include road, light-rail and marine disciplines for a range of applications. As detailed in Section 10.7.1.1. the Onllwyn clean coal/hydrogen power plant project is currently held up in the planning process, but may well succeed in the near future.

There is also an increasing amount of hydrogen related research and development being conducted in Wales. As detailed in Section 4.2.3, the University of Glamorgan's Hydrogen Research Unit has become recognised internationally for its work on hydrogen, particularly for research on dark fermentative hydrogen production. In addition to this, the University of Glamorgan and other organisations in Wales have research programmes into areas such as biological fuel cells, alkaline fuel cells, hydrogen in internal combustion engines, novel cryogenic hydrogen storage as well as economic, social and policy research related to hydrogen.

The expertise and experience present in Wales provides an ideal basis for early development of hydrogen energy demonstration work. Whether this can be translated into a genuine early hydrogen economy will depend on the continuation of active policy support, particularly from the Welsh Assembly Government.

At present there are promising early signs. In October 2004, the Welsh Assembly Government published its Sustainable Development Action Plan 2004-2007. The action plan contains a top ten commitments. The sixth of these is as follows:

- We will commission a project to investigate the benefits and barriers to promoting the uptake of alternative fuels in Wales, such as biofuels, biogas, natural gas and hydrogen.

11 Economics

11.1 Economics of Hydrogen Energy

How does hydrogen compare?

In all but a few cases it can be argued that simple economics struggle to support the use of hydrogen as an energy carrier at the present time. For hydrogen to be adopted as an economically viable energy carrier, it must be competitive with the current alternatives. Hydrogen is one of the most abundant elements on earth, but it does not occur naturally in molecular form so has to be produced from a primary energy source. Therefore, hydrogen costs more than that primary energy source. Although today's common fuels like petrol or natural gas also incur production and distribution costs, they are still generally cheaper to produce than hydrogen. In addition, the relative difficulty of storing and distributing hydrogen adds to its cost at point of use.

Table 11.1 and Figure 11.1 give a comparison of costs for various energy sources, demonstrating the variation in cost of hydrogen based on current production technologies. It also demonstrates the impact of taxation on petrol and market price fluctuation on the price of natural gas.

Table 11.1 Energy cost comparison

Fuel / Energy Carrier	Price	£/GJ
Petrol	84p/litre (pump price)[1]	£26.25/GJ
	16.6p/litre (pre-tax estimate)[2]	£5.19/GJ
LPG	39p/litre (forecourt price)[1]	£15.28/GJ
	29p/litre (pre-duty)	£11.36/GJ
Natural Gas	$8.00/MMBtu (Oct 2004 Peak) [3]	£3.92/GJ
	$2.98/MMBtu (Base cost assumption) [4]	£1.80/GJ
Hydrogen	Reforming Natural Gas	£6.5/GJ
(typical production cost values)	Partial Oxidation of Oil	£7.5/GJ
	Coal Gasification	£7.01/GJ
	Biomass Gasification	£8.28/GJ
	Hydroelectric Electrolysis	£7.64/GJ
	Wind Electrolysis	£16.5/GJ
	Solar Thermal Electrolysis	£24.84/GJ
	Solar Photovoltaic Electrolysis	£28.66/GJ

[1] AA (2004)

[2] UKPIA /IP (2002)

[3] Oilnergy.com (2004)

[4] Basis for the cost of hydrogen from natural gas feedstock

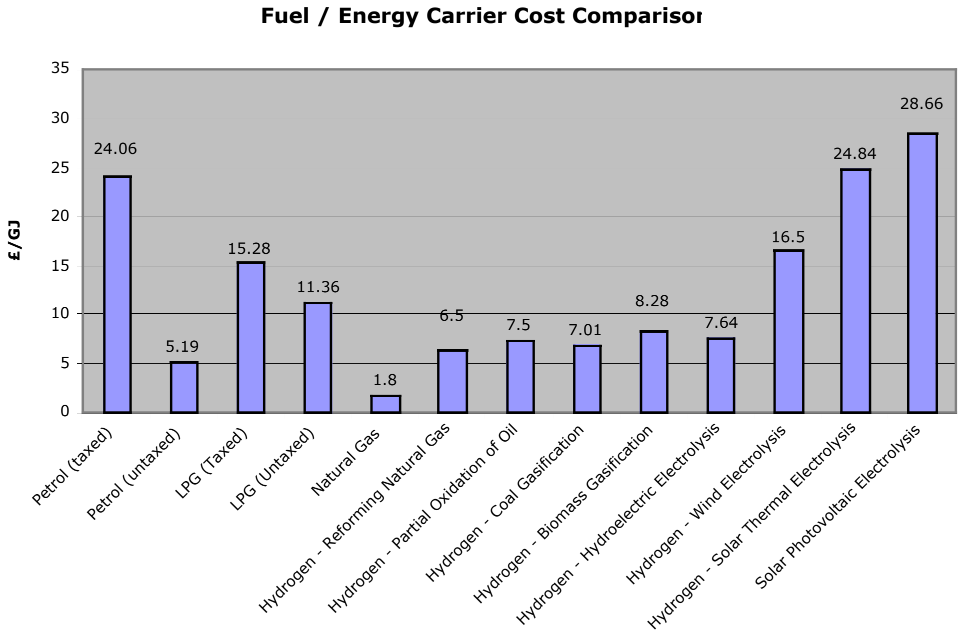


Figure 11.1 Fuel / energy carrier cost comparison

Environmental and Social Costs

However, the current costs do not give the whole picture. An adequate comparison of the cost of energy technologies also needs to assess the environmental and social costs. Momirlan and Veziroglu (2002) argue that the costs of the prevention or abatement of pollution and the potential adverse effects on the climate of burning fossil fuels should also be considered in any comparison between hydrogen and other energy systems. These external costs, or externalities (Baumol & Oates, 1988) should be internalised, wherever possible, in a sustainable development decision-making process.

Veziroglu (1997) responds to the advocates of letting hydrogen compete in a free market economy. He reports how the Senator chairing a congressional committee investigating the hydrogen economy, asked him, "Dr Veziroglu, in this country we have a free market economy. If hydrogen is so good, let it compete and win." Veziroglu answered "Senator, in this country we may have a free market economy, but we do not have a fair market economy. You pass a law making every product responsible for its environmental damage, nobody will sell petroleum, but hydrogen".

Among other studies considering the externalities of hydrogen and fuel cells, Hörmandinger and Lucas (1996) indicate that including external costs, the comparison of fuel cells against diesel in transport is not straightforward. Clearly, many externalities such as costs of abatement can only be approximated, whilst social cost or climate change impact are difficult if not impossible to fully calculate. In the absence of broadly accepted norms for external costs, any comparison of technologies will understandably depend on whether high or low estimates for the externalities are used.

Even if externalities were easier to calculate, it is unlikely in the short term that they would be fully factored in due to:

- The overall scale of the real costs for air quality preservation, climate change impacts, etc.
- Reluctance of one government to act unilaterally to fully implement these costs, for fear of making their industry uncompetitive.
- Whilst there is a rise in "ethical" investments, shareholders and other investors are fundamentally impressed by financial returns. As yet, it is difficult to build externalities into the balance sheet.

Fiscal Measures

Tax regimes for energy systems that penalise greenhouse gas emissions and other air pollution, combined with incentives for environmentally or socially beneficial developments help to improve the economic attraction of hydrogen as an energy carrier, particularly when produced from sustainable, non-CO_2 producing processes. In the UK, fiscal measures are in place that provide a degree of support to a nascent hydrogen energy market, including:

- Exemption from road fuel duty for hydrogen vehicles
- Granting enhanced capital allowances with 100% first-year write-down for investment in hydrogen fuel infrastructure
  (DTI, 2003a)

Clearly, these are kick-start measures to provide a short-term incentive to development. Longer term, it is likely that a desire for protection of tax revenue will lead to an erosion of these benefits, as has already been seen in Germany where a fuel tax is already being applied to hydrogen, irrespective of production route. If this is to be the case, timing is critical to avoid a reversal and should be backed up with an extension of the current measures, namely:

- Increased vehicle excise duty for high CO_2 emitters
- Increased company car taxation on high CO_2 emission vehicles

As experience with the introduction of CNG vehicles in Argentina has shown, preferential taxation is essential in creating competitive viability for a new fuel. However, even in this case with CNG at only two-thirds the price of diesel and one-third the price of petrol the market penetration of CNG in Argentina is still only 18% in the last decade. This would suggest that hydrogen will need to be much better than equivalent in price to existing fuels to achieve market acceptance.

The role and impact of emissions trading has been discussed in Section 10.4.7. Despite some potential inefficiency in this system, greenhouse gas trading goes some way to demonstrate how governments can create a framework for a market mechanism to be applied that addresses the costs of externalities. The start of the European greenhouse gas trading mechanism from January 2005 will extend this. However, the failure to include transport processes in the scheduled activities misses the single sector with the greatest potential greenhouse gas burden and where economic incentives to decarbonize would have the greatest effect. For carbon trading to have maximum impact, there needs to be a global trading scheme and provision to include transport within the mechanism. Kyoto potentially provides the framework for this, but the refusal to ratify from the United States and the exclusion of transport from many of the existing trading mechanisms reduces the overall benefit.

Making the transition

The economic argument for implementation of a hydrogen economy is not a simple one. Kiesling (2003) suggests that these doubts have existed at various stages of energy transition. The handling attractions of oil over coal as a transport fuel were realised at an early stage, but the high initial cost of oil and useful oil products was a barrier to oil supplanting coal as an energy source. However, economies of scale led to improvements in the costs of oil products, particularly for transport, leading to the ascendancy of oil. Scott (1995) describes this as "snag and tug". The attraction of an environmentally beneficial, more resource equitable hydrogen energy system provide the tug, whilst the barriers to implementation, whether economic, technical, social or political provide the snag.

The significant national and international research, development and demonstration funds currently being promised are reported in Chapter 10 of this report. Keisling (2003) argues that whilst subsidies may help to nurture new technologies, as needed for hydrogen energy to become a reality, there is a danger that subsidies in the end may stifle innovation and entrepreneurialism. Cognizant of this danger the US DoE has set a range of development targets for hydrogen and related technologies and a milestone of 2015 for the decision to proceed with national commercialisation of hydrogen. In addition, the US and European hydrogen development programmes are not simply grant subsidies, rather they require a significant contribution (financial and physical) from organisations to gain partial project funding (typically 35% reimbursable for a European 6th Framework project). As well as this financial demonstration of commitment required, the level of excellence required for a successful project proposal is a major barrier to entry for many organisations.

Substantial investment will be required to realise a hydrogen economy. The IEA have estimated that a global investment of at least $1trillion will be required if a hydrogen economy based on fuel cell technology is to be realised (Haug, 2004), although a hydrogen economy based on combustion technology could cost less than half of this figure. As well as nurturing through government actions, investment from the private sector will clearly be required. Many companies have already spent millions of pounds on company hydrogen and fuel cell programmes, but the scale of overall investment will eventually need to be much more for a realistic change to take place. Similarly, private investors of any kind will only fund ventures where the perceived risk is manageable and of a scale commensurate with the investment. Despite a growing number of potential private investors in hydrogen and related technology, the relatively small sums actually provided to date suggests that risks are seen as being too great in too many cases at present.

Hydrogen Substitution of Petrol and Diesel in Wales

If Wales is to embrace hydrogen technology, particularly in the transport sector, then a good starting point would be to adopt the European Commission's targets for the replacement of petrol/ diesel with hydrogen (as indicated in Section 10.7.2.4, European Commission, 2001). In 2003, the estimated total consumption of petroleum and diesel in Wales was 2.5million tonnes in a UK total of 50 million tonnes (DfT, 2003b). Table 11.2 shows the required amounts of hydrogen for Wales if these targets are to be met. The table shows the amount of hydrogen substitution required based on transport energy usage remaining constant at 2.5million tonnes and also on the basis of continued transport energy growth (average 1.22% annual growth in the decade 1993-2003).

Table 11.2 Calculated hydrogen substitution of petroleum and diesel for transport in Wales

	2015	2020
Hydrogen Substitution, based on constant transport energy usage	17900 tonnes H_2 per year = 2150 Terrajoules (2.04 tonnes H_2 per hour)	44800 tonnes H_2 per year = 5380 Terrajoules (5.11 tonnes H_2 per hour)
Hydrogen substitution, based on 1.22% transport energy growth rate (1993-2003)	20700 tonnes H_2 per year = 2480 Terrajoules (2.36 tonnes H_2 per hour)	55000 tonnes H_2 per year = 6600 Terrajoules (6.27 tonnes H_2 per hour)

11.2 Costs

Sections 11.2.1-11.2.4 of this report consider the costs of the technologies associated with hydrogen energy in a greater level of detail. The information is based on recently published information, and is presented in a standardised form. All costs have been converted to a lower heating value (LHV) basis for hydrogen. Currency used is pounds sterling for a UK/Wales audience. However, absolute values must be used with some caution. Dates of the cost estimates are given with each reference, so the impact of inflation must be considered. Conversely, greater experience levels would tend to reduce the costs. Capital and unit hydrogen costs have been presented on a "best-fit" curve from the reported data. Where there is a significant sensitivity, for example due to plant feed costs, a general indication of the impact is also shown on the cost curve.

Whilst references include authors from several parts of the world, the majority of the cost survey work referred to is US based. This may have a tendency to under estimate the cost if applied in the UK, particularly in the case of larger plant installations, due to additional impact of, for example, UK health and safety legislation on project cost. Alternatively, it may be fair to assume that costs are generic and not based on competitive quotations from suppliers. The market approach of competitive tendering would tend to reduce the costs, again for the larger plant installations.

Despite these potential discrepancies, the costs are intended as an indication of the state-of-the-art or the current prediction of future cost.

11.2.1 Production economics

A number of published systematic surveys of the economics of hydrogen technologies have been conducted recently, notably for the US National Renewable Energy Laboratory. This Section of the report brings together the most recent and relevant economic comparisons, in particular drawing on the surveys conducted by Padro and Putsche (1999), Adamson and Pearson (2000), Dutton (2002), Simbeck and Chang (2002), Larsen *et al.* (2003) and Boyce *et al*. (2004).

Steam Methane Reforming

Each of the surveys conclude that steam methane reforming (SMR) (See Section 5.1.1) is not only the most common, but also in most circumstances the least expensive method of producing hydrogen (with the possible exception of localised chloralkali plant by-product hydrogen. See Section 5.1.4). However, the following issues need to be taken into account:

- The additional cost and complexity of capturing the CO_2 produced from steam methane reforming (or other hydrocarbon based production processes)
- The impact of natural gas prices on the cost of hydrogen produced
- The size of plant required and whether this is to be a central distribution hub or a localised production facility (e.g. at a fuelling station forecourt)

Gaudernack and Lynum (1998) indicate that for a large SMR plant the addition of CO_2 sequestration adds a further 27% to the total cost (capital and operating cost). This allows for the CO_2 to be scrubbed from the process and flue streams and taken to shallow sea disposal via a relatively short pipeline. For a similar size plant, Ogden (2002) suggests a figure closer to an additional 10% where there is a relatively nearby reservoir for CO_2, with good injection characteristics. It is likely that the costs for CO_2 sequestration in many countries (including Wales) would be towards the upper end of these estimates (Gough *et al.,* 2002). There is potential to biologically sequester CO_2 produced in this way, but we should be realistic about the potential for forest planting to capture our wasteful carbon production. For a large 120,000 Nm^3/hr SMR hydrogen plant, producing 2400 tonnes per day of CO_2 an equivalent area of some 3000 hectares per year would need to be planted to biologically sequester the carbon produced (estimated from Gough *et al.,* 2002). In addition, any carbon captured would also be instantly released in the event of a forest fire.

Natural gas prices have climbed significantly over the past decade. With spot prices reaching as high as $9.50/MMBTU (£5.63/GJ) (Oilnergy.com, 2004) the impact on SMR hydrogen can be dramatic. At the September 2004 average natural gas price of $6.50/MMBTU (£3.85/GJ), typical SMR hydrogen costs would be £7.04/GJ compared with £4.36/GJ hydrogen at an average of $3/MMBTU (£1.78/GJ) price for natural gas that was realistic 2 years earlier. Boyce *et al.* (2004) report a 74% rise in hydrogen production cost with a doubling of natural gas feedstock price. Whilst the transient effects of natural gas price can often balance out in the longer term, there is a continuing general upward trend in natural gas price. The potential impact on hydrogen produced from natural gas should be recognised, particularly when compared to hydrogen from renewable resources like wind and biomass, that are relatively unaffected by geo-political instability and oil and gas price increases. Larsen *et al.* (2003) have indicated the impact on the ratio of SMR operating expenses (OpEx) and capital expenditure (CapEx) for varying feedstock (See Figure 11.2). They suggest a trade off between OpEx and CapEx and that an SMR plant designer can design the plant for low total investment when feed costs are expected to be low and to minimise feed consumption when the feedstock costs are high.

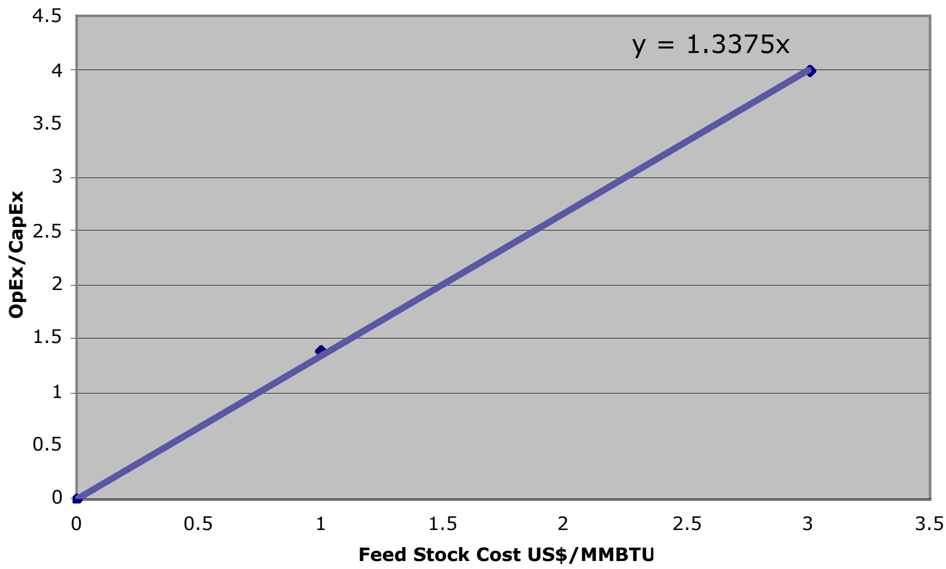


Figure 11.2 Ratio of operating expenditure and capital expenditure for SMR plant

In addition, the impact of export steam credit can have a major effect on the overall production cost for an SMR. Where there is a market (internal or external) for co-produced steam Boyce *et al.* (2004) suggest that hydrogen costs can typically drop by 28% for a doubling in export steam credit value.

Most current commercial SMR plant designs follow a similar flow sheet, whether the capacity is hundreds of thousands of Nm^3/hr or just a few hundred. However, there are economic difficulties in scaling down to below production capacities much lower than 500Nm^3/hr. As the reported cost data below shows, there is a significant specific cost advantage in larger SMR plant capacities. There is a large amount of research ongoing to improve the economics of steam methane reforming at lower throughputs, down to on-board vehicle reforming (although this latter option has now been dropped from US DoE research programmes).

Figure 11.3 shows an indication of the capital investment required for various sizes of steam methane reforming plant and Figure 11.4 shows the unit cost of hydrogen over a range of plant capacities based on a collection of the reported specific cost data for steam methane reforming plant. In both cases an indicative equation is given to calculate the respective values.

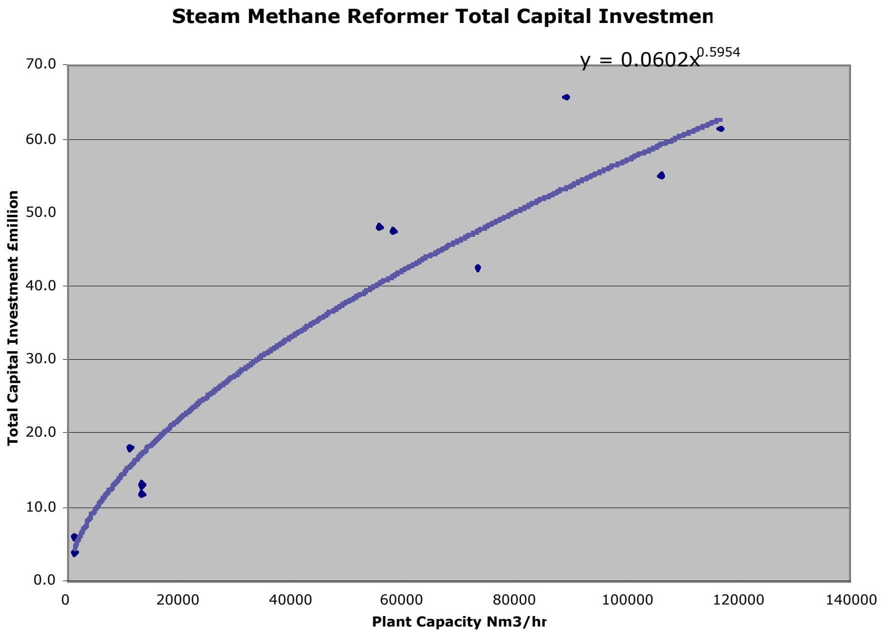


Figure 11.3 Reported capital costs for steam methane reforming plant

References: Padro and Putsche (1999), Dutton (2002), Simbeck and Chang (2002), Basye and Swaminathan (1997), Boyce et al., (2004).

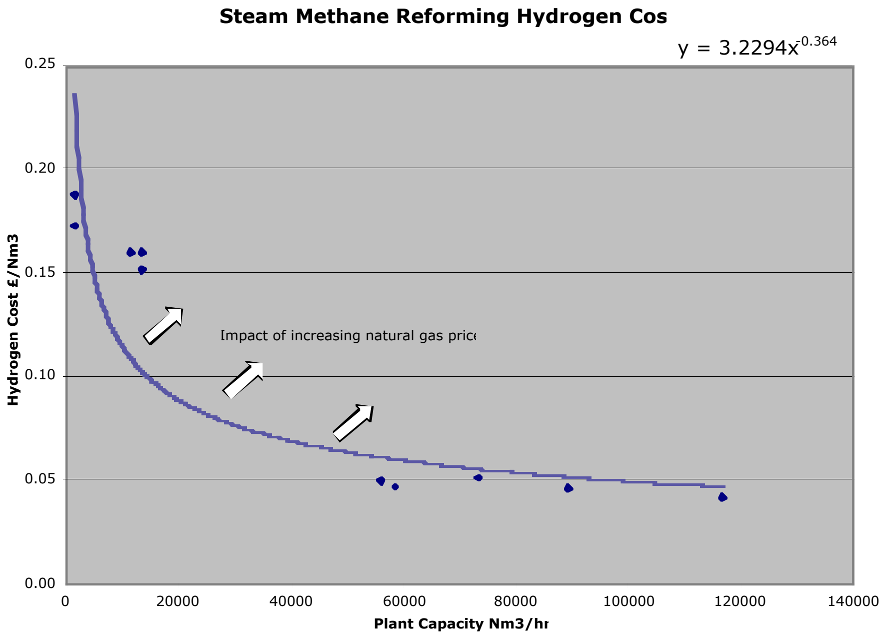


Figure 11.4 Hydrogen costs from steam methane reforming plant

References: Padro and Putsche (1999), Dutton (2002), Simbeck and Chang (2002) and Basye and Swaminathan (1997).

Partial Oxidation of Oil

Over the last ten years there has been an increase in the use of partial oxidation (POX) of oil as a process to produce hydrogen. The primary drivers are reduced sulphur specification in fuels increasing the need for hydrogen in the refinery and a relative surplus of heavier oils providing a more cost effective route than "over-the-fence" steam methane reforming within the refinery. Any hydrocarbon feedstock can be used in a partial oxidation plant, but typically heavy oil is used for this in refinery processes. Efficiency of the partial oxidation process at 50% is typically significantly lower than SMR at 65-75% (Dutton, 2002).

The minimum economic capacity for partial oxidation plants typically starts from approximately 0.5 million Nm³/day, although smaller plants are now starting to be economically competitive. Partial oxidation plants usually require pure oxygen feed and associated air separation technology, which can also represent a significant capital and operating outlay, or utility cost. Estimated costs for POX hydrogen are shown in Figures 11.5 and 11.6, based on reported data. (Padro and Putsche (1999), Adamson and Pearson (2000), Dutton (2002), Simbeck and Chang (2002)).

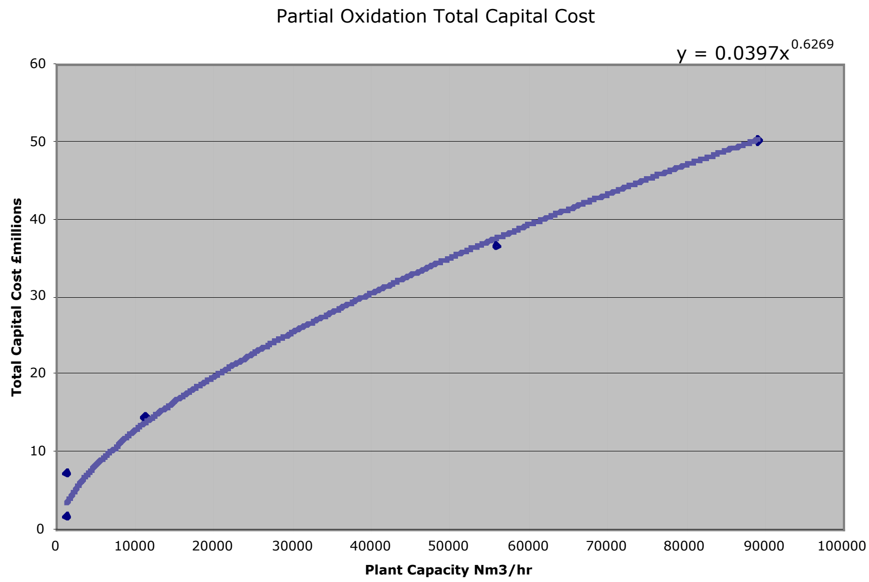


Figure 11.5 Reported capital costs for partial oxidation plant

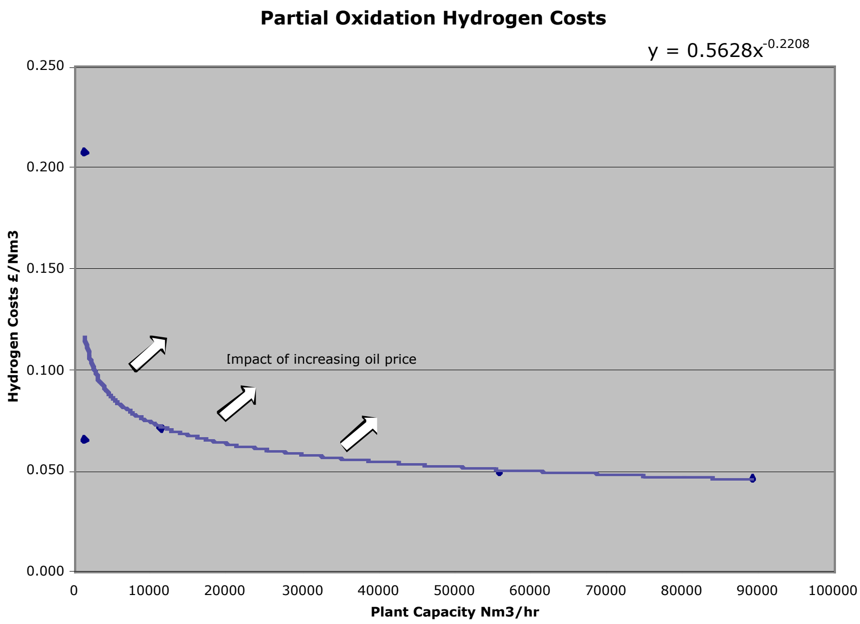


Figure 11.6 Hydrogen costs from partial oxidation plant

gasification

The production of hydrogen using coal gasification is a well-established technique (see Section 5.1.2) and has proven to be an economic choice in parts of the world where oil or natural gas is expensive and coal is available. Typical efficiencies (30-40%) are lower than steam methane reforming or partial oxidation. However newer integrated gasification combined cycle (IGCC) designs include the integration of a power producing turbine cycle and are likely to improve the overall efficiency and economics of the technology as it moves beyond the demonstration phase.

As with other hydrocarbon routes to hydrogen, the CO_2 and H_2S produced by the process have to be sequestered to prevent environmental impact, adding to the capital and unit cost of the hydrogen and energy produced. In addition, the economic and environmental impact of the feedstock extraction/procurement and of solid waste is an additional consideration. Typically plants are of in the range 200-800MW power recovery, but smaller modular units in the range 50-150 MW are predicted.

Figure 11.7 and Table 11.3 show estimated cost data for hydrogen from coal gasification based on reported data.

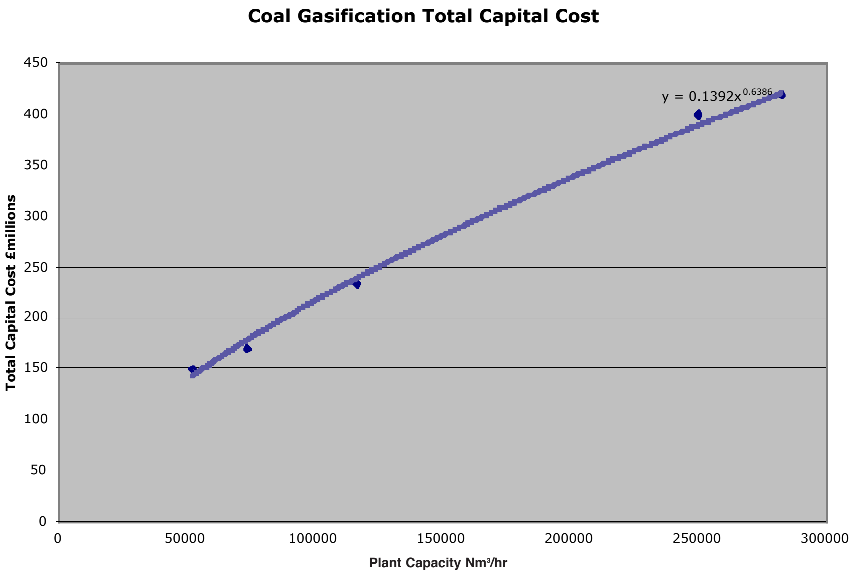


Figure 11.7 Reported capital costs for coal gasification plant

Table 11.3 Reported cost of hydrogen from coal gasification

Plant Size (10^6 Nm^3/day)	Hydrogen Cost (£/Nm^3)	References
2.8	0.077	Kirk-Othmer (1991) in [1]
6.78	0.066	Foster-Wheeler (1996) in [1]
	0.057	Bailey(1980) in [2]
	0.046	Bailey(1980) in [2]
	0.028-0.133	Leipa and Borhan (1989) in [2]
1.76	0.070	Simbeck and Chang (2002)
	-	Tavoulareas and Charpentier (1995)

[1] Padro and Putsche (1999), [2] Adamson and Pearson (2000)

Hydrocarbon Pyrolysis

Hydrogen can be produced from hydrocarbons without producing CO_2 using a pyrolysis process (see Section 5.1.3). High temperature pyrolysis of methane (or other hydrocarbon feedstock) produces hydrogen and carbon black and has been used commercially in the Kvaerner "Carbon black and hydrogen process". Gaudernack and Lynum (1998) have indicated that the economics of hydrogen production from methane pyrolysis can compare favourably with steam methane reforming, particularly where there is credit given for a revenue stream from the carbon black produced and especially when compared with the SMR case with CO_2 sequestration (see Table 11.4).

Table 11.4 Reported specific cost data for hydrogen from hydrocarbon pyrolysis plant

Plant size (10^6 Nm^3/day)	Total Capital Investment (£million)	Hydrogen Cost (£/Nm^3)	References
6.72	350	0.070	CB&H process without carbon black revenue. Gaudernack and Lynum (1998)
6.72	350	0.038	CB&H process with carbon black revenue. Gaudernack and Lynum (1998)

Biomass Gasification

The potential to use biomass as a non-polluting feedstock to gasification plant is being widely explored (see Section 5.2.4). When combined with CO_2 capture techniques, there is the potential for a negative carbon balance process (i.e net carbon removal from the atmosphere). However, the use of woody biomass as a feedstock to produce power and hydrogen from a gasification process is currently limited. Further application is dependant on the development of cost effective technology. Table 11.5 shows the reported costs of hydrogen from biomass gasification.

Table 11.5 Estimated capital and unit hydrogen costs biomass gasification plant

Plant size (10^6 Nm^3/day)	Total Capital Investment (£million)	Hydrogen Cost (£/Nm^3)	References
0.72	67	0.087	Mann (1995a) in [1]
2.16	109	0.058	Larson (1992) in [1]
2.26	148	0.067	Larson (1992) in [1]
		0.053 – 0.067	Ogden et al (1995) in [2]
1.76	176	0.119	Simbeck and Chang (2002)

[1] Padro and Putsche (1999), [2] Adamson and Pearson (2000)

Biomass Pyrolysis

Pyrolysis of biomass is similar to the pyrolyisis of other hydrocarbons (see Section 5.2.4). Typically, thermal decomposition of the biomass takes place in the absence of oxygen to produce a bio-oil that can be used to produce hydrogen via steam reforming and then purified as with a standard SMR. The economics of the process are sensitive to on-site or purchased bio-oil feedstock and the potential production of a phenolic resin co-product. Table 11.6 shows the reported capital and unit hydrogen costs for biomass pyrolysis plant.

Table 11.6 Reported cost data for hydrogen from biomass pyrolysis plant

Plant size (10^6 Nm^3/day)	Total Capital Investment (£million)	Hydrogen Cost (£/Nm^3)	References
0.024	2	0.085	Mann (1995b) in Padro and Putsche (1999)
0.243	11	0.067	Mann (1995b) in Padro and Putsche (1999)
0.811	33	0.059	Mann (1995b) in Padro and Putsche (1999)
0.066		0.186	Iwasaki (2003)

Electrolysis

The production of hydrogen from the electrolysis of water has been known as a process for over 200 years and is well established as a commercial technique (see Section 5.1.5). Indeed electrolysis accounts for a significant number of existing hydrogen production sites world wide, if only accounting for some 4% of the global hydrogen production volume. Electrolysis has particular advantages where hydrogen is needed and pipeline natural gas or tanker deliveries of LPG (for steam methane reforming) are absent. Figure 11.8 and 11.9 presents reported cost data for hydrogen from electrolysis plant from a range of renewable electricity inputs.

The most significant benefit of electrolysis over hydrocarbon routes to hydrogen is the absence of greenhouse CO_2 produced when using renewable electricity as the driver. For this reason, it is the most likely hydrogen production technology to be linked with renewable electricity production.

Often omitted from many analyses of the costs of producing hydrogen from electrolysis is the benefit of co-produced pure oxygen. The economics of electrolytic hydrogen production can be significantly enhanced when this oxygen can be utilised *in situ*, e.g. for industrial or medical use. An oxygen credit of £0.10-0.15/Nm^3 can have a significant bearing on the profitability of an electrolysis scheme.

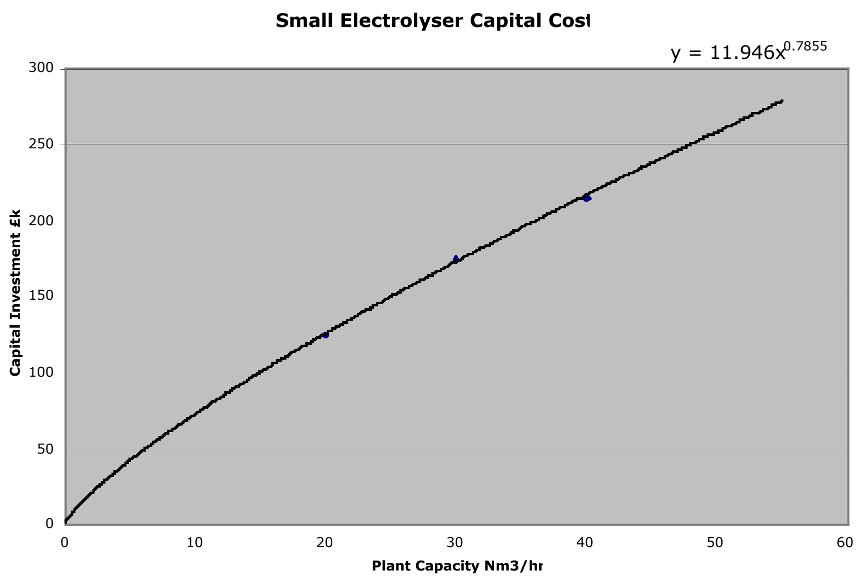


Figure 11.8 Reported costs for small electrolyser plant

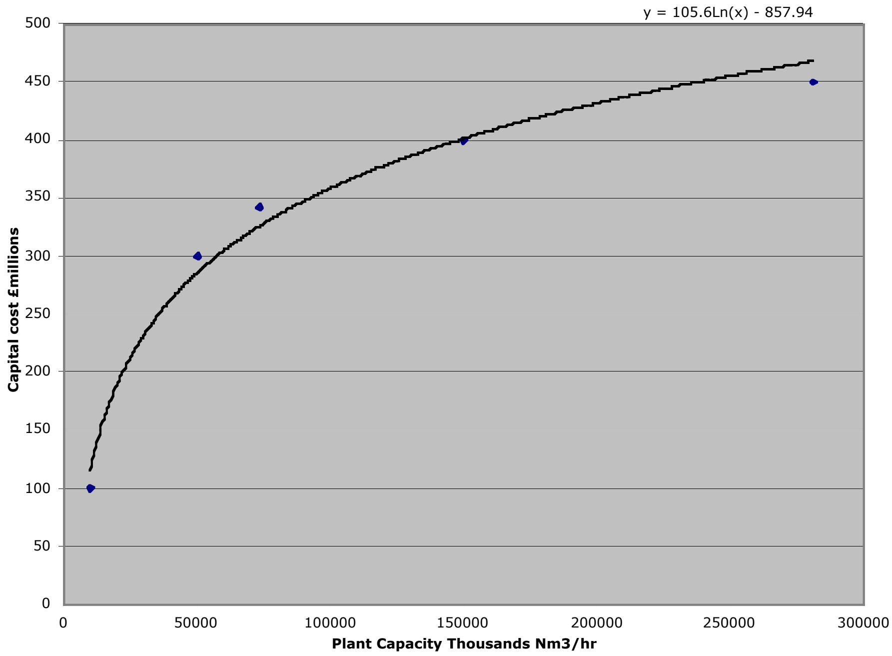


Figure 11.9 Reported costs for large electrolyser plant

Wind / Electrolysis

It is likely that government commitments (Europe, UK & Wales) to renewable energy provision will continue to rely on on-shore and off-shore wind for the majority of their renewable energy quota for at least the next ten to fifteen years. However, the intermittent nature of wind and hence wind energy poses some problems. Electricity supply has to match demand, and the transmission system needs to be continuously balanced. In the UK, the British Electricity Trading and Transmission Arrangements (BETTA) and its forerunner the New Electricity Trading Arrangements (NETA) incorporate this need for balance, but have tended to penalise smaller, intermittent renewable sources like wind generation in the balancing mechanism. Although these trading mechanisms are evolving, there is still a greater financial risk for operators of less predictable sources, like wind.

The coupling of a hydrogen electrolysis plant to wind electricity generation provides a practical solution to the problem of wind intermittency, the hydrogen acting as an energy storage medium. In some locations, the cost of electricity from wind is competitive with electricity from fossil fuel sources, but coupled electrolytic hydrogen production struggles to be competitive in most circumstances. However there are significant economies of scale that can be derived from investment in larger electrolysis plant. Additional economic benefits could also be derived from mass production of electrolysis plant, rather than the bespoke units installed for current demonstration plants. It is also clear that the economics of electricity production and hence hydrogen production from wind will vary considerably with mean wind speed.

Solar Photovoltaic (PV)

As with many renewable energy sources, solar energy is clearly intermittent and the benefits of electrolytic hydrogen production in overcoming this intermittency can apply. Grants up to 50-60% are currently available for PV installation in the UK. However, the high capital cost element of solar PV electrolysis currently makes the technology relatively expensive and hence a route to hydrogen that may be difficult to pursue. In part, this is due to the limited scale of the production plant studied, but it is difficult to envisage how the technology can compete in all but a few locations, even if economies of scale can be achieved. An exception to this is where solar panels can be used instead of architectural glass, as proposed in the USHER project in Cambridge, which was unfortunately abandoned when part of the financing was withdrawn (Slater 2002).

Concentrated Solar Energy

Concentrated solar energy can be used to generate a.c. current to feed to an electrolyser to produce hydrogen. Research into this technology is currently ongoing, with some economic promise. However, cost projections still make the technology appear uncompetitive at this stage (Glatzmaier *et al.* 1998).

High Temperature Electrolysis

Traditional electrolysis relies on electricity consumption as the main energy driving force. By significantly increasing the temperature of operation the consumption of electricity can be reduced. In this case, steam is converted to hydrogen and oxygen by a.c. current and heat. This technology is currently at the research stage and it is not clear how much cost benefit (if any) will be derived from the technique (Glatzmaier *et al.* 1998).

Table 11.7 Reported cost data for hydrogen from various electrolysis plant

Plant size (10^6 Nm^3/day)	Total Capital Investment (£million)	Hydrogen Cost (£/Nm^3)	References
Non specific Electrolysis Plant			
0.096	7	0.191	Andreassen (1998)
2.814	1	0.138	Kirk-Othmer (1991)
6.75	510	0.163	Foster-Wheeler (1996)
1.76	342	0.268	Simbeck and Chang (2002)
Wind/ Electrolysis Plant			
0.247	95	0.134	Mann *et al.* (1998)
0.279	63	0.074	Mann *et al.* (1998)
0.0005	0.06	0.120	Dutton *et al.* (2000)
0.005	0.3	0.095	Dutton *et al.* (2000)
Solar PV			
0.195	230	0.279	Mann *et al.* (1998) (projection for 2010)
0.209	123	0.165	Mann *et al.* (1998) (Projection for 2020)
Concentrated Solar Energy			
0.015	14	0.432	Glatzmaier *et al.* (1998) (projection for 2010)
0.015	13	0.403	Glatzmaier *et al.* (1998) (projection for 2020)
0.7	384	0.272	Glatzmaier *et al.* (1998) (projection for 2010)
0.829	375	0.227	Glatzmaier *et al.* (1998) (projection for 2020)
High Temperature Solar Electrolysis			
Not specified	180 (£/GJ)	0.327	Glatzmaier *et al.* (1998) (projection for 2020)
Not specified	238 (£/GJ)	0.415	Glatzmaier *et al.* (1998) (projection for 2020)

Biological Production

Biologically, hydrogen can be produced either photosynthetically or from dark fermentative processes (see Section 5.2.3). Bio-hydrogen production from biomass is, again, CO_2 neutral and sustainable. Fermentative technology is at the stage of moving from R&D lab to pilot-scale. Research work is ongoing to achieve sustained continuous production and optimised processes. The photosynthetic route faces considerable difficulties in the design of photo-reactors and existing hydrogen yields are economically unpromising. Dark fermentative H_2 production is possibly a more promising technology for the future and may provide lower costs of hydrogen in the longer term. However, there are still a number of issues to overcome to make the technique viable beyond lab scale. Hence overall comparative economics are not fully established.

There has been limited reporting of comparative unit costs of fermentative hydrogen production. Tanisho (1996) reports a unit cost of hydrogen production from sugar cane of 0.26 DM/kWh (£29/GJ). Whilst this compares favourably with some of the other renewable routes to hydrogen, there is still significant scope for improvement and a promise of more competitive process economics towards the target figure of $15/GJ (£9.38/GJ) set by the US Department of Environment Hydrogen Program. Work at the University of Glamorgan suggests that the estimated cost of hydrogen from dark fermentation of biomass could be as low as £4.8 - £6/GJ (£0.04 – 0.06/Nm^3) on the basis of similar anaerobic digestion technology (Hawkes *et al.,* 2004).

By-product Hydrogen

Some of the cheapest existing production sources of hydrogen in the world are to be found at chlorine production plants using the Chloralkali process (see Section 5.1.4). Essentially this is the electrolysis of a brine solution to produce chlorine, sodium hydroxide and hydrogen. The hydrogen by-product is typically burned, often as a supplementary fuel to satisfy on-site power needs, but sometimes simply flared. The chloralkali process accounts for 95% of the world's 42 million tonnes per year chlorine production, co-producing approximately 1.2 million tonnes per year of hydrogen at an estimated cost of £2.5/GJ (World Chlorine Council, 2002).

The attraction of the low cost of hydrogen produced by this process has to be tempered by the limited growth potential for the chloralkali process, the location specific hydrogen production and the potential for harmful emissions from the process, e.g. mercury.

11.2.2 Hydrogen Storage Economics

For hydrogen to be adopted as a common energy carrier, it is important that cost-effective hydrogen storage systems are developed. More than this, hydrogen storage needs to be efficient in terms of the space taken up, particularly for use in the automotive industry, or for portable applications. Although there are a number of promising alternatives emerging, current practical hydrogen storage choices are supply limited (see Chapter 6). Storage in metal compressed gas cylinders dominates the current market, despite this type of storage having a relatively low product density. This is a barely tolerable storage solution for stationary applications or buses, and is particularly ineffective for smaller applications such as passenger cars.

The hydrogen storage challenge

A typical family saloon car has a fuel tank of some 58 litres, shaped neatly to the body of the vehicle. A fuel efficiency of 8 litres per 100km (35.3 mpg) gives a maximum distance between refuelling of 725km (450 miles). The fuel tank represents only a small fraction of the overall vehicle cost.

Assuming a fuel cell vehicle efficiency of 45%, achieving the same 450 mile range would require 8.1kg of hydrogen. With current 180 bar cylinder technology, this would require 13 cylinders, each 1500mm long and 230mm diameter. Excluding current cylinder delivery costs, the hydrogen in the 13 cylinders would currently cost £377 (i.e. over 8 times as much as the taxed unleaded fuel).

In the "National Hydrogen Energy Roadmap"(US DoE, 2002a), the US Department of Energy indicated that none of the current storage technologies satisfy the attributes sought by manufacturers and end users, neither in functionality nor cost.

The report of the UK Chief Scientific Adviser's Energy Research Review Group (Office of Science and Technology, 2002), recognised the current short comings in the state-of-the-art for hydrogen storage. The report commented:

> *"Research priorities should include storage technologies, particularly those which could lead to a step change in performance, and sustainable methods of hydrogen production. "*

US DoE Targets

In July 2003, the US Department of Energy issued the "Grand Challenge" for basic and applied research, development and demonstration of hydrogen storage systems to meet the objectives as detailed in Table 11.8

Table 11.8 US Department of Energy hydrogen storage targets

Storage Parameter	Units	2005	2010	2015
Usable, specific-energy from H_2	kW.hr/kg	1.5	2	3
(net useful energy/max system mass)	(kg H_2/kg)	(0.045)	(0.06)	(0.09)
Usable energy density from H_2	kW.hr/L	1.2	1.5	2.7
(net useful energy/max system volume)	(kg H_2/L)	(0.036)	(0.045)	(0.081)
Storage system cost	$/kWe.hr net	6	4	2
	($/kg H_2)	(200)	(133)	(67)
Fuel cost	$ per gallon gasoline equivalent at pump	3	1.5	1.5
Loss of useable hydrogen	(g/hr)/kg H_2 stored	1	0.1	0.05

Hydrogen Storage Costs

In presenting the costs of a number of hydrogen storage options, availability and maturity of technology needs to be taken into account. Compressed gas storage is widely available and an established technology. Liquid hydrogen storage is also a mature technology, but the current absence of production facilities in many parts of the world (including the UK) reduces availability and can add to current costs.

Despite the technology being known for several decades, metal hydride hydrogen storage applications have limited commercial availability. Although manufacturer's claims vary, current low temperature metal hydride storage technology still suffers from a low hydrogen capacity by weight (typically 2% hydrogen by weight). As there is currently a significant amount of research effort aimed at improving metal hydride performance, costs may well improve.

A range of hydrogen storage costs is presented in Figures 11.10 and 11.11 and Table 11.9. Taken from Padro & Putsche (1999), the table covers storage in the form of compressed gas, liquid hydrogen, metal hydride. In this case the specific total capital investment is given in terms of the total capital investment divided by the annual throughput. Storage cost represents the ongoing cost per GJ of hydrogen.

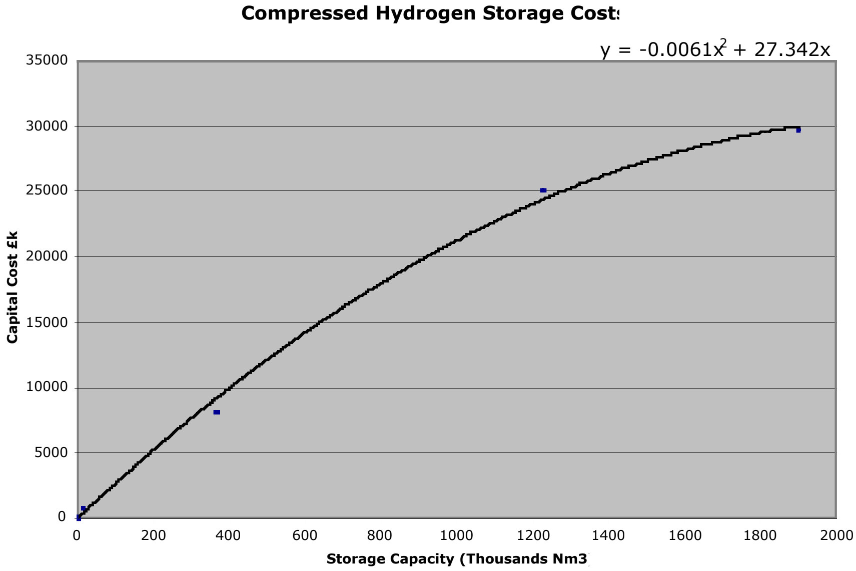


Figure 11.10 Reported compressed hydrogen storage costs

Although costs have been reported for compressed hydrogen storage at capacities well in excess of 2 million Nm3, it is unlikely that compressed systems would be installed above this capacity due to the high capital cost.

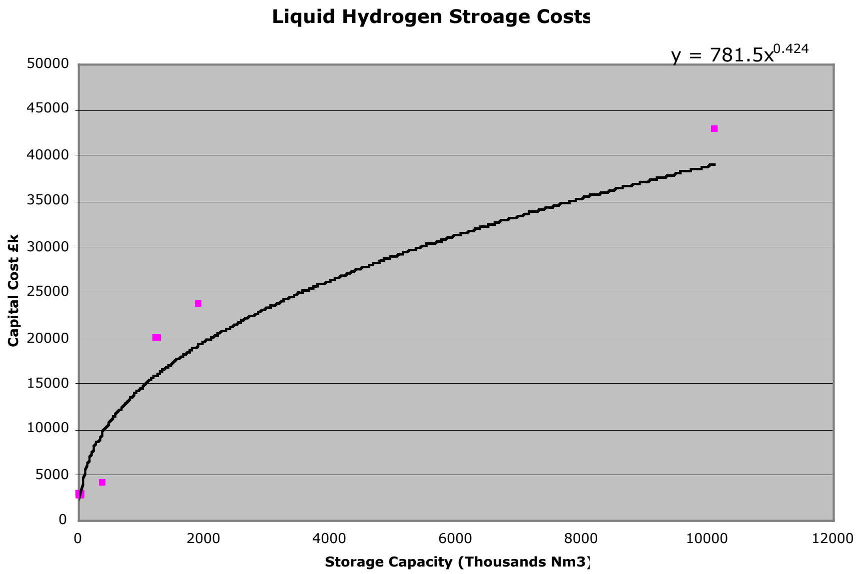


Figure 11.11 Reported liquid hydrogen storage costs

Table 11.9 Reported costs for other hydrogen storage options

Storage System/Size (GJ) Metal Hydride	Specific Total Capital Investment (£/GJ)	Ongoing Storage Cost (£/GJ)	References
Short term (1-3 days)			
131-130,600	2680	1.85-4.78	(1)(3)(6)
Long term (30 days)			
3,900	11777	132	(1)(3)(6)
Cryogenic Carbon (one day)			
	2737	17	(3)
Liquid Organic Hydrides			
1 day - based on methylcyclohexane -toluene-hydrogen (MTH)	900	43	(7)
100 days (MTH)	9.6	43	
Other Chemical Intermediates			
Methanol	£18.90/GJ	Based on methanol purchase at $7/GJ cost (HHV)	(8)
Ammonia	£24.93/GJ	Based on ammonia purchase at $160/ton	(8)

References used for storage costs: (1) Amos 1998; (3) Schwarz and Amankwah 1993; (6) Sandrock 1997; (7) Newson *et al.* 1998; (8) Berry 1996. All these references cited in Padro and Putsche (1999).

The current economic status of the various methods of hydrogen storage can be summarised as follows:

Compressed hydrogen gas

- Currently the most commonly available method of storing hydrogen in the UK
- Economical for short-term storage, particularly for relatively low volumes
- Compression energy costs are significant, particularly at higher rates of production
- Cost of the pressure vessels significant, particularly for longer storage times
- Increasing turnover rate improves economics
- Ultimately composite cylinders/ containers are likely to improve the economics of compressed gas storage

Underground hydrogen storage

- Can provide the cheapest overall form of storage, for large hydrogen volumes
- Cost significantly dependant on the availability and location of suitable storage sites
- Compression energy costs are also a significant contributor
- Provide an opportunity for seasonal storage to buffer variation in demand
- Cost of ongoing distribution to the consumer may be high

Liquid hydrogen storage

- Currently few production sources (none in UK) limiting availability
- Cost is location specific, particularly for imported liquid
- Provides a higher energy density, so beneficial for applications where space is at a premium, e.g. vehicles
- Costs are high at low rates, but economics improve at higher rates of production
- Determining factor is the energy cost of the liquefaction process

Supercritical hydrogen storage

- Space travel experience is still to be translated to terrestrial applications and is not yet being considered by any national research programme
- Vessel costs similar to liquid hydrogen at present, but benefits from ability to use more varied shapes yet to be exploited
- Higher energy density than liquid hydrogen and lack of ullage space improves still further
- Energy cost of liquefaction / supercritical production are determining

Metal Hydride

- Limited commercial availability of existing hydrides
- No real economies of scale, dominated by capital cost of the metal hydride
- High temperature hydrides require additional energy (cost) to liberate hydrogen
- Low temperature hydrides suffer from poor capacity per unit mass
- Uneconomic for long storage times at high rates
- May become cost effective for small (micro) storage applications
- Longer term resource / supply concerns may limit economic viability

Carbon Based Systems

- Not currently a viable commercial offering
- Combination of compression and required cryogenic temperature significantly add to cost
- Longer term, carbon nano-structure storage costs should benefit due to lack of cryogenic requirement

Chemical Hydrides

- Niche opportunities for long-term, seasonal hydrogen (energy) storage
- Costs vary, dependant on storage duration and chemical intermediate
- Some long established methods (e.g. via ammonia) with proven technology
- Can be expensive due to number of production steps

Vehicle Hydrogen Storage

As indicated, one of the most significant challenges to confront in the transition to a hydrogen economy is the issue of on-board hydrogen storage. Lipman and Delucchi (1996) summarised the existing cost of the current feasible options. Their results are indicated in Table 11.10

Table 11.10 Estimated costs for on-board hydrogen storage

Storage Option	Estimated Cost £/GJ	Comments
Compressed gas in fibre-reinforced composite tanks	3270	Current steel vessels would be cheaper, but have a significantly lower energy density. The costs estimated here are for 551 bar pressure and an energy density of 3.4 MJ/litre
Liquid hydrogen	820 – 1630	The costs estimated here are for a liquid hydrogen tank giving losses of up to 3% per day. Improved designs can now reduce this loss significantly
Metal hydride	2690 - 4500	This estimate is based on a Fe-Ti metal hydride storage system

For current bespoke conversions, Frates (2004) estimates a hydrogen storage tank cost of $4000 plus a further $1000 for a fuel shutoff valve for Shelby Cobra hydrogen conversions. In this small vehicle, the current tank range is only 80 miles.

Supercritical hydrogen storage could be a promising vehicle storage mechanism, with costs similar to liquid hydrogen, but with the advantage of formed tanks to match vehicle body shape, lower long-term boil off and no ullage space losses. Actual costs and proof of the technology in this environment are yet to be demonstrated. However, there is clearly scope for cost reduction through mass production of all vehicle hydrogen storage systems.

11.2.3 Distribution Economics

Whilst progress can and is being made to produce less expensive hydrogen, it is essential to ensure that this hydrogen can be effectively distributed to the point of use for a transition to a hydrogen energy economy to take place. The most effective delivery system will depend on the means of production and the final application (see Chapter 7).

At present, hydrogen is distributed in Wales and the rest of the UK by a very limited number of dedicated pipelines and as compressed gas in cylinders or tube trailers. The small amount of liquid hydrogen distributed in the UK is currently imported from mainland Europe. As can be see from Table 11.11 below, distribution for cylinders, manifolded cylinders or tube trailers are predominantly about moving the mass of the container. Typically the product mass accounts for less than 1% of the total container or vehicle mass for compressed hydrogen.

Table 11.11 Current hydrogen distribution modes in the UK

Distribution Method	Typical Quantities (UK) Normal Volume	Mass	Energy (LHV)	Characteristics
Cylinder	1.5 to 7.2 Nm^3	0.128 to	0.016 to 0.616kg	180 bar cylinder. Larger cylinder total 0.078 GJ mass 65kg of which <1% is hydrogen.
Manifolded Cylinder Pallet	108 Nm^3 @ 180 bar	9.2kg	1.166 GJ	180 bar cylinders. Total mass 1300kg of which <1% is hydrogen.
Tube trailer	3300 Nm^3 @230 barG	280kg	35.6 GJ	230 bar cylinders. Total vehicle mass 28 tonnes of which 1% is hydrogen. Infrastructure charges will also apply typically (storage, manifolds, etc.)
Liquid Tanker	3.53×10^4 Nm^3	3000kg	381 GJ	Typical total vehicle mass 40 tonnes of which 7.5% is hydrogen. Infrastructure charges will also apply typically (storage, etc.)
Pipeline	500 Nm^3/hr to 44,000 Nm^3/hr	1 to 90 tpd	5.4 to 475 GJ/hr	Typically part of a multi-year contract attached to a purpose built hydrogen plant. Various charging structures apply
Sources: BOC (1990) and Air Products (2003)				

Compressed Trailer Hydrogen Distribution

The majority of merchant hydrogen currently distributed in the UK is transported in compressed hydrogen road trailers. With steel manifolded cylinders containing the hydrogen there is a low ratio of product mass to vehicle and container mass. Typically a tube trailer is carrying no more than 300kg hydrogen product (Simbeck and Chang, 2002). As a result compressed hydrogen trailer distribution cost is high. Storage pressure and construction materials are the current limiting factor with typical current storage pressures between 170 and 250 barG. The emergence of lower weight composite cylinders with higher pressure capacity could significantly improve the distribution economics for compressed hydrogen trailers.

Although UK vehicle costs may be slightly higher, Amos (1998) estimates that a typical tube trailer currently costs $250k (including tractor unit). Table 11.12 presents the findings of Amos (1998) on the delivered costs for compressed trailer hydrogen.

Table 11.12 Compressed hydrogen trailer distribution costs

Trip Distance km	TCI £/GJ	Transport Cost £/GJ	Quantity Transported GJ/yr
16	2.5625	2.9375	458,000-45.8 million
161	5.125	6.625	458,000-45.8 million
322	8.56- 10.25	11.44-11.63	45,800-45.8 million
805	18.875	25.6875	45,800-45.8 million
1,609	36	49.44-49.81	45,800-45.8 million

Hydrogen Distribution: Passenger Vehicles in Wales

Fossil Fuel Basis - *There were 1.2 million passenger cars registered to owners in Wales at the end of 2003 (DfT). Assume each vehicle travelled an average of 9300 miles per year and consumed 250 gallons in doing so (1136 litres or 36.35 GJ). So the total fuel usage of these passenger cars alone was some 1.36 x 10^9 litres (= 43.5 PJ or 4.35 x 10^{16} J). Assuming unleaded fuel at a current average of 84p/litre (£26.25/GJ), total passenger vehicle fuel expenditure in Wales was £1.142 billion.*

Hydrogen Equivalent - *Consider by comparison the hypothetical case of all of these vehicles being powered by fuel cells rather than internal combustion engines. Assume a fuel cell vehicle efficiency of 45% compared to an averaged internal combustion engine efficiency of 25%. This equates to an individual fuel requirement of 20.19 GJ to travel same distance, equivalent to 159kg hydrogen. For a total passenger vehicle fleet, this equals 191,000 tonnes hydrogen per year or 523 tonnes per day.*

Hydrogen Distribution - *To satisfy this demand, there would have to be an equivalent of 174 liquid H_2 tanker deliveries per day in Wales, or 1867 compressed hydrogen trailer deliveries per day, based on existing hydrogen transport capacities.*

Forecourt Price - *For the Welsh consumer to pay the same total amount (i.e total annual expenditure should be £1.142 billion) the price per kg of hydrogen at the forecourt would be approximately £6/kg (£47.15/GJ)*

Liquid Hydrogen Distribution

As with any cargo, the more you can carry on the vehicle, the more economic the distribution. Distributing hydrogen in liquid form has an advantage over gaseous distribution due to the increased proportion of the loaded vehicle weight that is actually hydrogen. A number of studies indicate that liquid hydrogen incurs the lowest distribution costs due to this higher product density (See Table 11.13).

Whilst compressed gaseous transport is the most common means, economic distribution range tends to be limited to a few hundred miles. By comparison, liquid hydrogen is currently trucked thousands of miles, e.g. from Quebec to California, a round trip of over 6000 miles. However, bulk liquid hydrogen distribution in the UK is currently limited to a small number of vehicles importing liquid hydrogen from mainland Europe for use in the UK.

Due to the need to maintain very low temperatures and avoid excessive boil-off, liquid hydrogen tankers are more expensive than other cryogenic tankers. Amos (1998) estimates a cost of $500k for a liquid hydrogen tanker including motive unit.

Table 11.13 Liquid hydrogen tanker distribution costs

Trip Distance km	Total Capital Investment £/GJ	Transport Cost £/GJ	Reference
16	0.28-6.88	0.15-1.0	Amos 1998 in Padro & Putsche
161	0.48-6.88	0.33-1.15	Amos 1998 in Padro & Putsche
322	1.38-6.88	0.63-1.38	Amos 1998 in Padro & Putsche
805	1.69-6.88	1.25-1.94	Amos 1998 in Padro & Putsche
1,609	3.19-6.88	2.44-2.94	Amos 1998 in Padro & Putsche
80	2.11*	0.25	Mercuri *et al.* 2002 (*assumes 80% tanker utilisation)
210	1.19	0.89	Simbeck & Chang 2002

Pipeline Distribution

Pipelines provide a cost effective way of distributing hydrogen, particularly in large quantities over short distances. Typically, the production element of cost is lower for pipeline distribution than for liquid tanker or compressed trailer installations due to the relative complexity and hence capital intensity of the tanker/trailer filling systems.

However, Simbeck and Chang (2002) indicate that laying pipelines is capital intensive, mostly due to acquiring right-of-way and occasionally due to routing difficulties (natural obstacles, public access, etc.). In their study of central hydrogen production delivering to numerous forecourts, they indicate that hydrogen distribution by pipeline provides the most expensive overall route compared to liquid or compressed gas distribution by road, due to the capital intensity of the pipeline itself. This conclusion does not hold in all cases, particularly where pipeline routing is relatively easy. Indeed pipeline cost multiplying factors of 2 or more can be applied for difficult terrains. Table 11.14 presents reported costs for pipeline hydrogen distribution costs.

Table 11.14 Hydrogen pipeline distribution costs

Transmission Rate GW or Tonnes per Day	Distance km	Specific TCI £/GJ delivered	Hydrogen Transmission Cost £/GJ	Reference
0.15	161	13.26	1.77	Amos 1998
(102 tpd)		8.84	1.27	Oney *et al.* 1994
	805	66.40	8.65	Amos 1998
		42.21	5.54	Oney *et al.* 1994
	1609	131.45	17.02	Amos 1998
		83.86	10.88	Oney *et al.* 1994
0.5	161	3.00	0.52	Oney *et al.* 1994
(340 tpd)	805	13.01	1.80	Oney *et al.* 1994
	1609	24.26	3.40	Oney *et al.* 1994
1	161	1.66	0.36	Oney *et al.* 1994
(680 tpd)	805	6.75	1.00	Oney *et al.* 1994
	1609	13.00	1.80	Oney *et al.* 1994
1.5	161	1.77	0.52	Amos 1998
(1020 tpd)		1.33	0.31	Oney *et al.* 1994
	805	7.24	1.31	Amos 1998
		4.67	0.73	Oney *et al.* 1994
	1609	13.94	2.21	Amos 1998
		8.83	1.27	Oney *et al.* 1994
0.22 (150tpd)	600	5.42	1.30	Simbeck and Chang 2002

All references derived from Padro and Putsche (1999) except Simbeck and Chang

Pipeline Transmission Cost

Ogden (1999) has suggested a formula for the cost of hydrogen delivery by pipeline. For a relatively small 3 inch (75mm) pipeline, costing a typical $1million/mile, the formula is:

Transmission cost ($/GJ) = 1.2 x distance (in km)/ flowrate (in million standard cubic feet /day)

which equates to: Transmission Cost (£/GJ) = 85835 x distance (in km)/ flowrate (GJ/yr)

The high capital requirement for laying new pipelines has led various studies to consider the cost effectiveness of reusing existing natural gas pipelines, either for replacement with hydrogen product, or with a hydrogen natural gas mixture as a transition technology. Typically natural gas pipeline cannot be used for hydrogen without upgrading due to material incompatibilities and potential losses by diffusion.

Liquid hydrogen pipelines are a more remote possibility, due to the cost of (vacuum) insulation required. The liquid hydrogen pipelines that do currently exist are related to space programmes. Realistically, liquid hydrogen pipelines can only be considered for very short distances adjacent to the liquefaction plant.

Transport in Metal Hydrides

Transporting hydrogen in metal hydride form gives some advantages due to the relatively high storage density. The capital cost of the metal hydride and containers is dominant. Amos (1998) assumes a cost of $2200/kg H_2 for a metal hydride intermodal transport unit (excluding vehicle cost). Table 11.15 shows the results reported by Amos (1998) indicating that metal hydrides may become competitive for distribution of hydrogen over short distances.

Table 11.15 Metal hydride hydrogen distribution costs

Trip Distance km	TCI £/GJ	Transport Cost £/GJ	Quantity Transported GJ/yr
16	4.71	1.64	458,000-45.8 million
161	9.43	3.59	458,000-45.8 million
322	15.71	6.13	45,800-45.8 million
805	34.55	13.7	45,800-45.8 million
1,609	65.96	26.32	45,800-45.8 million

Other Means of Hydrogen Distribution

At the lower volume end of hydrogen supply, distribution by cylinder or manifolded cylinder pallet has been well established as a means of delivery. However, as one might expect for lower volumes of supply, the delivered cost rises sharply as volumes decrease. Table 11.16 shows the punitive impact on unit cost as the volume of the cylinder decreases.

Table 11.16 Cylinder hydrogen supply costs

Cylinder supplied	Gas Cost £	Delivery cost £	Combined cost £/Nm^3	Combined cost £/GJ
Manifolded Cylinder Pallet 108Nm^3	439.83	25.95	4.31	399.47
K size cylinder 7.2Nm^3	29	25.95	7.63	704.49
B size cylinder 1.5Nm^3	18	25.95	29.30	2746.88

Source: Verbal quotation from BOC Customer Service Centre 20.3.03

A less common means of distributing hydrogen is in the form of a transportable liquid hydrogen dewar. As with liquid hydrogen tanker distribution, transportable dewars have the advantage of a greater proportion of product in the overall transported mass. This mode is seldom available in the UK. Amos (1998) reporting on Oy (1992) indicates the following cost profile for liquid hydrogen supplied by transportable dewar (Table 11.17).

Table 11.17 Liquid Hydrogen Dewar Distribution Costs

Content(kg)	Cost/kg(£/kg)	Cost £/GJ	Reference
0.089-8.9	314-450	2470 - 3543	Oy (1992) in Amos (1998)

Larger volumes of hydrogen, particularly liquid hydrogen can be transported by rail or by ship. The Amos (1998) study considered the costs of rail and ship transportation of hydrogen. The results are presented in Table 11.18 and Table 11.19.

Table 11.18 Hydrogen distribution costs by rail

Transport Method/ Transport Time	Amount Transported (GJ/yr)	Specific TCI (£/GJ transported)	Transportation Cost (£/GJ)
Liquid Hydrogen			
1 day (< 984 km)	45,600	7.03	1.37
	455,600	2.81	0.83
	45.6 million	2.53	0.79
2 days (< 1970 km)	45,600	7.03	1.37
	455,600	4.22	1.01
	45.6 million	0.04	0.48
Compressed Gas			
1 day (< 984 km)	45,800	33.62	13.72
	457,600	30.26	13.29
	45.8 million	30.26	13.29
2 days (< 1970 km)	45,800	50.43	15.88
	457,600	50.43	15.88
	45.8 million	50.43	15.88
Metal Hydride			
1 day (< 984 km)	45,700	117.79	19.81
	457,00	106.01	18.30
	45.7 million	106.01	18.30
2 days (< 1970 km)	45,700	176.69	27.36
	457,00	176.69	27.36
	45.7 million	176.69	27.36

Table 11.19 Liquid hydrogen distribution costs by ship

Distance km	Specific TCI (£/GJ transported)	Transportation Cost (£/GJ)
322	5.27	8.55
805	10.53	9.22
1,609	15.76	9.90

Chemical Intermediates

As we have seen the cost of distributing gaseous hydrogen is high due to the low ratio of product to container. Although this improves for liquid hydrogen, there is a significant energy cost of liquefaction. An alternative means of gaining the benefit of liquid product density is by transporting hydrogen in the form of a chemical intermediate. In particular, methanol or ammonia are candidate chemical hydrogen carriers (see Section 6.2.3).

In their comparison of pure hydrogen and methane as an (hydrogen) energy carrier, Adamson & Pearson (2000) concluded that, "There is no clear economic reason why one fuel should be favoured over the other." Another comparison study by Sato *et al.,* (1998) indicates that a liquid hydrogen energy distribution system is more energy efficient than either methanol or ammonia, although there is only marginal cost difference between the three systems. More work is needed to clearly establish or eliminate both methanol and ammonia as large-scale (hydrogen) energy carriers.

11.2.4 End Use Economics

The two principal end uses for hydrogen as an energy medium are either to use its properties as a fuel for combustion in internal combustion engines or gas turbines, or to employ hydrogen to produce electricity and heat in a fuel cell. These options are increasingly being applied to a wide range of applications, whether in industrial scale energy plant, domestic power plant, vehicle drives, or potentially smaller applications. Different scales and types of fuel cell design are evolving to meet these end requirements economically.

As experience grows in using hydrogen end use devices, costs are reducing. However, it is clear that despite significant growth, most hydrogen energy end use technology is still at a relatively early stage of commercial development. Current costs should reduce significantly as end use technology goes through the transition from "hand-made" to modern manufacturing processes.

A potential dilemma is that current costs for some technologies and risk aversion on the part of technology investors could prevent adequate investment to encourage development and, through experience, reduce costs. Thankfully, recent governmental research, development and demonstration investment commitments from certain countries may help to break this catch-22. However, it would not be unkind to say that, with some notable exceptions, the UK has not been at the forefront of investment in hydrogen end-use technologies. Without a commitment to increase RD&D spending in the UK, there is a danger that our manufacturing industry will miss out on opportunities that better funded foreign firms will be in a position to exploit (Chase *et al.,* 2003). The current relative paucity of Welsh manufacturers involved in potential hydrogen end-use technology is a situation that needs to be addressed if Welsh firms are to establish a role in the hydrogen economy. Thankfully recent initiatives, particularly by the WDA are starting to address this issue.

Fuel Cells

A number of recent studies have given an indication of the capital and operating costs associated with the various types of fuel cell, at various stages of development. Many of these studies give an indication of current costs and a forecast of future costs based on economies from experience and mass manufacture.

For many applications, fuel cells are starting to come out of the laboratory and in to the commercial world. Cropper *et al.,* (2003) estimate that over 6900 fuel cell systems have been built and operated worldwide since the 1950s (not including metal-air fuel cells or those sold for educational purposes). They indicate that this number is increasing dramatically, despite investor concerns over new technology firms. Development of fuel cells has been strongest in Canada and the USA, followed by Japan and Europe (See Figure 11.12). This pattern of development can be explained by a number of factors, technical, political and economic, also by the emergence of a number of larger and more established fuel cell manufacturing firms (Cropper *et al.,* 2003).

The UK currently has only a very small number of commercial fuel cells. The installation of a 5kW Plug Power PEM fuel cell for remote power to a telecommunications tower in Huntley, Aberdeenshire and a very small number of other installations ensure that the UTC fuel cell in Woking is not the UK's only working example.

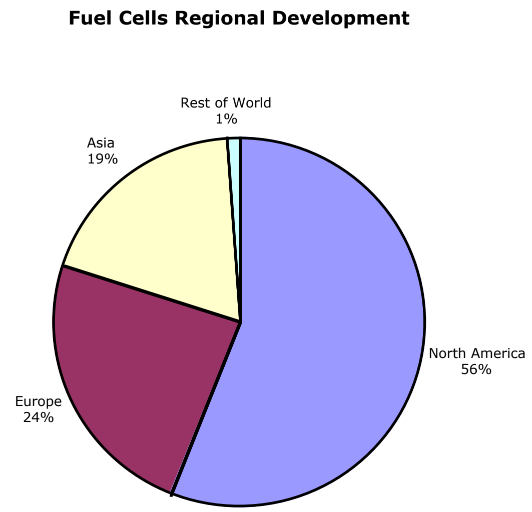


Figure 11.12 Regional development of fuel cells (% of total units produced) (Cropper et al., 2003).

Of the fuel cells installed, Cropper et al., (2003) indicated that proton exchange membrane units have been the most dominant type (See Figure 11.13), particularly because of their versatility. This is followed by the phosphoric acid fuel cell that is limited to larger applications. The direct methanol fuel cell is also included in their figures, which is suited to small (<1kW) applications.

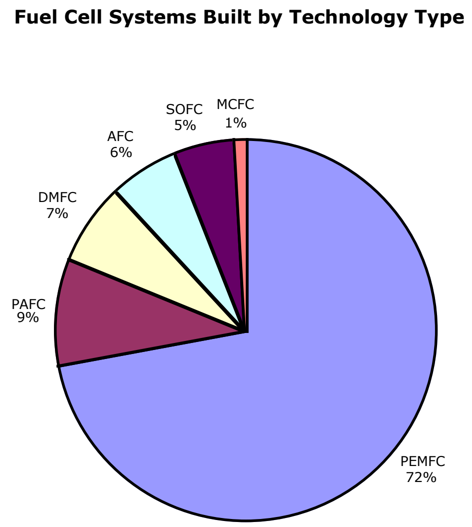


Figure 11.13 Fuel Cells by technology type (Cropper et al., 2003).

The largest number of fuel cell applications has been for portable devices, with spectacular growth in this sector over the last two years. Transport and stationary applications are also significant, with dramatic recent growth in the small stationary sector (See Figure 11.14). Large stationary and transport applications show steadier growth, though these have also increased considerably in the last five years (Cropper *et al.,* 2003).

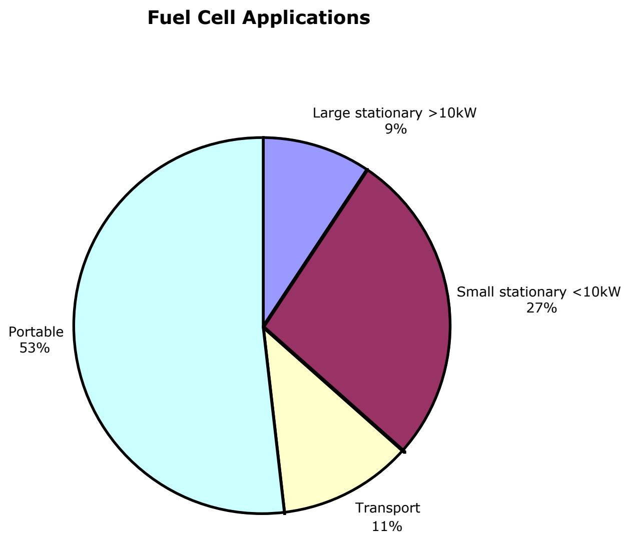


Figure 11.14 Fuel Cell Applications (Cropper et al., 2003).

Phosphoric Acid Fuel Cell

Phosphoric acid fuel cells (PAFC) are the dominant current technology for large stationary applications and have been available commercially for some time, mostly operating on natural gas feedstock. There have been approximately 480 PAFC developments world-wide (Cropper & Jollie, 2002), with the number still growing rapidly as the commercial offering improves. There is possibly less potential for PAFC unit cost reduction than for some other fuel cell systems (see Table 11.20) (DTI, 2002).

Table 11.20 Phosphoric acid fuel cell costs

Fuel Cell Size	Date for estimated costs	Installation Cost £/kW	Operating Cost £/kWh	Source
25kW	Future	1440	0.08	Mugerwa and Blomen, 1993
200kW	1998	1925	Not indicated	Garche, 1998
250kW	Future	1565	0.08	Mugerwa and Blomen *et al.,* 1993
100MW	Future	640	Not indicated	EPRI 1995
200kW	2002	Commercial	3400	Lokurlu *et al.,* 2003
Independent of size	2002	1721	Not indicated	Bauen (personal communication 2002)
Independent of size	2005	1515	Not indicated	Bauen (personal communication 2002)
Independent of size	2010	1181	Not indicated	Bauen (personal communication 2002)
Independent of size	2015	950	Not indicated	Bauen (personal communication 2002)
Independent of size	2020	847	Not indicated	Bauen (personal communication 2002)

Solid Oxide Fuel Cell

The solid oxide fuel cell (SOFC) gives significant flexibility due to its large power range and represents one of the most promising technologies for stationary applications. Operating at a higher temperature, the waste heat can also have commercial value. Approximately 200 systems have been installed worldwide for static applications (Cropper & Jollie, 2002), although the technology is not suitable for transport applications. Significant further development and cost reduction is anticipated for SOFC, particularly in the development of planar designs that will offer potential for lower cost manufacture (see Table 11.21) (DTI, 2002).

Table 11.21 Solid oxide fuel cell costs

Fuel Cell Size	Date for estimated costs	Installation Cost £/kW	Operating Cost £/kWh	Source
n/s	Future	641	0.04– 0.05	Murugesamoorthi, 1993
n/s	Future	1282(system) 449 (fuel cell alone)	Not indicated	Ippommatsu *et al.,* 1996
n/s	Future	449	Not Indicated	GRI, 1999
100kW	2002 Demonstration	13,700	Not Indicated	Lokurlu *et al.,* 2003 (Siemens Westinghouse Power Corporation)
Independent of size	2002	3492	Not indicated	Bauen (personal communication 2002)
Independent of size	2005	1612	Not indicated	Bauen (personal communication 2002)
Independent of size	2010	714	Not indicated	Bauen (personal communication 2002)
Independent of size	2015	447	Not indicated	Bauen (personal communication 2002)
Independent of size	2020	375	Not indicated	Bauen (personal communication 2002)

Proton Exchange Membrane

More proton exchange membrane (PEM) fuel cells have been developed and sold than any other to date (approximately 2750, Cropper *et al.*, 2003). The quick start-up times and size range make PEM fuel cells ideal for domestic heat and power applications. PEM is also the dominant technology for vehicle applications. The significant development efforts in the transport sector suggest that there will continue to be substantial cost reductions for PEM fuel cells over the next 20 years.

The largest cost component of a PEM fuel cell is the catalyst at 41% of the total (James *et al.,* 1997). A 90% reduction in the amount of precious metal required has been reported (Fuel Cell 2000, 2003) and further reductions are anticipated, reducing the costs of PEM fuel cells. Donitz (1998) indicates a reduction in platinum catalyst loading from 4mg/cm^2 in 1990 to 2.2mg/cm^2 in 1998 to a longer term target of 0.3mg/cm^2, equating to a 98% reduction in cost. Reported costs for PEM fuel cells are presented in Table 11.22.

Table 11.22 Proton exchange membrane fuel cell costs

Fuel Cell Size	Date for estimated costs	Installation Cost £/kW	Operating Cost £/kWh	Source
10kW	1997	1923	0.16 – 0.19	Barbir & Gomez, 1997
10kW	Near Future	737	0.055 – 0.06	Barbir & Gomez, 1997
7kW	2001	5448	Not indicated	Plug Power, 1999
7kW	2003	2564	0.044 – 0.06	Plug power, 1999
5kW	Near Future	769	Not indicated	Garche, 1998
Independent of size	2002	2563	Not indicated	Bauen (personal communication 2002)
Independent of size	2005	1125	Not indicated	Bauen (personal communication 2002)
Independent of size	2010	444	Not indicated	Bauen (personal communication 2002)
Independent of size	2015	295	Not indicated	Bauen (personal communication 2002)
Independent of size	2020	231	Not indicated	Bauen (personal communication 2002)
250kW	2002 Demonstration	6860	Variable on a number of factors	Lokurlu *et al.*, 2003 (Ballard Power Systems)
250kW	2002	3846	Not indicated	DTI, 2002d

Alkaline Fuel Cells

Alkaline fuel cells (AFC) have been predominantly used for space and military applications. It is estimated that some 240 systems have been developed (Cropper & Jollie, 2002). Lindstrom and Lavers (1997) indicate the potential for large scale AFC power plant integrated into existing ammonia production. AFCs has the advantage of being a relatively simple technology and hence lower manufacturing costs than some other fuel cells. The fouling potential for CO_2 with AFCs must be considered, although this is not a concern if pure hydrogen is available. Further cost reduction should be achievable to maintain AFC as the lowest specific cost fuel cell technology (DTI, 2002). Reported costs for AFCs are presented in Table 11.23.

Table 11.23 Alkaline fuel cell costs

Fuel Cell Size	Date for estimated costs	Installation Cost £/kW	Operating Cost £/kWh	Source
163MW	Future	Not indicated	0.04	Lindstrom and Lavers, 1997
Independent of size	2002	1014	Not indicated	Bauen (personal communication 2002)
Independent of size	2005	822	Not indicated	Bauen (personal communication 2002)
Independent of size	2010	411	Not indicated	Bauen (personal communication 2002)
Independent of size	2015	308	Not indicated	Bauen (personal communication 2002)
Independent of size	2020	206	Not indicated	Bauen (personal communication 2002)

Molten Carbonate Fuel Cells

The relative complexity of molten carbonate fuel cells has tended to limit development efforts to larger scale stationary applications. The technology is effectively still at the pre-commercial development phase with an estimated 40 installations globally (Cropper *et al.*, 2003). Specific costs are similar to those for PEM fuel cells, although MCFCs are typically much larger. Reported costs for MCFCs are presented in Table 11.24.

Table 11.24. Molten carbonate fuel cell costs

Fuel Cell Size	Date for estimated costs	Installation Cost £/kW	Operating Cost £/kWh	Source
25kW	Future	869	0.08	Mugerwa and Blomen, 1993
250kW	Future	1115	0.07	Mugerwa and Blomen, 1993
2MW	Future (pre-commercial)	1090	Not indicated	EPRI, 1995
2MW	Future (commercial)	769	Not indicated	EPRI, 1995
3.25MW	Future	853	0.06	Mugerwa *et al.*, 1993
100MW	Future	385	0.04	Mugerwa *et al.*, 1993
100MW	Future (external reforming)	1859	0.07	Bohme *et al.*, 1994
100MW	Future (internal reforming)	1282	0.06	Bohme *et al.*, 1994
100MW	Future (with fuel recycle)	1090	0.05	Bohme *et al.*, 1994
280kW	2003	5488	Not indicated	Lokurlu *et al.*, 2003 (MTU Hot Module)
Independent of size	2002	2465	Not indicated	Bauen (personal communication 2002)
Independent of size	2005	1433	Not indicated	Bauen (personal communication 2002)
Independent of size	2010	688	Not indicated	Bauen (personal communication 2002)
Independent of size	2015	519	Not indicated	Bauen (personal communication 2002)
Independent of size	2020	467	Not indicated	Bauen (personal communication 2002)

Fuel Cells & Commercial Competitiveness

As part of the United States FreedomCAR programme (see Section 10.7.3.1) a series of performance and cost targets have been set (see Table 11.25).

Table 11.25 US FreedomCAR Performance and Cost Goals (all 2010 except as noted)

	Efficiency	Power	Energy	Cost	Life	Weight
Fuel Cell System	60% (hydrogen)	325 W/kg	-	$45/kW $30/kW (2015)	-	-
Electric Propulsion	-	>55kW 18s 30kW cont.	-	$12/kW peak	15 years	-
Materials	-	-	-	-	-	50% less
Engine Powertrain System	45% peak	-	-	$30/kW	15 years	-

To extend fuel cell application beyond existing niche markets, their cost needs to reduce significantly. In line with the US government targets, the DTI (2002b) has suggested the targets in Table 11.26 for fuel cell technology to be competitive:

Table 11.26 DTI fuel cell competitiveness targets

Application	Cost Target	Lifetime Target
Passenger Car	£30/kWe	5,000 hours
Bus	£120/kWe	20,000 hours
Residential CHP	£100/kWe	Up to 100,000 hours
Distributed Power	£500/kWe	100,000 hours
Commercial CHP	£800/kWe	100,000 hours

Clearly these cost targets are considerably below the current costs for all fuel cell types and represent a significant challenge for commercialisation of the fuel cell to become a reality.

Bauen *et al.* (2003) also indicate that successful and wide-spread commercial application of fuel cells is dependent on projected cost reductions. They indicate that the electricity generated from the fuel cell will have to be competitive with current centralised and distributed power generation options, before fuel cells can gain commercial acceptance. Figure 11.15 gives their estimated unit costs for various fuel cell size ranges and Figure 11.16 presents fuel cell cost projections by type (Bauen, 2002).

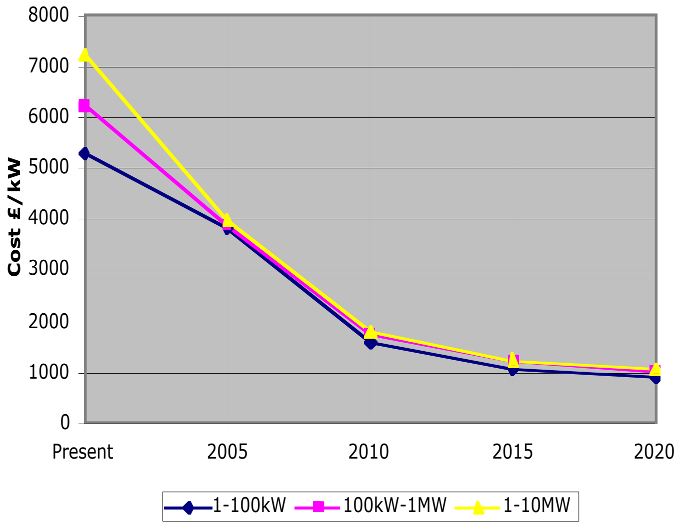


Figure 11.15 Fuel cell cost projections by size (Bauen et al. 2003)

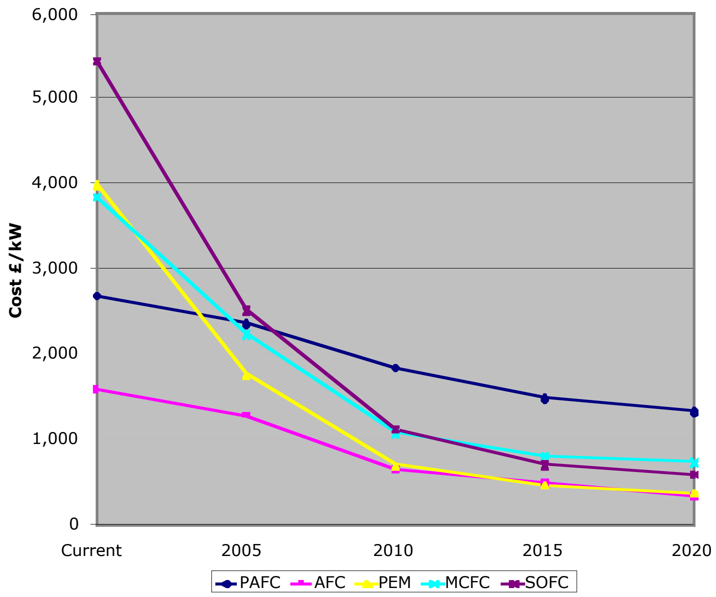


Fig. 11.16 Fuel cell cost projections by type (Bauen 2002, personal communication)

Bauen *et al.* (2003) indicate that if these cost reductions are met, fuel cells could achieve up to 50% penetration of the world distributed energy market by 2020. In some regions, they predict that fuel cells could become competitive with centralised power generation over the next decade.

Lokurlu *et al.* (2003) compare the published costs of fuel cells with a conventional CHP of >1000 to 500 €/kW for <100-1000 kW. They conclude that stationary fuel cell systems are not yet competitive with conventional CHP. They envisage fuel cell CHP systems will become competitive if costs can be reduced. In particular, they point to the following:

- stack running times can increase from 40,000 to 70,000 hours
- maintenance costs reduce from US$0.025/-$0.01/kW

Erdmann (2003) also indicates that the market for stationary fuel cell systems is quite promising (in Germany in this case) so long as the targeted cost reductions for fuel cell systems can be achieved. However, Doran *et al.,* (2003) caution that the current financial climate is not supportive of investment in new technology firms like those in the fuel cell sector. They observe that since the collapse of the "technology" bubble of 2000, investors have more demanding requirements and are likely to be more cautious in backing technology sector firms. The projected cost reductions for fuel cells are unlikely to occur without sufficient investment in the sector. Hence continued efforts of various governments to support and stimulate research, development and demonstration in the fuel cell sector remain essential if the economic and social benefits of the technology are to be met.

Fuel Cells for Vehicles

"Our aim is to bring the cost of fuel-cell vehicles to the internal-combustion level, but we're not there yet," Johannes Ebner, Director of Infrastructure at Daimler's fuel-cell project.

The dominant fuel cell technology for vehicle applications is the Proton Exchange Membrane, due to its relatively simple construction, operability and high power density. There remains a significant gulf between the current price of a PEM fuel cell and the economic targets referenced above. However, the significant R&D investment power of nearly all the major vehicle manufacturers is supporting the development of fuel cells for vehicle applications, in an attempt to bridge the technology cost gap.

According to the Fuelcell 2000 web site there are currently at least 60 active fuel cell vehicle trials being conducted by motor manufacturers, and 30 active bus trials ongoing. Current cost for demonstration vehicles is high, but a number of studies have assessed the comparative costs of fuel cell vehicles against a range of other alternatives, in terms of initial capital and total life cycle costs. Clearly motor vehicles represent a highly diverse market and hence there is a wide range of quoted vehicle prices. Tables 11.27 and 11.28 give some of the published estimates of relative fuel cell vehicle costs once in mass production. However, the current position is that the commercialisation efforts of the vehicle manufacturers currently extend only to small numbers of demonstration vehicles in controlled trials. Existing fuel cell vehicle costs are high and not available to the public in any case. Full public commercial availability is unlikely to be realised before 2010.

Table 11.27 Estimated costs of fuel cell cars

Vehicle Base Cost	Cost (Ratio to Base Vehicle)			Reference
	Fuel Cell Vehicle	Hydrogen Internal Combustion Engine Vehicle	Hybrid Vehicle	
Light Duty Vehicles				
£11,540 (Petrol)	£12,950 (1.122)	-	£12,750 (1.106)	Thomas *et al.,* 1998 (estimates)
£12,370 (Petrol)	£17,243 (1.394)	£13,951 - £16,856 (1,128 – 1,363)	-	Lipman and DeLuchi, 1996 (estimates)
£12,370 (Petrol) for comparison	£13,429 (1.086)	-	£13,319 (1.077)	Thomas *et al.,* 2000 (estimates)
	£33,000	Westminster City Council fuel cell battery hybrid van by Zevco in 1998 (actual) (Planet Ark, 2001)		
	£2500 more than equivalent diesel	London fuel cell battery hybrid taxi introduced in 1999 by Zevco (actual) (DTI, 1999)		
	£19000	Estimated cost of Necar 4 vehicle in 1999 (Evworld, 2003)		

Table 11.28 Estimated costs of fuel cell buses

Vehicle Base Cost	Fuel Cell Vehicle Cost (Ratio to Base Vehicle)	Reference
Heavy Duty Vehicles £160k standard diesel Citaro bus (Daimler Chrysler, 2001).	£1.28million (8.0) (estimate in 2000)	United Nations' Global Environment Facility (GEF) for hydrogen Fuel Cell bus trials in Mexico city, Sao Paolo, Cairo, Beijing and Shanghai. (UNDP-GEF, 2003)
	£320k (estimate for 2006) (2.0)	
	£1.2 million (7.5)	Actual price $8.4 million (Can) for 3 Ballard fuel cell buses in Vancouver
	£790k (4.93)	Actual price of DaimlerChrysler's prototype hydrogen fuel cell 'Citaro' bus costs Foley (2001) http://www.daimlerchrysler.com/

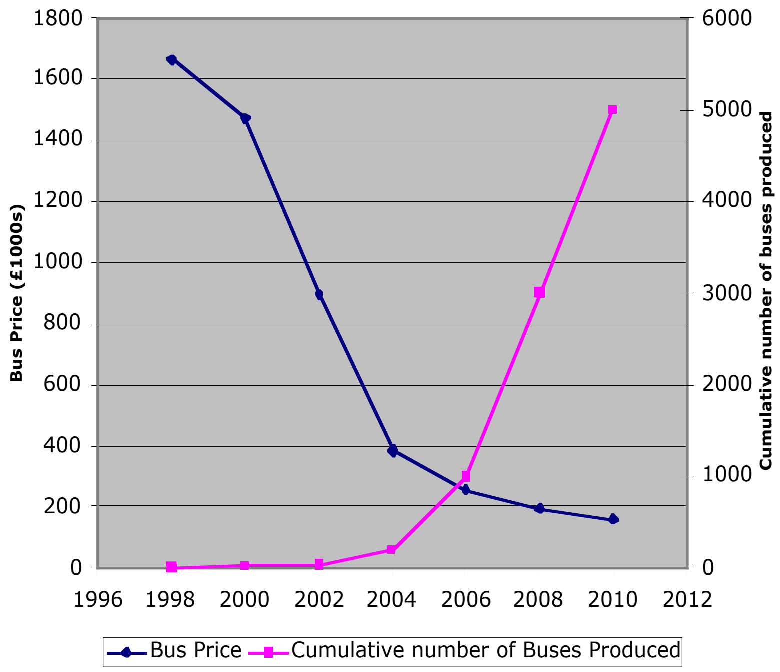


Fig. 11.17 Fuel cell bus price estimates (UNDP Global Environment Facility, 2003)

Internal Combustion Engines

The majority of the current effort in the area of hydrogen for vehicle applications focuses on fuel cells. However, it is often overlooked that there are many economic attractions in retaining the internal combustion engine (ICE) for vehicles to make a transition between petrol and hydrogen as a fuel. Although fuel cells promise higher efficiencies than standard IC engines, there have been significant improvements in combustion engine performance over the last decade. In addition, there is still a need for fuel cells to demonstrate high efficiencies, together with durability and reliability. Admittedly, without additional technology IC engines will continue to emit NO_x, though a combination of advanced combustion and post combustion techniques can minimise the NO_x emitted from IC hydrogen engines. The main economic benefit comes from the ease of transition to hydrogen IC engine technology. The world scale engine design and assembly facilities of the motor manufacturers could make a transition to hydrogen fuelled internal combustion more easily than the larger step change to fuel cells. In addition, earlier introduction of ICE hydrogen vehicles on a mass production basis can overcome some of the barriers to introducing a hydrogen re-fuelling infrastructure. Hence ICE hydrogen vehicles could act as an effective transition technology for the longer-term introduction of fuel cell vehicles. BMW have followed this path of developing a hydrogen fuelled ICE in preference to using fuel cells as the main vehicle drive for over 25 years. The latest versions of the BMW 750hL has a dual liquid hydrogen/ petrol internal combustion engine and also includes a fuel cell as an auxiliary power unit as a replacement to the traditional lead acid battery. Although there are no published costs for the BMW vehicle, they maintain that this combination enables costs of the overall system to remain "within reasonable limits", which is consistent with their aim of the early introduction of production hydrogen vehicles (BMW, 2002).

Ford, with their Model U concept car have also followed the route of hydrogen powered ICE, in this case as an electric drive hybrid, with compressed hydrogen on-board storage. Again, no costs are quoted, but the concept is to make an affordable, environmentally friendly vehicle. Ford also have parallel fuel cell drive development programmes with other vehicles (Ford, 2003).

Bespoke hydrogen internal combustion engine vehicles are now becoming available in very limited quantities. The Hydrogen Car Co. of Los Angeles is able to sell converted Shelby Cobra sports cars that run on hydrogen for $149,000 (compared with a typical price of $100,000 for a standard gasoline version). Intergalactic Hydrogen offer a cost of $60,000 to convert a Hummer. Although this might be seen as a paradox, by converting one of the least fuel-efficient vehicles, there is significant symbolic benefit as well as improving the vehicles' performance.

Whilst it is possible to use a hydrogen powered internal combustion engine for stationary applications, there is little work in this area and no specific costs have been found.

One further possibility is the use of IC engine technology with hydrogen mixture fuels. Mixing hydrogen with gaseous fuels like natural gas or injecting into liquid fuels like diesel or petrol has been demonstrated to give emissions improvements (Das, 2002; Kumar *et al.*, 2003; Lambe and Watson, 1993.)

Gas Turbines

There is very limited published literature covering the costs of hydrogen gas turbines for stationary applications. Padro & Putsche (1999) report that the performance and cost of gas turbines operating on hydrogen should be similar to natural gas. They quoted natural gas turbines in the range £128-£385/kW and combined cycle systems of £205-£770/kW. Sørensen (2001) gives a cost of £650/kW. Bauen (2002) estimates a cost of £800/kW.

Keller (2003) reports that gas turbines are the fastest growing power technology and that they can provide a transition strategy for stationary power to an eventual carbon free energy system. As gas turbine technology is relatively mature, particularly for use with hydrogen rich syngas streams, they can provide an attractive power investment option where hydrogen or hydrogen rich streams are available at relatively low cost (e.g. refinery streams, chloralkali hydrogen byproduct, etc.). This is likely to remain the case even when large fuel cell costs start to become competitive. Continued research and development of gas turbines is likely to improve performance, reduce costs and increase the range of applications, improving the attractiveness of this as a stationary hydrogen energy conversion device.

12. Social aspects of the hydrogen economy

As demonstrated earlier in this report, the technical aspects of the hydrogen economy are the subject of a large and increasing level of research and development. As the technology starts being proven in demonstration trials, the economic aspects of a future hydrogen economy are also becoming clearer. However, one area has to date received relatively little specific attention, namely the social implications of a transition to a hydrogen economy. This section of the report deals with this aspect, reporting on published work and identifying much of the work in progress.

In the Section 11.1 of this report, the concept was introduced of external costs being applied to a technology. This concept is taken further in this section, particularly concentrating on externalities that affect society and social well-being.

In addition, this assessment is set in the particular context of Wales, and attempts to address some of the issues affecting the people of Wales through the transition to a hydrogen economy.

Social issues surrounding hydrogen energy

The introduction and wider application of a new technology is always likely to have social implications. The introduction of the steam engine, motor-car, aeroplane, telephone or personal computer have all had significant social impact (De Sola Pool, 1977, Pettifer, 1984). Transition to a hydrogen economy is likely to be no different. At the same time, the impacts of climate change, air pollution, and potential fossil fuel scarcity could all have substantial social impacts.

Some of the main social issues associated with the transition to a hydrogen economy in Wales can be summarised as follows;

- Social impact of global climate change
- Social impact of air pollution
- Energy supply issues
- Transport issues
- Social improvement through employment
- Public acceptance, education and training

There is clearly a degree of overlap between these issues. Social improvement through employment includes industry, commerce, agriculture and tourism, all particularly relevant in Wales.

UKSHEC Socio-Economic Research

The multi-disciplinary UK Sustainable Hydrogen Energy Consortium (UKSHEC) has been established under the EPSRC Supergen initiative and comprises eight UK research institutions (including the University of Glamorgan) and the Greater London Authority (GLA). As part of a broad research programme, UKSHEC is addressing many of the research challenges faced in the sustainable production, storage, distribution and utilization of hydrogen. In addition, UKSHEC is addressing the feasibility and desirability of the introduction of sustainable hydrogen through a range of socio-economic research projects.

This socio-economic work is being conducted jointly by the University of Salford, the Policy studies Institute in collaboration with the GLA and building on the experience of other members of the consortium and other stakeholders. The objectives of the socio-economic research are to make an important contribution to the identification of what a sustainable hydrogen economy will be like in the UK, inform and assess the types of policy measures to promote and develop the hydrogen economy and to identify the extent to which the change will be socially and environmentally acceptable.

The specific research aims are to:

- Delineate alternative configurations of a Sustainable Hydrogen Energy Economy, within a wider global context and a realistic time-scale.
- Identify plausible pathways and route-maps to these possible futures, whilst identifying interim technological solutions and milestones.
- Identify the economic, institutional and wider social conditions under which these transitions might take place.
- Identify barriers to a hydrogen future, and policies and measures, which might overcome these.

Project work packages are addressing the following:

- technology characterisation
- policy/urban and regional infrastructure drivers
- hydrogen futures scenarios
- economics of the hydrogen economy
- risk assessment and public perceptions
- modelling pathways to hydrogen futures
- institutional/policy assessment
- public acceptability

The progress of the UKSHEC project as a whole, including the socio-economic research can be viewed on the UKSHEC website (UKSHEC, 2003).

12.1 Social impact of global climate change

The most comprehensive assessment of the impacts of climate change are set out in detail in the IPCC third assessment report (IPCC, 2001b). The report concludes that it is clear that recent regional climate changes are already showing signs of affecting human systems. In particular the impact is starting to be observed in increased frequency of floods and droughts in some areas. The report also indicates that some human groups are more vulnerable than others to climate change, based on geographic location, time, and existing social, economic and environmental conditions. In general those with least resources to adapt are the most vulnerable to the impact of climate change. The report projects adverse impacts on human systems:

- Reduction in crop yields for most tropical and sub-tropical regions
- General reduction in crop yields for most mid-latitude regions (with some exceptions to this trend)
- Decreased water availability for many populations
- Adverse effects on human health through disease and an increase in heat stress mortality
- Widespread increase in the risk of flooding, from increased precipitation and sea-level rise
- Increased energy demand for space cooling due to higher summer temperatures

Whilst Wales may escape some of the most severe impacts of climate change, the consequences are nonetheless significant. Farrar and Vaze (2000) outline the potential impacts on Welsh natural and cultural habitats, health, and on the impacts on the Welsh economy. Table 12.1 summarises some of the projected changes outlined in the report.

Table 12.1 Summary of the impacts of climate change in Wales (from Farrar and Vaze, 2000)

Impacts of climate change on the natural and cultural habitat:

Costal flood risks
- Most of the major towns in Wales are coastal, as is much of the significant industry and a large amount of seasonal tourism is based in coastal areas.
- Increased storm frequency and storm surge events, sea level rise and increased precipitation will increase the risk from flooding to significant numbers of the Welsh population and to their sources of income.

River basin flood risks
- The low lying estuaries of the Neath, Loughor, Taf and Towy and the catchment basins from the Dee, Severn and Wye are all subject to flood risk.

Ecological impacts
- Changes to individual habitats and species are likely to be significant and initial impact is already being observed
- There is also potential for adverse impact on the characteristic freshwater habitats in Wales

Historic heritage
- Increased flood threat, prolonged wet or dry spells and indirect impacts such as changes in farming practice or flood defence construction may have an adverse effect on historical artefacts and the historic heritage of Wales

Impacts of climate change on health:

Direct effects
- Increased rates of illness and death related to exposure to thermal extremes
- Death, injury, psychological disorders and potential damage to public health infrastructure, due to increased frequency of extreme weather events.

Indirect Effects
- Changes in incidence of certain vector-borne diseases, due to changes in the range and activity of certain vectors and infective parasites
- Increased incidence of water borne disease
- Reduction in food productivity and consequent impact on health
- Other impacts due to infrastructure and resource supply changes to society and economy

Impacts of climate change on the Welsh economy:

Agriculture and Forestry
- Plants and animals are likely to suffer adverse impacts from temperature extremes, drought and waterlogging, storm impact, and pests
- Land management practice is likely to be impacted through intensive rainfall in winter and the need to manage grazing resources in summer. Some new opportunities may arise due to adverse impacts in other areas of the world.

Manufacturing Industry
- Accounting for approx 55% of GDP in Wales, the impacts on industry may be varied. Many industries planning horizons are too short to consider the impact of climate change. Increased rain, wind, and dry spells may all have varying impacts on manufacturing industry.
- Increased insurance costs, particularly for organisations in coastal or high flood risk areas are likely to increase significantly.

Transport
- Transport infrastructure may be more susceptible to disruption due to adverse weather effects

Infrastructure (electricity, gas, water)
- Increased disturbance and infrastructure damage due to storms
- Potential for increased damage to underground services
- Increased summer scarcity of water

Tourism
- Sea level rise and increased storm incidence may adversely effect Welsh beaches
- Changes in landscape and ecology may have a negative impact

Socio-economic impact of climate change

The impact of climatic and socio-economic factors is difficult to quantify. Clarkson and Deyes (2002) have attempted to estimate the social cost of climate change due to carbon emissions. They identify two routes from existing studies, cost benefit analysis (CBA) and the marginal cost (MC) approach. CBA attempts to find the level of emissions at which the marginal cost of reducing emissions is equal to the marginal damage caused, hence to derive a level for carbon taxation at this "optimal level of emissions". The MC approach attempts to calculate the future damage by a marginal change to the current level of emissions.

In reviewing a number of previous studies, Clarkson and Deyes conclude that the estimated cost range of $5-125 per tonne of carbon (IPCC, 1996) may underestimate the true uncertainty associated with climate change. This may be due to the limited number of impact categories considered and due to a number of uncertainties and differences in methodology. These uncertainties can be summarised as follows:

Scientific:
- Measurement of emissions present and future predicted
- Translation of emissions to atmospheric concentration
- Estimating climate impact of different concentrations
- Identification of physical impact of climate change

Economic uncertainties:
- Estimating monetary values for non-market impacts (particularly social costs)
- Predicting how relative and absolute values of impacts will change in the future
- Determining how damage should be aggregated across regions with different levels of national income
- Determining the rate at which future impacts should be discounted at today's prices.

Eyre *et al.*, (1998) study for the European Commission's ExternE is cited by Clarkson and Deyes as being the most comprehensive and sophisticated in the field and indicates that UK marginal abatement costs could be as high as £100/tC, but settles for an equity weighted figure of £70/tonne. This increased level of cost is reflected in the IPCC's 2001 report (IPCC, 2001b), which suggests a range from $15-$150/tC to meet the targets set out in the

Kyoto protocol, although this is still below the range suggested by Clarkson and Deyes of £35-£140/tC. The ExternE work has now been taken forward by another European Commission funded project NewExt, coordinated by the Institute of Energy Economics and the Rational Use of Energy (IER) University of Stuttgart (IER 2003).

12.2 Social impact of air pollution

The adverse health impact from air pollution is set out in some detail in Table 10.2 in Section 10.6 of this report. The World Health Organisation (WHO, 2000b) estimates:

- 3 million people die each year because of air pollution. This figure could be as high as 6 million annually because of uncertainty in the estimates
- Life expectancy can be significantly reduced in communities with high levels of particulate matter
- Indoor air exposure to suspended particulate matter increases the risk of acute respiratory infections, one of the leading causes of infant and child mortality in developing countries.
- Around 30-40% of cases of asthma may be linked to air pollution in some populations
- Studies in São Paulo, Brazil, have shown that a 75 µg/m^3 increase in concentrations of nitrogen dioxide (NO_2) was related to a 30% increase in deaths from respiratory illness in children under five years of age
- Air pollution also damages plant and animal life and contaminates water sources, threatening economic and social welfare as well as health.

Legislative pressure has reduced the concentrations of air borne pollutants in Wales, but in certain areas, particularly urban or industrial centres, the level of air pollution consistently remains above the air quality indicators for a significant percentage of the time (Neath-Port Talbot, 2000). A combination of particulates, nitrogen oxides and carbon monoxide from industry and road traffic causes adverse health effects and detracts from local quality of life.

Socio-economic impacts of air pollution

The European Commission's ExternE programme has incorporated the socio-economic impact of air borne pollutants on health, crops, building materials, forests, and ecosystems. Developed by IER of Stuttgart, the EcoSense model assesses the common pollutants and the different impacts of these in different countries. Country and area figures vary due to the difference in population density and the consequences on population (adverse health impacts).

The externalities calculated for the UK are given in Table 12.2

Table 12.2 Estimated air pollutant external costs for the UK in per tonne of pollutant emitted

SO_2	NOx	Particulates
6027 - 10025	5736 - 9612	8000 – 22917

Source: Eyre *et al.*, 1998/ ExternE (1999)

The figures for the UK are similar to countries with comparable population densities and higher than less densely populated countries like Ireland, Portugal or Sweden. The impacts for these local pollutants are not surprisingly site specific, impacts on urban areas are greater than rural ones.

Impacts are technology related. Energy from coal, oil or natural gas will result in a greater impact than energy from hydrogen. Clearly, the impact of clean, renewably produced hydrogen energy is going to be a reduced level of airborne pollutants when compared with hydrogen produced from fossil fuels. Hörmandinger and Lucas (1996) report on the externalities from air pollution identified in a number of studies (see Table 12.3).

Table 12.3 Low and high reported values of air pollution external costs

Type of Emission	Lowest value 1993$/kg	Highest Value 1993$/kg
NOx	1.0	28.7
SO_2	0.9	21.4
CO	1.6	5.4
Particulates	0.4	19.4

Source: All references cited in Hörmandinger and Lucas (1996)

Ogden *et al.* (2003) assess the societal lifecycle cost as a basis for comparing alternative engine and fuel options. The air pollution component of the societal lifecycle cost was estimated from full fuel cycle emissions, i.e. the emissions from the vehicle and from the upstream operations like fuel extraction, production, refining, storage and distribution. The estimates are based on the GREET transportation fuel cycle model developed by the Argonne National Laboratory (Wang, 1999). The GREET model gives the grams/ mile for the vehicle including the full fuel cycle. Specific air pollutant social (external) costs are derived from the ExternE programme and adjusted to suit US population densities.

The social externalities resulting from air pollutant emissions could therefore be adopted for Wales from sources such as Hörmandinger and Lucas (1999) or Ogden *et al.*, (2003), but would need adjustment for the population densities. The values for e.g. Swansea or Wrexham would therefore be greater than for an equivalent operation in rural mid-Wales.

12.3 Social aspects of energy supply

The majority of the concerns about energy supply identified in this report have centred on the long-term provision of oil or natural gas to satisfy energy demand. However, access to a choice of fuels and the impact of fuel poverty are also significant social elements to consider.

Security of supply

Rifkin (2003) puts forward an argument for a decentralised hydrogen energy system, as an effective response to the vulnerabilities with a present power infrastructure, dominated by large centralised power plants. Rifkin's vision is of a hydrogen society with a significant redistribution of electricity, in a peer-to-peer network, creating a decentralised form of energy generation and use. Rifkin argues that a shift to a renewable hydrogen energy regime with distributed hydrogen energy generation webs will enable billions of people to emerge from poverty, particularly in countries where no existing energy network exists. By generating hydrogen on a distributed and locally owned basis, Rifkin proposes a democratisation of energy supply provision through hydrogen.

Barreto *et al.* (2002) present a scenario for the development of a sustainable hydrogen economy bringing substantial improvements to energy intensity and security of supply. They describe a long-term hydrogen based global energy system in qualitative and quantitative terms, illustrating the role of hydrogen in the long-term transition toward a clean and sustainable energy future. In the transition they describe the introduction and diffusion of hydrogen technology, produced initially from fossil fuel sources to allow performance and cost improvements in the related technologies. Once established, the production of hydrogen shifts progressively towards renewable sources and hence to a society freed from many of the progressive strictures of fossil fuel supply. They project a society where fuel cells play an important role in the transformation to a flexible and less vulnerable distributed energy system. This transition brings benefits of a cleaner, more efficient and cost-effective energy provision. In addition, significant payback in terms of security and equity of supply, with a resulting low carbon impact.

Although painstakingly modelled, this is of course simply a scenario. The scenario has a positive outlook of an increasingly affluent, low population growth society that is oriented towards equity and sustainability. This society embraces hydrogen technology as a means to overcome concerns of global warming and security of supply.

Fuel Poverty

A fuel poor household is one that cannot afford to adequately keep warm at a reasonable cost, with the most widely accepted definition being a household that has to spend more than 10% of its income on fuel to heat rooms to an adequate standard of warmth. There were an estimated 4 million fuel poor households in the UK in 2000 (DEFRA, 2001b). The figure for Wales is less clear as no direct estimates exist. The number of households eligible for the home energy efficiency scheme (HEES) is likely to be close to the number of households suffering fuel poverty, as the potential beneficiaries from the scheme are likely to be in the susceptible groups. In 1997/98 there were an estimated 222,000 households in Wales eligible for the HEES scheme.

Fuel poverty is primarily caused by a combination of factors, such as poor energy efficiency of the home, high fuel costs, low household income. Whilst home energy efficiency and household income are not addressed in this report, these are nonetheless important aspects in any future hydrogen energy economy. In particular, improvements in home energy efficiency should be seen as a parallel focus to obtaining energy from cleaner sources. Fuel poverty typically affects the vulnerable in our society. Older people, children and people who are disabled or suffer form a long-term illness are more likely to be in fuel poor households and are also likely to suffer most from the effects of inadequate heating.

The reason for highlighting fuel poverty and particularly fuel poverty in Wales in this report is that any future hydrogen energy economy must confront the issue of fuel poverty. High system costs or operating costs are unlikely to help with the diffusion of hydrogen energy into the home, but will also not help to address the issue of fuel poverty.

One contributory factor to fuel poverty is the lack of adequate competition for energy supplies. This is especially due to incomplete coverage of the existing natural gas transmission network (see Section 3.4). This problem is particularly relevant for rural areas in Wales. An estimated 44,000 homes do not have access to the natural gas network in Wales. As a result these homes, many of which fall into the vulnerable categories, have to provide energy for their homes from bottled gas, oil, electricity or coal, all typically more expensive than heating with natural gas.

A hydrogen energy system that is wholly dependant on hydrogen transmission by pipeline will give rise to similar problems. Conversely, an adequate mix of hydrogen infrastructure, consisting of pipeline supplies and local production and energy conversion is more likely to provide a satisfactory solution to fuel poverty problems.

12.4 Social aspects of hydrogen transport

Access to transport is a defining social factor that most of us have now taken for granted. Increases in car ownership in Wales, as with the UK as a whole, indicate a preference by many for the convenience of personal transport as opposed to public transport. At the same time there is a year-on-year increase in the use of road transport to carry freight.

The social impacts of these transport patterns are numerous. Local air pollution and contribution to climate change are potentially the most significant factors in relation to the transition from oil based transport to hydrogen. Other aspects are also relevant to consider, namely road congestion and rural transport difficulties.

Hart and Hörmandinger (1998) and Bauen and Hart (2000) examine the environmental benefits of using fuel cells in cars, buses and stationary combined heat and power plants. The reduction in emissions from fuel cells in general, and from vehicles in particular are a source of significant social gain. The comparisons in these studies between fuel cell applications and existing technologies consider the emissions for the supply chain and end use in a UK context. In all cases, fuel cell technologies have substantially reduced emissions when compared to conventional technologies, confirming the environmental and social benefits of using fuel cells in vehicles (and stationary applications).

As reported in Section 12.2, Ogden *et al.,* (2003) use societal lifecycle cost as a basis for comparing alternative engine and fuel options. Their study considers several fuel and engine options including hydrogen ICE and fuel cell options. Hydrogen from natural gas, coal and wind power is considered. Their calculation of societal lifecycle cost for a vehicle option is:

Societal LCC = vehicle first cost + present value of lifetime costs for (fuel + non-fuel operation and maintenance + full fuel cycle air pollutant damages + full fuel cycle GHG emission damages + oil supply insecurity)

Their conclusion is that the hydrogen fuel cell car emerges as having the lowest externality costs for any of the options considered. Assuming mass production and with high values attached to externalities, the hydrogen fuel cell vehicle also has the lowest projected life cycle cost. Strictly the analysis is based on conditions in Southern California, but a similar result would apply to most locations (especially with high population density). Externality valuations are in line with the ExternE valuations, with an estimate for oil supply insecurity cost based on the marginal cost of maintaining oil supplies from the Persian Gulf. The result of this study can be interpreted such that hydrogen fuel cell vehicles present the best societal option of those considered.

Ogden *et al.* (2003) point out that current high cost of fuel cells and lack of infrastructure are major barriers to be overcome to achieve the conditions applied in the study. They also indicate that other options also offer considerable benefits over current vehicles i.e. reductions in externalities, with lesser barriers to full implementation. As a result they suggest that the route to hydrogen fuel cell vehicles should not be a path followed exclusively. Instead they suggest the implementation of bridging technology options whilst the barriers to full introduction of hydrogen fuel cell vehicles are reduced. This analysis agrees with the findings of Ricardo Consulting (2002).

Winebrake and Creswick (2003) apply a perspective-based scenario analysis to the decision making process involved in the transition to a hydrogen fueling infrastructure. They integrate the analytical hierarchy process (AHP) with scenario analysis techniques to explore the best routes to commercialisation of future hydrogen fuel processor technologies. In assessing three future scenarios (likely market, economic milieu and environmental milieu) they rank a series of fuel supply chains to fuel cell technologies. In the economic milieu and environmental milieu scenarios centralised production of natural gas was the preferred option. The likely market scenario ranked fuel station reforming of natural gas to hydrogen as the preferred option, ahead of on-board gasoline reforming, on-board natural gas reforming or on-board methanol.

12.5 Employment from the hydrogen economy

The promotion of hydrogen as an energy medium, in this document and elsewhere, is primarily based on the drivers of climate change, air quality and security of supply. Whilst these remain the dominant factors, the development of a hydrogen economy brings with it the potential benefit of economic and social growth through a number of elements. A study for the European Commission's ALTENER programme, led and reported by ECOTEC (no date of publication) identifies the impact of renewables on employment and economics. Adopting the principle that hydrogen is the effective mechanism to eventually deliver a substantially renewable global energy infrastructure, the benefits identified in this study can be extended to the implementation of hydrogen energy.

Renewably produced hydrogen is likely to provide a dispersed energy resource. Utilising on- and off-shore wind, tidal, wave or solar power sources, or producing hydrogen from biomass will typically lead to a larger number of smaller power / hydrogen centres, with dispersed connections to the energy grid. This is part of the attraction in terms of security of supply, but has the additional benefits of creating employment and local / regional development. Renewable energy and hydrogen energy is typically more labour intensive than traditional energy production technologies. Specialisation in particular technologies can also lead to job creation through export potential.

The ECOTEC led study indicates that 900,000 new jobs would be created in Europe from the adoption of renewable energy to a level of 8.2% (1066 TWh) by 2020. These are after any reduction in employment from conventional energy production. However, as the target for penetration of renewable energy in Europe has increased to 12% of gross energy consumption by 2010, the potential for job creation is further enhanced if this target is achieved. One warning from the study is that the anticipated level of job creation in the UK would be low in comparison to similar sized member states with a higher expectation of renewable energy penetration. The study is based on projections of renewable energy outputs in the UK of 46TWh by 2010 and 58TWh by 2020.

Without putting a figure on the number of jobs created in Wales, the number of jobs created will be larger for a greater implementation of renewable energy sources. The National Assembly for Wales has set a target of 4TWh renewable output by 2010, which roughly equates to 5000 new jobs, by interpolating the figures from the ECOTEC study. The report from this study also predicts that of the renewable technologies the greatest positive impact on jobs comes from energy provision from biomass, whether through thermochemical or biological routes. Again the report does not specifically address the employment implications of hydrogen production from biomass. However, it would be fair to conclude that the employment created by the production of hydrogen from biomass sources would be at least as high as combustion or anaerobic digestion processes. The added benefit in the case of biomass is the location of job creation. Agricultural regions are typified in Europe and in Wales by a decline in jobs and resulting social dislocation. Promotion of energy crop production is therefore likely to preserve and improve the levels of employment in rural areas.

The National Trust (2001) estimated that over 117,000 jobs were associated with the management and use of the Welsh environment. With 20% of these jobs being related to tourism, it is important that any renewable energy or hydrogen energy installations do not threaten these jobs. EHN (2003) have demonstrated that an approach to renewable energy installations that is sympathetic to the local environment and local cultural sensitivities can have a positive effect on tourism. This is particularly true when supported by an ethos of public consultation and education.

12.6 Public understanding and acceptance of hydrogen energy

Over the last century, the involvement of the public in the provision of our energy needs has decreased significantly. A coal based energy society called for a much greater level of consumer participation than our current society that revolves around consumer convenience. Current production of energy is remote from the user, who typically has little interest or understanding of how the energy is provided (ACTS, 2003).

There is a significant challenge of public information and acceptance to confront before the widespread adoption of hydrogen energy can take place (Goltzov and Veziroglu, 2001). Industrialised society has become used to technology changes being made remotely to improve levels of convenience or to reduce cost impacts. At the other end, our society, particularly in the UK, has become used to products at the end of their life "disappearing into another unknown black box labelled waste" (Giddings *et al.,* 2002). In addition, Giddings *et al.* contend that policy has tended to favour the economic argument above society and environment. Whilst there is certainly an economic case to be made for hydrogen energy in the longer term, there is a danger that delaying the transition for too long will perpetuate the use of oil and to a lesser extent natural gas with the attendant damage to society and the environment that has been discussed in this report. Critical in achieving this transition at an earlier stage is the public understanding of the damage that their continued emissions of carbon and other air pollutants cause.

Roe *et al.* (2001) suggest that a wide range of US consumers are willing to pay small amounts for tangible improvements in air emissions, even where there is no change to the source of supply, with a smaller segment of the population willing to pay a further premium for emissions reductions and a switch to renewable energy sources. This would suggest that US consumers were starting to have an appreciation of the causes and impacts of climate change and are willing to pay a small premium to help alleviate the problem. There is a danger that the survey overestimates consumer's willingness to pay and their stated intentions would not be matched, particularly in the event of general energy price increases.

Mourato *et al.* (2003) conducted a study of driver's preferences for fuel cell taxis in London. Using a contingent valuation methodology, involving focus groups of taxi drivers, the study investigated the driver's preferences for driving fuel cell vehicles, as part of a pilot and later as production vehicles roll out. Contingent valuation is a survey based technique used to establish the monetary value of goods or services that are not traded in markets. The results demonstrated a general enthusiasm to pay to take part in a pilot study, although this was motivated by anticipation of financial gain, rather than environmental reasons. The study did reveal that environmental factors did influence the longer term thinking on vehicle purchase. Other findings were as follows:

- A significant proportion of drivers perceived a health risk from air pollution in their jobs
- Even higher numbers supported the introduction of cleaner fuels and technologies in the taxi fleet
- However, less than 5% felt familiar or very familiar with information on fuel cells.
- Driving hydrogen vehicles did not raise safety concerns amongst the drivers

As the study suggests, it is essential to understand the benefits to the user of fuel cell vehicles and the factors behind potential user demand for the technology to be introduced successfully.

Adamson (2003) describes how fuel cell vehicles will need to pass beyond the initial niche markets before gaining mass-market acceptance. In achieving this transition, public awareness and acceptance needs to grow in order to establish a viable market. The primary niche market is described as a new product entering the market because it cannot be replicated by another marketed product. This technological niche appeals to an early adopter group (societal niche) who are willing to pay a premium for the product due to the value the group places on the product attributes. Hydrogen energy projects and early fuel cell demonstrations are currently at this phase and appeal to a societal niche that includes government or regional administrations and organisations keen on demonstrating the benefits of the technology to a broad based stakeholder group. Public perception is increased through publicity of demonstration projects, but at this stage public awareness and understanding is limited. Technology push, instead of market pull, dominates.

Once the primary niche becomes saturated, the product then moves to a secondary niche, where the product starts to compete with existing market products. Secondary niche adopters take on the new product on the basis of subjective utility, rather than being constrained by issues such as budgetary constraints. In the case of hydrogen energy systems, this would involve competition with existing energy production systems and secondary niche adopters being in specific locations, such as remote communities, municipal buildings, hospitals, schools and colleges. Fuel cell vehicles start to penetrate bus fleets, taxi fleets and develop into luxury markets and other such grouped applications. Public (consumer) awareness grows through increasing exposure and the introduction of targeted marketing. Technological development continues in an environment where economics is not the overriding concern and learning effects reduce costs and improve standardisation. Market pull grows, in parallel to technological push.

Adamson explains that fuel cell vehicles and stationary hydrogen applications will have to establish a market pull during the niche market phases to achieve mass-market adoption, as well as bringing down the price to a point where adoption is not budget constrained. The significant difficulties in moving from secondary niche market to mass market are described by Adamson as crossing the "commercialisation death-valley". Despite all the good intentions and noble aims of hydrogen energy and fuel cell vehicles, this significant step will have to be made and will need to be accompanied by a systematic and progressive programme of public education to increase awareness.

Although many awareness surveys are planned, one of the few published surveys on the acceptance of hydrogen technologies was carried out by LBST (1998). Three surveys were carried out in Munich:

1. 410 secondary school students were questioned about their knowledge of, acceptance of and need for information about hydrogen technologies (Table 12.4)
2. Passengers on the world's first regular hydrogen bus service in Munich were polled for their acceptance of the bus, environmental awareness, associations with hydrogen and need for information about hydrogen (Table 12.5)
3. Comparative polling of students on the bus and others in the classroom. (Table 12.6)

Table 12.4 Survey 1: Results from 410 secondary school students

Issue	Results
Acceptance of hydrogen technologies	Hydrogen technology and its further development were well accepted by the group. Two exceptions were the willingness to pay more for hydrogen than gasoline (only marginally positive). The students also had a perception of the dangers of hydrogen explosion
Obstacles to the broad introduction of hydrogen technologies Knowledge about hydrogen technologies	Ranked in order of perceived importance: 1. Cost (individual and social) 2. Danger 3. Lobbyism 4. Efforts of production 5. Lack of public acceptance 6. Too little public information 7. Technology not well developed. Knowledge of hydrogen as a fuel was disappointing with none of the students questioned being able to correctly answer all four of the questions posed and only 14 able to get 3 correct answers.
Associations with hydrogen	66% Chemical associations 11% Hydrogen technologies 9% Hydrogen bomb 3.4% Environmental friendliness 3.1% Threatening associations 0.3% Hindenburg/ dirigible
Demand for knowledge about hydrogen technologies	Large majority of the students questioned indicated a desire for greater knowledge about hydrogen and hydrogen technologies

Table 12.5 Study 2: Polling passengers on the hydrogen bus

Issue	Results
Acceptance of hydrogen technologies	Higher levels of acceptance than the student sample
Associations with hydrogen	40% Positive environmental aspects, 32% Chemical knowledge, 13% Hydrogen bomb, 6.4% Hydrogen technologies and 5.3% Threatening associations
Demand for knowledge about hydrogen technologies	A majority of the passengers were interested in more information about hydrogen

Table 12.6 Study 3: Comparison between students on the bus and in the classroom

Issue	Results
Acceptance of hydrogen technologies	Higher levels of acceptance in the bus than in the classroom
Associations with hydrogen	Chemical knowledge scored highest in both cases, but the students on the bus demonstrated a significantly higher association with positive environmental impact

The results show a relatively high level of acceptance, if not understanding of hydrogen technology. A criticism of the survey is that it is not representative of the public at large, for example a number of the students had previous exposure to hydrogen technology as part of their school studies. Passengers on a hydrogen bus are unlikely to give negative answers about the safety of the bus.

However, the survey does tend to reveal a general acceptance of the technology and support for further development. Negative associations were limited and far fewer than positive associations and it is clear that introduction to hydrogen energy technology through the demonstration project improved the positive perception and acceptance of the subject group.

ACCEPTH_2

In support of the future introduction of hydrogen-fuelled buses, there is a European 5th Framework Programme project entitled "Public Acceptance of Hydrogen Transport Technologies" (ACCEPT H_2), coordinated by Imperial College, London. The project is conducting a thorough evaluation of public values and perceptions of the issues surrounding the introduction of hydrogen as a transport fuel, for fuel cell buses in particular. The research seeks to address both public acceptability and economic viability of hydrogen buses, through detailed surveys connected to the hydrogen bus demonstration projects in London, Munich, Luxembourg, Perth and Oakland (European Commission, 2003c).

12.7 Public Communication Strategy in Wales

Focus group work

On behalf of the University of Glamorgan, People, Science and Policy Ltd. carried out focus group survey based research into the public perception of hydrogen as an energy source in Wales (University of Glamorgan, 2004). The aim of the research was to inform the development of an outline strategy to engage adults in Wales in discussions about hydrogen fuel. The objectives set out for the project by the University of Glamorgan team can be summarised as follows:

- To understand public perceptions of hydrogen fuel.
- To determine the broad acceptability of hydrogen fuel technologies.
- To identify educational needs and the appropriate level of communication.
- To develop an outline framework for the delivery of a public engagement strategy in Wales.

Two focus group workshops were run in Cardiff in September 2004. Both of the workshops lasted two hours and each comprised one focus group of nine women and a separate focus group of seven men; all were aged 25-55. A member of the University of Glamorgan H2 Wales technical research team took part in the second workshop to provide answers to the questions identified by participants in the first sessions.

From the analysis, specific issues that might be debated with the public to raise awareness of the potential of hydrogen fuel as a substitute for fossil fuels have been identified. The main objections to hydrogen that should be addressed relate to production with respect to:

- The methods of production.
- The safety of production plants.
- Emissions from production plants and their visual impact on the landscape.
- The role of Government/politics.
- The role of big business.
- The benefits of hydrogen as against other potential energy sources.

The other main issues are cost and safety at the point of use.

Further research based on these initial findings is planned and it is intended that the results will be published in a refereed journal and publicised on the project website www.h2wales.org.uk.

Consultant's recommendations for dialogue projects

As a result of the research carried out, the consultant has made the following recommendations in respect of future public communication work.

Exhibition and public meetings

An exhibition that travels to sites such as libraries, schools, leisure centres, museums, art galleries, shopping centres, public foyers, etc. could be developed. Technical staff will need to be available much of the time to provide more in-depth explanations, to listen to people's concerns and record their questions. Local meetings could also support these exhibitions. Such meetings could be open to all comers or set out to target and give incentive to specific groups. In running such meetings the important things to bear in mind are:

- People are more likely to speak in small groups of people similar to themselves.
- Having people with different points of view can stimulate a wider debate.
- Venues are important – a university is not somewhere most people have ever been, neither are town halls or four/five star hotels but public halls and 3 star hotels are good venues.
- Facilitators should listen to the points raised and respond by enabling the participants concerns to be further explored. This does not need to turn into a question and answer sessions.

Dialogue with business and the public

Further events that target potential investors in, and manufacturers of, hydrogen and associated equipment can be held. This might involve demonstration projects, posters, talks and debates. Such high profile events with international attendance could be used to generate wider publicity and may well attract the support of Government keen to promote inward investment. There might also be a public exhibition with explainers as an addition to this type of event.

To reach the widest audience work with the local media basing stories around 'news', such as new developments or research findings, or even large international meetings held in Wales on the topic. Visits from large companies that are household names, seeking to invest in the region, would also attract media attention. This is a long term and opportunistic strategy as it relies on 'happenings' that will catch the media's attention.

Demonstrations and open days

Organisations currently producing hydrogen related technology or researching new or more cost effective ways of producing and using hydrogen, could run open days and demonstration projects for the public. Such events could also be used to stimulate press interest, especially locally. These events should be interactive, that is, enable the public to question and give their views. They should also be open in the evening and at a weekend to ensure that those in work during the day can attend and possibly bring their children.

Further research

There is scope for a larger research project in Wales on the public's perception of hydrogen as a fuel source. For example, a telephone survey of a nationally representative sample of 1,000 adults, each interview lasting about 10 minutes, could yield important data on the extent of awareness, the proportion of the population who hold negative images of hydrogen and the relative importance of the concerns identified in Section 12.7.1, especially the issues of cost and environment. It would also serve to provide more precise data on the differences between men and women and different age and socio-economic groups. In particular, the rural/urban divide needs to be explored given the recognition that pollution could merely be displaced from the point of use (towns and cities) to the point of production (more rural areas). Such surveys can be used to generate publicity.

Any project that sets out to engage the public with hydrogen fuel must provide information about the cost, safety and production of the fuel. In addition, all dialogue/communication activities to engage with the public must use illustrations, since visuals made a clear impact on views in the focus sessions. Based on the initial focus group research, the biggest issues related to the future of hydrogen fuel are mainly related to production, safety at the point of use, cost and performance against the alternatives. However, some participants were sceptical of politicians, while others were sceptical of scientists, hence it is recommended that any event includes a spread of experts.

References

AA (Automobile Association) (2003) UK Fuel Prices Mar 2003 [online] Available at: http://www.theaa.com/allaboutcars/fuel/ Accessed today November 2004.

AA (Automobile Association) (2004) AA Petrol Busters. UK fuel price comparison November 2004 [online] Available at: http://www.aapetrolbusters.com/ Accessed 3rd .

Abedi, J., Yeboah, Y.D., Howard, J., and Bota, K.B., (2001) Development of catalytic fluid bed steam reformer for the production of hydrogen from biomass, 5th Biomass conference of America, Abstracts available [online] at www.eprida.com/hydro/hydrproduction.pdf Accessed November 2004.

Abraham, S. (2003) Videotaped Remarks by US Energy Secretary Spencer Abraham to the International Energy Agency Hydrogen Seminar Paris March 3, 2003.

ACTS (Advanced Catalytic Technologies for Sustainability). (2003) Sustainable hydrogen an environmentally clean energy carrier. Outline of an ACTS research programme. [online] Available at: http://www.nwo.nl/NWOHome.nsf/pages/NWOP_59HK9C Accessed 1st May 2003.

Adamson, K. and Pearson, P. (2000) Hydrogen and methanol: a comparison of safety, economics, efficiencies and emissions. Journal of Power Sources. 86. 548-555.

Adamson, K. A. (2003) An examination of consumer demand in the secondary niche market for fuel cell vehicles in Europe. International Journal of Hydrogen Energy. 28, 771-780.

Air Products (2003) Cylinder Gases [online]. Air Products and Chemicals, Inc. Available from: http:// www.airproducts.co.uk/cylindergases/index.htm

Alleau, T, (2002) Hydrogen and fuel cell activities in western Europe, WHEC 2002, Montreal, Canada.

Amos, W.A., (1998) Cost of Storing and Transporting Hydrogen, National Renewable Energy Laborotory, Technical Report NREL/TP-570-25106.

Andreassen, K. (1998) Hydrogen Production by Electrolysis. In: Hydrogen Power: Theoretical and Engineering Solutions, Kluwer Academic Publishers, the Netherlands, 91-102.

Annan, K. (2001) United Nations Secretary General Kofiannan speech to The Fletcher School of Law and Diplomacy on May 20, 2001. [online] Available at: fletcher.tufts.edu/forum/arts25-2/annan.pdf Accessed 1st May 2003.

Arnason, B. and Sigfusson, T. (2000) Iceland – a future hydrogen economy. International Journal of Hydrogen Energy. 25 389-394.

Audus, H., Kaarstad, O. and Kowal, M. (1996) Decarbonisation of fossil fuels: hydrogen as an energy carrier. In: Hydrogen Energy Progress XI, Proceedings of the 11th World Hydrogen Energy Conference, Stuttgart, Germany, 23-28 June 1996.

Aurand, (2000) Supercritical water gasification of biomass, Iowa energy centre [online]. Available from: www.energy.iastate.edu/renewable/biomass/cs-water.html Accessed 1st May 2003.

AWEL (2003) AWEL [online] Available from: http://anglesey-wind.co.uk Accessed 1st May 2003.

Bahbout, A. Tartaglia, G.P. and Bünger, U. (2000) Hydrogen activities in the European Union work programme. Paper delivered at the 21st World Gas Conference. June 6-9 2000, Nice, France.

Bailey, P.S. (1980) Assessment of potential future markets for the production of hydrogen from water in Canada. International Energy Agency Report.

Baptiste, J-P. and Ducroux, R. (2003) Energy policy and climate change. Energy Policy. 31. 155-166

Barbir, F. and Gomez, T. (1997) Efficiency and economics of proton exchange membrane (PEM) fuel cells. International Journal of Hydrogen Energy, 22 (10/11) 1027-1037.

Barbir, F (2003) Safety issues of hydrogen in vehicles. Proton energy systems available at: http://www.gave.novem.nl/novem_new/index.asp?id=32. accessed 15/12/03

Barreto, A., Makihira, A., and Riahi, K., (2002) The hydrogen economy in the 21st century: a sustainable development scenario. International Journal of Hydrogen Energy, 28 (3), 267-284.

Basye, L. and Swaminathan, S. (1997) Hydrogen production costs - a survey. SENTECH, Inc., US Department of the Environment Report DOE/GO/10170-778.

Bauen, A. and Hart, D. (2000) Assessment of the environmental benefits of transport and stationary fuel cells. Journal of Power Sources 86, 482-494.

Bauen, A. (2001) Prospects for H_2 production using renewable energy sources, Presentation to IPPR seminar "Hydrogen – driving the future?" London, 29th March 2001.

Bauen, A. (2002) Imperial College London. Personal communication on the cost projections of various fuel cell types and hydrogen gas turbine cost estimates.

Bauen, A., Hart, D. and Chase, A. (2003) Fuel cells for distributed generation in developing countries– an analysis. International Journal of Hydrogen Energy. 28 (7) 695-701.

bioenergy.ornl.gov (2002) bioenergy conversion factors [online]. Available from: http://bioenergy.ornl.gov/papers/misc/energy_conv.html. Accessed 1st May 2003.

Baumol, W. J. and Oates.W.E. (1988) The theory of environmental policy. Second edition. Cambridge University Press. Cambridge.

Bernard P and Chahine R (2004) Assessment of hydrogen storage on different carbons. Available [online] at: www.eere.energy.gov/hydrogenandfuelcells/hydrogen/iea/pdfs/NN0094v.pdf. accessed 21/10/2004

Berry, G. (1996) Hydrogen as a transportation fuel: costs and benefits. Lawrence Livermore Laboratory. UCRL-ID-123465, March.

Blair, T. (2003) Speech Sustainable development and climate change. 24th February 2003. http://www.number-10.gov.uk/output/Page3073.asp

Blok, K., Williams, R., Katofsky, R. and Hendriks, C. (1997) Hydrogen production from natural gas: sequestration of recovered CO_2 in depleted gas wells and enhanced natural gas recovery. International Journal of Hydrogen Energy. 22(2/3), 161-168

BMW (2002) BMW Group Clean energy World Tour [online] BMW Group Available at: http://www.bmw.com/bmwe/pulse/enterprise/cleanenergy3/ Accessed 1st May 2003

BOC (1990) Industrial gas cylinder identification data. BOC Gases. BOC Limited Works Notice 14F/1990.

Bockris, J O'M. (2002) The origin of ideas on a Hydrogen Economy and its solution to the decay of the environment. International Journal of Hydrogen Energy, 27 (7-8) 731-740

Bohme, O., Haus, U., Leidlich, F., Salge, H. and Wendt, H. (1994) Process engineering and cost estimation of MCFC power plants. 1994 Fuel Cell Seminar, Program and Abstracts. 61-64.

Bose, T K. Gringas, O. G., (2000) Removing unnecessary barriers through the activities of ISO/TC 197 of hydrogen technologies' Hydrogen Energy Progress XIII, International Association of H_2 energy, Vol 1.

Bowen, P (2003) Private communication, Cardiff University.

Boyce, C.A., Crews, M.A. and Ritter, R. (2004) Time for a new hydrogen plant. In Hydrocarbon Engineering, Palladian Publications, February 2004.

BP (2004) British petroleum statistical review of world energy BP [online] Available from: www.bp.com Accessed 1st November 2004.

Browning, D., (2000) DERA Research on H2 Storage and Generation Methods for Fuel Cells; H2Net presentation [online] H2NET. Available from: http://www.h2net.org.uk/PDFs/Stor2000/H2nettalk_Nov00.pd Accessed 1st May 2003.

Bünger, U. (2002) HyNet evaluation of all hydrogen related EoIs. [online] Available at: http://www.hynet.info/ecactiv/index00.html Accessed 1st May 2003

Bush. G.W. (2003) State of the Union address [online] Available at: http://www.whitehouse.gov/news/releases/2003/01/20030128-19.html Accessed 1st May 2003

Brussels, 7.11.2001 COM (2001) 547 COMMUNICATION FROM THE COMMISSION TO THE EUROPEAN PARLIAMENT, THE COUNCIL, THE ECONOMIC AND SOCIAL COMMITTEE AND THE COMMITTEE OF THE REGIONS on alternative fuels for road transportation and on a set of measures to fromote the use of biofuels available [online] at http://europa.eu.int/comm/taxation_customs/taxation/information_notes/fuel.htm Accessed 21/10/04

Butler C (2004) Examples of On-going work, Fuel Cell Research Meeting, HSL 18/03/04 Palace Hotel, Buxton

Cadwalader L C and Herring J S (1999) Safety issues with hydrogen as a vehicle fuel, Idaho National Engineering and Environment Laboratory. INEEL/EXT.99.0052

Caglar A and Dimirbas A., (2001) Hydrogen-rich gaseous products from tea waste by pyrolysis. Energy Sources 23, 739-746.

CARB (2003) California Air Resources Board Home [online] Available from: http://www.arb.ca.gov Accessed 1st May 2003.

Carpetis, C. (1994) Technology and costs of hydrogen storage. TIDE (TERI Information Digest on Energy), Vol.: 4:1, March, pp. 1-13.

Chalk, S (2003) "The President's Hydrogen Initiative: US DOE's Approach" A Paper for the Biennial Asilomar Conference on Energy and Transportation on "The Hydrogen Transition" July-August 2003 Available [online] at: http://www.eere.energy.gov/hydrogenandfuelcells/documents.html Accessed 21/10/04

Champion, N (2003) Private communication, Cambridge University.

Chapman, T., (2002) The hydrogen economy blast off [online] Institute of Physics. Available from: http://physicsweb.org/article/world/15/7/10 Accessed 11th December 2002.

Chase, A. Bauen, A, Hart, D. Hailes, R. Howes, J. and Arwas, P. (2003) Review of fuel cell commercial potential for DTI and the Carbon Trust. Final Report. E4Tech, London, February 2003. [online] Available at: www.dti.gov.uk Accessed 3rd November 2004

CIA (2004) Chemical Industries Association, Issue Statements: Energy Policy & Pricing 13 October 2004 [Online] Available at: http://www.cia.org.uk/cgi-bin/dbman/db.cgi?db=topissues2&uid=default&view_records=1&ID=105&ww=1 Accessed 23rd November 2004.

Claassen, P. A. M. (2003) A novel bioprocess for hydrogen production from biomass for fuel cells [online]. Available from: http://europa.eu.int/comm/research/quality-of-life/ka5/en/01267.html Accessed 1st May 2003.

Clarkson, R. and Deyes, K. (2002) Estimating the social costs of carbon emissions. HM Treasury and DEFRA. [online] Available at: http://www.hmtreasury.gov.uk/documents/taxation_work_and_welfare/taxation_and_the_environment/tax_env_GESWP140.cfm Accessed 1st May 2003

Cole, S. (1998) Applied Transport Economics – Policy, Management and Decision Making, second edition, London: Kogan Page Ltd, ISBN 0 74942303 X.

College of the Desert (2001) Hydrogen fuel cell engines and related technologies: Rev 0, December 2001, USA

COM(2001) 370 Available [online]at http://europa.eu.int/eur-lex/en/com/wpr/2001/com2001_0370en.html Accessed 21/10/04

Connor, P. M. (2003) UK renewable energy policy: a review. Renewable and Sustainable Energy Reviews. 7 (1) 65-82.

Council Of The European Union (1998). Minimum stocks of crude oil and/or petroleum products. Directive 98/93/EC. [online] Avaialble at: http://europa.eu.int/scadplus/leg/en/lvb/l27045.htm Accessed 3rd November 2004.

Cropper, M. and Jollie, D. (2002) Fuel cell systems: a survey of worldwide activity. 14 November 2002. Available at: www.fuelcelltoday.com

Cropper, M. Geiger, S. and Jollie, D. (2003) Fuel cell systems: a survey of worldwide activity. 5 November 2003. [online] Available at: www.fuelcelltoday.com Accessed 3rd November 2004

CUTE (2002) Clean urban transport for Europe- a fuel cell bus project in 9 European cities, Belgium: European Communities, available at EvoBus GmbH, E/ES, Dr Manfred Schuckert, Kasbohrerstrasse 13, D – 89077 ULM, Germany.

Daimler Chrysler (2001) First fuel cell vehicles for customers. [online] Available at: http://www.daimlerchrysler.com/index_e.htm?/news/top/2000/t00406_e.htm Accessed 1st May 2003

Das L.M. (2002), "Hydrogen engine: research and development programmes in Indian Institute of Technology, Delhi", International Journal of Hydrogen Energy, 27, pp.953-965.

De Sousa, S.N.M. (2000) Hydrogen energy progress XIII. Proceedings of the 13th World hydrogen energy conference, Beijing China, 12-15 June 2000:116

DEFRA. (1999) A better quality of life: a strategy for development for the UK. [Online] Available at: www.sustainable-development.gov.uk/UK_strategy/index.htm Accessed 1st May 2003

DEFRA. (2000) Climate Change Programme [online] Available at: www.defra.gov.uk/environment/climatechange/cm4913/index.htm Accessed 1st May 2003.

DEFRA. (2001a) A summary guide to the UK emissions trading scheme. [online] Available at: http://www.defra.gov.uk/environment/climatechange/trading/ Accessed 1st May 2003

DEFRA, (2001b) The UK fuel poverty strategy. DEFRA, DTI, Department for Social Development, The Scottish Executive and The National Assembly for Wales. November 2001

DEFRA. (2002) Framework for Sustainable Development on the Government Estate. [Online] Department for Environment, Food & Rural Affairs. [online]
Available at: www.sustainable-development.gov.uk/sdig/improving/index.htm Accessed 1st May 2003

DEFRA, Scottish Executive, National Assembly For Wales, And Department Of The Environment In Northern Ireland. (2000) The air quality strategy for England, Scotland, Wales and Northern Ireland: working together for clean air [Online] Available at: http://www.defra.gov.uk/environment/airquality/strategy/ Accessed 1st May 2003

DEFRA (2004a) UK Government's Sustainable Development Unit available at http://www.sustainable-development.gov.uk/areas/subject/env_nat_res2.htm Accessed 28.10.04

DEFRA (2004b). UK announces plans on EU emissions trading scheme. News release [online] Available at: http://www.defra.gov.uk/news/2004/041027a.htm Accessed 5th November 2004.

Demirbas, A (2003) Hydrogen rich gas from fruit shells via super critical water extraction. International Journal of Hydrogen Energy. 29, 1237-1243. Elsevier Science Ltd.

De Sola Pool, I. (ed.) (1977) The social impact of the telephone. MIT Press, Cambridge, MA.

DETR (2000). The air quality strategy for England, Scotland, Wales and Northern Ireland: Working together for clean air January 2000. Department of the Environment, Transport and the Regions in partnership with the Scottish Executive, The National Assembly for Wales and the Department of the Environment in Northern Ireland. [online] Available at: www.defra.gov.uk/environment/ airquality/strategy/pdf/foreword.pdf Accessed 23rd November 2004.

Dey, R (2003) ISO/TC 197 activities, presentation given at round table discussion during the European Hydrogen Energy Conference 3rd October 2003, Grenoble France.

DfT (1998) A New Deal for Transport: Better for Everyone. Transport White Paper [online] Department For Transport Available at: http://www.dft.gov.uk/itwp/paper/ Accessed 1st May 2003

DfT (2000) Transport 2010 - the ten year plan. [Online] Department For Transport. Available at: www.dft.gov.uk/trans2010/ Accessed 1st May 2003

DfT (2002) Powering Future Vehicles: the government strategy [Online] DFT, DTI, DEFRA and HMT Available at: www.roads.dft.gov.uk/ Accessed 1st May 2003.

DfT (2003a) Transport Statistics, Vehicles [online]. Department For Transport. Available from: http://www.transtat.dft.gov.uk/roadvehs/index.htm

DfT (2003b), Transport Statistics for Great Britain 2004 Edition. [online] Available at: http://www.dft.gov.uk/stellent/groups/dft_transstats/documents/page/dft_transstats_031999.hcsp accessed 18th October 2004.

DfT (2004) Department for Transport – 2003 Transport Statistics for Great Britain 2004 Edition. Available [online] at: http://www.dft.gov.uk/stellent/groups/dft_transstats/documents/page/dft_transstats_031999.hcsp Accessed 18th October 2004.

DfT (2004b) Transport Statistics, Vehicles [online]. Available from: http://www.transtat.dft.gov.uk/roadvehs/index.htm Accessed 3rd November 2004

DTI (1999) New Review [online]. Department of Trade and Industry. Available at: http://www.dti.gov.uk/NewReview/nr38/html/world.html

DTI (2000) Utilities Act [Online]. Department of Trade and Industry. Available at: www.hmso.gov.uk/acts/acts2000/20000027.htm Accessed 1st May 2003

DTI (2001a) New and renewable energy: prospects for the 21st century. The Renewables Obligation statutory consultation. August 2001.

DTI (2001b) DTI consultation on the impact of NETA on smaller generators. [online] Available at: http://www.chpa.co.uk/presre75.htm Accessed 1st May 2003

DTI (2001c) DTI fuel cell competitiveness targets. [online] Department of Trade and Industry Available at: http://www.dti.gov.uk/renewable/fuelcell.htm

DTI (2002a) Energy: its impact on the environment and society, Department of Trade and Industry DTI/Pub 6144/6k/07/02/NP. URN 02/1055.

DTI (2002b) Route Map Paper Hydrogen [online]. DTI Available from: www.dti.gov.uk/renewable/routemap.htm Accessed 1st May 2003.

DTI (2002c) Digest of UK energy statistics. [Online] Avaiable at: www.dti.gov.uk/energy/inform/dukes/index.shtml Accessed 1st May 2003.

DTI. (2002d) Sustainable technology route maps: fuel cells [online]. Department of Trade and Industry Available at: www.dti.gov.uk/renewable/pdf/tech9.pdf

DTI (2003a) Energy White Paper: Our energy future - creating a low carbon economy. London: The Stationary Office [online]. Available at: http://www.dti.gov.uk/energy/whitepaper/index.shtml Accessed 1st May 2003

DTI (2003b) UK energy sector indicators. [Online] Avaiable at: www.dti.gov.uk/energy/inform/energy_indicators/index.shtml Accessed 1st May 2003

DTI (2003c) Options for a Low Carbon Future - Phase 2. [online] Available at: www.dti.gov.uk/energy/whitepaper/phase2.pdf Acccessed 1st May 2003

DTI (2003d), Energy Trends December 2003. Available online at http://www.dti.gov.uk/energy/inform/regional_energy/index.shtml

DTI (2004a) UK Energy Sector Indications 2004, Available [online] from: www.dti.gov.uk Accessed 21/10/04

DTI (2004b), 'Creating a Low Carbon Economy - First Annual Report on Implementation of the Energy White Paper'. Available online from http://www.dti.gov.uk/energy/sepn/firstannualreport.shtml accessed 21st October 2004

DTI and OFGEM. (2003) Joint Energy Security of Supply Working Group Reports. [Online] Avalable at: www.dti.gov.uk/energy/domestic_markets/security_of_supply/jessreport2.pdf Accessed 1st May 2003

Dönitz, W (1998) Fuel cells for mobile applications, status, requirements and future application potential. International Journal of Hydrogen Energy. 23 (7) 611-615.

Doran, P., Robeson, S., Wright, D. and Craven. J. (2003) Finance and the fuel cell industry: a review of the current financing climate. Short communication. International Journal of Hydrogen Energy 28 (7) 713– 715.

Dulas (2002) Woodfuel Heat and Power Solutions, Biomass – All you need to know [CD-ROM] Available from: Dulas, Dyfi Eco Parc, Machynlleth, Powys, SY20 8AX, UK.

Dutton, A, Bleijs, A, Dienhart, H Falchetta, W, Hug, W, Prischich, D and Ruddell, J, (2000) Experience in the design, sizing, economics and implementation of autonomous wind-powered hydrogen production systems, International Journal of Hydrogen Energy, 25, (8) 705-722.

Dutton, G. (2002) Hydrogen energy technology. Tyndall Centre for Climate Change Research. Working Paper No. 17. [online] Available at: http://www.tyndall.ac.uk/publications/pub_list_2002.shtml Accessed 1st May 2003.

Dunn, S. (2001) Hydrogen futures: towards a sustainable energy system. Worldwatch Paper 157 August 2001.

Dunn, S. (2002) Hydrogen in history. [Online] Avialable at : www.theeglobalist.com/Dbweb/storyid.aspx?storyID=2338 Accessed 1st May 2003

E4Tech (2003) Review of Fuel Cell Commercial Potential for DTI and The Carbon Trust (Final Report) [online] Available at: http://www.dti.gov.uk/energy/publications/pdfs/index.shtml Accessed 1st May 2003

ECOTEC. (No date of publication) The Impact of Renewables on Employment and Economic Growth, Altener Programme of the Directorate-General for Energy of the European Commission [online] Available at: http://www.eufores.org/Employment.htm Accessed 1st May 2003.

Egan, G (2004) private communication, Brehon Energy plc.

EHEC (2003) Proceedings from the European Hydrogen Energy Conference, Grenoble, France, 2-5 October 2003

EHN. (2003) Distinctive features of the group. [online] Available at: http://www.ehn.es/eng/textos/elgrupo01.html Accessed 1st May 2003

EIA (2002) IEA implementing agreement on enhanced oil recovery, presentation given 2002. Available at www.iea.org/dbtw-wpd/textbase/ work/2002/washington/2_can.pdf Accessed 21/10/04

EIA (2004) Country Analysis Brief, Energy Information Administration (EIA) Department of Energy Available at: http://www.eia.doe.gov/emeu/cabs/uk.html Accessed 21/10/04

EIHP (2003a) European Integrated Hydrogen Project presentation, [online] available at http://www.eihp.org accessed 16/9/04

EIHP (2003b) European Integrated Hydrogen Project draft proposals, [online] available at http://www.eihp.org accessed 16/9/04

EIHP (2003c) European Integrated Hydrogen Project outline, [online] available at http://www.eihp.org accessed 16/9/04

EIHP (2003d) European Integrated Hydrogen Project, final report, [online] available at http://www.eihp.org accessed 16/9/04

EIHP (2003e) European Integrated Hydrogen Project expected results, [online] available at http://www.eihp.org/public/results.html accessed 16/9/04

EIHP (2003f) European Integrated Hydrogen Project goals, [online] available at http://www.eihp.org/public/goals.html accessed 16/9/04

Eisenbeiss. G. (2003) German's hydrogen vision. Presented at the IEA Renewable Energy Working Party Seminar3 March, 2003 International Energy Agency 9 rue de la Fédération, Paris.

Elam, C, Padro, C, Sandrock, G, Luzzi, A Lindblad, P and Hagen, E (2003) Realizing the hydrogen future: the International Energy Agency's efforts to advance hydrogen energy technologies, International Journal of Hydrogen Energy, 28 (6) 601-607.

Eliasson, B., and Bossel, U., (2000) The Hydrogen Future: Bright or Bleak [online]. Available from: www.nrel.gov/ncpv/hotline/pdf/hydrogen_economy.pdf. Accessed 1st May 2003.

EPRI (1995) Technical brief: 2-MW direct carbonate fuel cell demonstration. Electric Power Research Institute. EPRI TB-105733, October.

EPSRC (2003) SUPERGEN [online] Available from: http://www.epsrc.ac.uk/website/index.aspx, Accessed 1st May 2003

Erdmann, G. (2003) Future economics of the fuel cell housing market. International Journal of Hydrogen Energy, 28. 7. 685– 694

ERU (1995) ERU 95.11: Hydrogen Generation from Stand Alone Wind Powered Electrolysis Systems [online]. Available from: http://www.eru.rl.ac.uk/broch95/eru11.html Accessed: 15th January 03.

ETSU (1983) The future role of hydrogen in the UK energy economy. Energy Technology Support Unit, Harwell, Oxon, UK.

European Commission (2001) Promotion of green energy (from renewable sources). Presentation on the 2001 Directive of the European Commission Directorate General For Energy And Transport [online] Available at: europa.eu.int/comm/energy/library/renouvelables-en.pdf Accessed 1st May 2003

European Commission (2001b). European transport policy for 2010: time to decide - White Paper. COM (2001) 370, 12 September 2001. [online] Available at: http://aei.pitt.edu/archive/00001187/ Accessed 5th November 2004.

European Commission (2001c) Alternative fuels for road transportation and (on a) set of measures to promote the use of biofuels. COM(2001) 547 Communication from the Commission to the European Parliament, the Council, the Economic and Social Committee and the Committee of the Regions. Brussels, 7.11.2001

European Commission. (2002) Intelligent energy for Europe: a multiannual programme for actions in the field of energy (2003-2006). April 2002. European Commission Directorate General For Energy And Transport [online] Available at: http://europa.eu.int/comm/energy/res/intelligent_energy/index_en.htm Accessed 1st May 2003

European Commission. (2003a) Commission communication to the European Parliament concerning the Council's common position on the adoption of a directive establishing a scheme for greenhouse gas emission allowance trading within the Community. [online] Available at: http://europa.eu.int/comm/environment/climat/emission.htm accessed 1st May 2003

European Commission (2003b) Hydrogen energy and fuel cells – a vision of our future. Draft Preliminary report of the European Commission High Level Group (HLG) on Hydrogen and Fuel Cells. [online] Available at: http://europa.eu.int/comm/research/energy/nn/nn_rt_hlg3_en.html Accessed 1st May2003

European Commission (2003c).European fuel cell and hydrogen projects 1999-2002. European Commission Directorate-General for Research document EUR 20718, Brussels, Belgium.

European HFP (2003) European hydrogen and fuel cell technology platform – HFP. [online] Available at: http://www.hfpeurope.org/ Accessed 5th November 2004

European Union. (1998) Council Directive 98/93/EC of 14 December 1998: Minimum stocks of crude oil and/or petroleum products. [online] Available at: http://europa.eu.int/scadplus/leg/en/lvb/l27045.htm Accessed 1st May 2003.

EV World (2003) Necar 4 costs [online] Available at: http://www.evworld.com/archives/interviews/dtran.html Accessed 1st May 2003

ExternE. (1999) The EcoSense Model [online] Available at: http://www.jrc.es/pages/f-search.html Accessed 1st May 2003

Eyre, N., T. Downing, R. Hoekstra, and K. Rennings (1998). ExternE Externalities of Energy - Volume 8 Global warming damages, Commission of the European Communities, Brussels, Belgium.

Eyre, N. Fergusson, M. and Mills, R. (2002) Fuelling road transport - implications for Energy Policy - study for DFT [Online] Available at: www.roads.dft.gov.uk/cv/fuelling/index.htm Accessed 1st May 2003

Faleschini, G, Hacker, V, Mur, M, Kordesch, K and Aronsson, R, (2003). Ammonia for high-density hydrogen storage [online], Available from: http://www.electricauto.com/HighDensity_STOR_COV.htm
Accessed 1st May 2003.

Farrar and Vaze (eds.) (2000) Wales: changing climate, challenging choices – a scoping study of climate change impacts in Wales. Report prepared for the National Assembly for Wales.

Farrell, J (2002) London Hydrogen Action Plan, second draft. Incorporating material from Clean Fuel for London event, July 2000.

Farrell, A.B., Keith, D.W. and Corbett, J.J. (2003) A strategy for introducing hydrogen into transportation. Energy Policy. 31. 1357-1367

Fisher Scientific (2003) Hydrogen Material Safety Data Sheet [online] available at https://www.cataloge.fisher.co.uk. Accessed 08/06/03

FoE (2001) Friends of the Earth press release: "Chancellor urged not to cave in on climate levy: 24 Sep 2001 [Online] Available at : http://www.foe.co.uk/resource/press_releases/20010924184811.html Accessed 23rd November 2004.

Foley, J.,(2001) H2: driving the future: the policy implications of developing hydrogen as a fuel for road vehicles. Institute for Public Policy Research. Emphasis Publishing Ltd. Guildford, UK. ISBN 1 86030 176 2.

Ford (2003) Ford model U. [online] Ford Motor Company Available at: http://www.fordvehicles.com/autoshow/suvs/modelu/ Accessed 1st May 2003

Forsberg, C (2003) Hydrogen, nuclear energy and the advanced high-temperature reactor. International Journal of Hydrogen Energy. 28, 1073-1081. Elsevier Science Ltd

Foster-Wheeler. (1996) Decarbonisation of Fossil Fuels. IEA Greenhouse Gas R&D Programme Report No. PH2/2.

Frates, L. reported in Llanos, M (2004) "Hydrogen cars ready to roll — for a price" MSNBC News 23rd June 2004. [online] Available at: http://www.msnbc.msn.com/id/4563676/ Accessed 28.10.2004

Fuel Cells 2000 (2003a) January 2003 technology update, [online] Available from: http://www.fuelcells.org/fcnews.htm Accessed 1st May 2003.

Fuel Cell 2000 (2003b) Fuel Cell 2000 Web site [online] Available from: www.fuelcells.org Accessed 1st May 2003.

Fuel Cell Bus Club (2003) CUTE clean urban transport for Europe, [online] Available from: www.fuelcell-bus-club.com/main_objectives.html Accessed 1st May 2003.

Fuel cell network (2003) The fuel cell network [online] Available from: http://fuelcellnetwork.bham.ac.uk/ Accessed 1st May 2003.

Fuel Cell Today (2002) Europe Vows to Go Hydrogen, 17 December 2002 [online] Available at: http://www.fuelcelltoday.com/FuelCellToday/IndustryInformation/IndustryInformationExternal/NewsDisplayArticle/0,1471,2252,00.html Accessed 1st May 2003

Fuel Cell Today (2003) US Fuel Cell Council study projects US$2 billion portable power fuel cell market by 2011. [online] Available at: http://www.fuelcelltoday.com/FuelCellToday/IndustryInformation/IndustryInformationExternal/NewsDisplayArticle/0,1602,2868,00.html Accessed 7th May 2003

Future Energy. (2003) Options for a low carbon future - Solutions phase 2 [Online] Available at: www.dti.gov.uk/energy/whitepaper/index.shtml Accessed 1st May 2003

Garche, J. (1998) Application of small-scale fuel cells in combined heat/power cogeneration. In Hydrogen power: theoretical and engineering solutions, Kluwer Academic Publishers, the Netherlands, 563-574.

Gaudernack, B. and Lynum, S. (1998) Hydrogen from natural gas without release of CO_2 to the atmosphere. International Journal of Hydrogen Energy. 23 (12), 1087-1093.

German Transport Energy Task Force. (2001) Transport energy strategy (TES): a joint initiative from politics and industry. Second Task force status report to the steering committee. 13.6.2001.

Giddings, B., Hopwood, B. and O'Brien, G. (2002) Environment, economy and society: fitting them together into sustainable development. Sustainable Development. 10, 187-196

Glam (2003) University of Glamorgan/wastewater website, [online] Available from: http://www.glam.ac.uk/wastewater/ Accessed 1st May 2003.

Glatzmaier, G., Blake, D. and Showalter, S. (1998) Assessment of Methods for Hydrogen Production Using Concentrated Solar Energy. National Renewable Energy Laboratory Technical Report NREL/TP-570-23629.

Goltzov, V. A. and Veziroglu. T.N. (2001) From hydrogen economy to hydrogen civilisation. International Journal of Hydrogen Energy. 26. 909-915.

Gough, C., Shackley, S. and Cannell, M.G.R., (2002) Evaluating the options for carbon sequestration. Tyndall Centre Technical Report 2, 2002 [online] Available at: http://www.tyndall.ac.uk/publications/pub_list_2002.shtml Accessed 1st May 2003

Granite, J.E., Pennline, H.W., and Hargis, R.A., (2000) Novel sorbents for mercury removal from flue gas, Industrial and Engineering Chemistry Research 39, (11) 1020-1029.

GRI (1999) GRI/EPRI unite to commercialize advanced fuel cells for power systems. Press release, February 25 [online], Gas Research Institute. Available at: http://www.gri.com. Accessed 1st May 2003

H2NET (2003) H2NET hydrogen network [online] Available from: http://www.H2NET.org.uk Accessed 1st May 2003.

H2FC (2003) Types of fuel cell, The hydrogen fuel cell investor, [online] Available from: http://www.h2fc.com/tech.html Accessed 1st May 2003.

Hao, X , Guo, l, Mao, X, Zhang, M and Chen, X (2002) Hydrogen production from glucose used as a model compound of biomass gasified in supercritical water, International Journal of Hydrogen Energy, 28, (1) 55-64.

Hallenbeck, P.C. and Benemann, J.R. (2002) Biological hydrogen production; fundamentals and limiting processes. International Journal of Hydrogen Energy. 27 (11/12), 1185-1193.

Halme, A., Zhang, X., and Ranta, A., (2000) STUDY OF BIOLOGICAL FUEL CELLS [online] Automation Technology Laboratory, Helsinki University of Technology. Available from: www.automation.hut.fl/research/bio/sfc00pos.htm Accessed 1st May 2003

Hart, D. and Hörmandinger, G. (1998) Environmental Benefits of transport and stationary fuel cells. Journal of Power Sources 71. 348-353.

Hart D, Freund P and Smith A (1999) Hydrogen - Today and Tomorrow IEA Greenhouse Gas R&D Programme, ISBN 1 898373 24 8. or [online] Available at: www.ieagreen.org.uk/h2rep.htm. Accessed 16/9/04.

Haug, M. (2004) Hydrogen – IEA activities and perspective. Paper presented at the UK/US Vision for Hydrogen Technology conference. 11-12 October 2004, London.

Hawkes, F.R., Dinsdale, R., and Hawkes, D. L., (2002a) Future technologies – hydrogen. In Johnston E (Ed.) The Welsh Potential for Renewable Energy, Cardiff: Institute of Welsh Affairs ISBN 1 871726 913. pp58-65.

Hawkes, F, Dinsdale, R, Hawkes, D and Hussy, I (2002b) Sustainable fermentative hydrogen production: challenges for process optimisation, International Journal of Hydrogen Energy, 27, (11-12) 1339-1347.

Hawkes,D., Maddy.J. and Hawkes, F. (2004) Hydrogen Production: Grand Challenges. Presented at the UK Sustainable Hydrogen Energy Consortium meeting 28-29th Oct 2004, Bath.

Heffel, J.W., (2002) NOx emission and performance data for a hydrogen fuelled internal combustion engine at 1500 rpm using exhaust gas recirculation. International Journal of Hydrogen Energy. 28 (8) 901-908.

Heinzman, T., MacIntosh, D., and Shaver, D., (1999) The world of fuel cells [online] Available from: http://www.oswego.edu/nova/facts/fuelcells/fuelcell.html Accessed on 1st May 2003.

Heydorn, B. (1994) Chemical Economics Handbook – CEH Review of Hydrogen. Menlo Park California, USA. SRI International.

HFP (2004) European HFP description Available [online] at http://www.hfpeurope.org/ Accessed 21/10/04

Hido (2003) Vienna Agreement [online] available at http:// www.hido.or.jp/ITSHP-e/TS/p16.htm accessed 23/09/03

Hörmandinger, G. and Lucas, N.J.D. (1996) Is clean enough? The influence of environmental externalities on markets for fuel cells in transport. Transportation Research D. 1, 63-78

House Of Commons. (1999) The Climate Change Levy. House of Commons Library Research Paper 99/93. 24 November 1999 [online] Available at: www.parliament.uk/commons/lib/research/rp99/rp99-093.pdf Accessed 1st May 2003.

House Of Lords Select Committee On The European Union. (2002) Energy Supply: how secure are we? [Online] Available at: www.parliament.the-stationery-office.co.uk/pa/ld200102/ldselect/ldeucom/ 82/8201.htm Accessed 1st May 2003.

Howes, J., (2002) The potential for renewable hydrogen as a transport fuel for the UK. Thesis (MSc). University of London.

HSC (1998) Safety in the installation and use of gas systems and appliances: Gas Safety Iinstallation and Use) Regulations 1998, approved code of practice and guidance, Health and Safety Commission, ISBN 0-7176-1635-5.

HSE (2003) Managing health and safety: five steps to success, published by the Health and Safety Executive INDG275 3/03 C500

HSE (2002) Fire and explosion: How safe is your workplace: A short guide to the dangerous substances and explosive atmospheres regulation, [online] available at http://www.hse.co.uk, accessed 16/04/04

Hussy I, Hawkes FR, Dinsdale R and Hawkes DL (2003) Continuous Fermentative Hydrogen Production from Wheat Starch Co-products by Mixed Microflora. Biotechnology and Bioengineering 84 (6) 916-926

Hydrogen (2002) Hydrogen – the likely development of hydrogen supplies for the UK, [online] Available from: www.hydrogen.co.uk/h2/h2_page2.htm Accessed 1st May 2003.

Hydrogen Fuel Cell Letter (2002) Toyota, Honda Launch California Fuel Cell Fleets With Back-to-Back Events. The hydrogen fuel cell letter, December 2002, ISSN 1080-8019 [online] Available from: http://www.hfcletter.com/letter/December02/ Accessed 1st May 2003.

Hydrogen society (2003) Codes standards and recommended practices, [online] available at http://www.hydrogensociety.net/hydrogen_codes.html, accessed 16/04/04

HyNet (2003) HyNet [online] Available from: http://www.hynet.info/index00.html Accessed 1st May 2003.

HyWeb (1998) BMBF focus of funding hydrogen technology and fuel cells. [online] Available at: http://www.hydrogen.org/Politics/bmbf.html Accessed 1st May 2003

HyWeb (1998) Hydrogen Gazette 3rd Quarter 1998: "Future of Hydrogen Technologies" dealt with in a question in the German Parliament. [online] Available at: http://www.hyweb.de/News/arcv398e.html#Future%20of%20Hydrogen%20Technologies%20dealt%20with%20in%20a%20question%20in%20the%20German%20Parliament%20July%2098 Accessed 23rd November 2004.

HyWeb (2003) HyWeb [online] Available from: www.hydrogen.org/index-e.html Accessed 1st May 2003.

IEA (2002) IEA implementing agreement on enhanced oil recovery. [online] Available at: www.iea.org/dbtw-wpd/textbase/work/2002/washington/2_can.pdf Accessed 3rd November 2004

IER (2003) “New Elements for the Assessment of External Costs from Energy Technologies”. Project financed by the European Union, DG Research, Technological Development and Demonstration (RTD) [online] Available at: http://www.ier.uni-stuttgart.de/public/de/organisation/abt/tfu/projekte/newext/ Accessed 5th November 2004.

IGER (2003) Grasses - Traits and Varieties, [online] Available at: http://www.iger.bbsrc.ac.uk/igerweb/Accessed on 1st May 2003.

ILEX. (2002) Quantifying the system costs of additional renewables in 2020. [online] Available at: www.dti.gov.uk/energy/developep/080scar_report_v2_0.pdf Accessed 1st May 2003.

Industry Canada. (2003) Canadian Fuel Cell Commercialization Roadmap. [online] Available at: http://strategis.ic.gc.ca/epic/internet/inmse-epe.nsf/vwGeneratedInterE/home Accessed 1st May 2003

Institut fur Technische Chemie (2003) Biomass [online]. Available from: www.fzk.de/inhalt/process/superprocess/biomass/eibiomass.fr Accessed 1st May 2003.

IPCC (1996) Climate change 1995: economic and social dimensions of climate change. Contribution of working group III to the second assessment report of the intergovernmental panel on climate change.

IPCC (2001a) Third Assessment Report.[online] Intergovernmental Panel On Climate Change Available at: www.ipcc.ch Accessed 1st May 2003.

IPCC (2001b) Third assessment report. Climate Change 2001: Working Group II: Impacts, Adaptation and Vulnerability

IPCC (2001c) Third assessment report. Climate Change 2001: Working Group III: Mitigation

Ippommatsu, M., Sasaki, H. and Otoshi, S. (1996) Evaluation of the cost performance of the SOFC cell in the market. International Journal of Hydrogen Energy, 21 (2) 129-135.

ISO (2004), International Organisation for Standardisation, [online] available at http://www.iso.ch/iso/en/ISOOnline.frontpage, accessed 16/04/04

Iwasaki, W, (2003) A consideration of the economic efficiency of hydrogen from biomass, International Journal of Hydrogen Energy, 28, (9) 939-944.

James, B D., Lomax, F.D.Jr., Thomas, C.E. and Colella,W.G. (1997) PEM fuel cell power system cost estimates: sulfur-free gasoline partial oxidation and compressed direct hydrogen. Directed Technologies Inc. Report for the Ford Motor Company, October 1997.

Janssen, M., and Hoekema S. (2003) Biological hydrogen production [online] Available from: www.ftns.wau.nl/prock/Research/Rene/Photobacteria.htm Accessed 1st May 2003.

Japanese Ministry Of Foreign Affairs. (2002) Strategy and Approaches of Japan's Energy Diplomacy. [online] Available at: http://www.mofa.go.jp/policy/energy/diplomacy.html Accessed 1st May 2003.

JNOC (2000) National energy policy of Japan. [online] Japanese National Oil Corporation Available at: http://www.jnoc.go.jp/english/stats/ Accessed 1st May 2003

Joffe, D. (2003) private communication, Imperial College.

Jones, A. (2002) Woking Energy services for the new millennium. Woking Borough Council, Woking, UK.

Kazim, A., and Veziroglu, T.N., (2002) Role of PEM fuel cells in diversifying electricity production in the United Arab Emirates. International Journal of Hydrogen Energy. 28 (3) 349-355.

Keller, J. (2003). Why Hydrogen? Building an Infrastructure. Presentation delivered at the G-CEP Workshop, Stanford Ca. 14-15 April 2003.

Kiesling. L. (2003) Are hydrogen fueling station subsidies necessary? [online]. Available at: http://www.rppi.org/hydrogenfuelingstations.html Accessed 7th May 2003.

Kirk-Othmer. (1991) Hydrogen. In: Encyclopedia of Chemical Technology. 4th edition, Vol. 13: Helium Group to Hypnotics. New York: John Wiley & Sons

Kosourov, S, Tsygankov, A, Seibert, M and Ghirardi M L. (2002) Sustained hydrogen photoproduction by *Chlamydomonas* reinhardtii: effects of culture parameters. Biotechnology and Bioengineering 78 (7) 731-740.

Kratzel T, Pantow E and Eichert H (1995) Modelling of hydrogen combustion: Turbulent flame acceleration and detonation, International Journal of Hydrogen Energy. 21 (5) 407-414. Elsevier Science Ltd.

Krause, E., and Bunger, U. Public demonstration of PEM fuel cells as a miniature household co-generation plant in Munich. [online] Available from: http://www.hydrogen.org/knowleage/demonstation_PEM_Cell.htm Accessed 27th January 2003.

Kruse, B, Grinna, S, and Buch, C., (2002) Hydrogen – Status og Muligneter, Bellona rapport nt.6-2002 ISBN 82-92318-0504. or [online] Available from: http://www.bellona.no/en/energy/hydrogen/report_6-2002/index.html Accessed 19 May 2003.

Kumar M.S., Ramesh A. and Nagalingam B. (2003), Use of hydrogen to enhance the performance of a vegetable oil fuelled compression ignition engine, International Journal of Hydrogen Energy, 28, pp.1143-1154.

Lahererre, J. (2001) Estimates of oil reserves. Paper presented at the EMF/IEA/IEW meeting IIASA, Laxenburg, Austria. June 19, 2001.

Lakeman, J.B., and Browning, D.J., (2001) Global Status of Hydrogen Research London: DTI, ETSU F/03/00239/REP.

Lambe S.M. and Watson H.C. (1993), "Optimizing the design of a hydrogen engine with pilot diesel fuel ignition", Int. J. of Vehicle Design, 14(4), pp.370-389.

Lamle, S, Vincent, K, Halliwell, L, Albracht, S and Armstrong, F (2003) Hydrogenase on an electrode: a remarkable heterogeneous catalyst. Dalton Transactions, 21, 4152-4157, the Royal Society of Chemistry.

Lanz A, Heffel J and Messer C (COD)(2001) Hydrogen fuel engines and related technologies: revision 0

Larsen, J., Michel, M., Zscommler, J.,Whysall, M. and Vanheertum, S. (2003) Large scale hydrogen plants. Uhde and UOP's experience. Paper presented at the AIChE Spring Meeting, March 30th-April 3rd 2003. [online] Available at: www.uop.com/objects/LgScaleHydroPlnts41b.pdf Accessed 3rd Nov 2004.

Larson, E.D. and Katofsky, R.E. (1992) Production of Methanol and Hydrogen from Biomass. The Center for Energy and Environmental Studies, Princeton University, PU/CEES Report no. 217.

Lau, F.S., Zabransky, R., Bowen, D.A., Kinoshita, C.M., Turn, S.Q and Hughes, E.E. (2002) Technoeconomic analysis of hydrogen production by gasification of biomass. In: Proceedings of the 2002 US DoE Hydrogen Program review. NREL/CP-610-32405.

Laurinavichene, T V, Tolstygina I V, Galiulina R R, Ghirardhi M L, Seibert M, and Tsygankov A A. (2002) Dilution methods to deprive *Chlamydomonas reinhardtii* cultures of sulphur for subsequent hydrogen photoproduction. International Journal of Hydrogen Energy 27 (11-12) 1245-1249.

Lay, J, Fan, K, Chang, J, and Ku, C (article in press) Influence of chemical nature of organic wastes on their conversion to hydrogen by heat-shock digested sludge International Journal of Hydrogen Energy (28) 12 P1361-1367

LBST (L-B-Systemtechnik GmbH) (1998) The acceptance of hydrogen technologies. [online] Available at: http://www.hydrogen.org/accepth2/ Accessed 1st May 2003

Leiby, S., (1994) Options for Refinery Hydrogen, A private report by the Process Economics Program, Report No. 212, SRI International, Menlo Park, CA.

Liepa, M.A. and Borhan, A. (1989) High temperature steam electrolysis: technical and economic evaluation of alternative process designs. International Journal of Hydrogen Energy. 11. 435-442

Li, H and Karim, G (2004) Knock in spark ignition engines. International Journal of Hydrogen Energy. 29 859-865. Elsevier Science Ltd.

Lindstrom, O. and Lavers, W. (1997) Cost engineering of power plants with alkaline fuel cells. International Journal of Hydrogen Energy, 22 (8) 815-823.

Lipman, T.E. and Delucchi, M.A. (1996) Hydrogen-fuelled vehicles. International Journal of Vehicle Design, 17 (5-6) 562-589.

Lokurlu, A., Grube, T., Höhlein, B. and Stolten,D. (2003) Fuel cells for mobile and stationary applications —cost analysis for combined heat and power stations on the basis of fuel cells. International Journal of Hydrogen Energy, 28 (7) 703-711.

London (2002) Hydrogen energy, [online] Available from: www.london.gov.uk/approot/mayor/energy/hydrogen.jsp Accessed 1st May 2003.

Maack, M.H. and Skulason.J.B. (2000) Hydrogen – reality in Iceland [online] Available at: www.newenergy.is/subjects/73/original/ video_cover/Subj73-0001.pdf Accessed 1st May 2003

Maeland, A (2003) Approaches to increasing gravimetric hydrogen storage capacities of solid hydrogen storage materials, International Journal of Hydrogen Energy, 28, (8) 821-824.

Mahler (2000) Mahler AGS receives order for the delivery of hydrogen plant for the UK [online] Mahler Available from: http://www.mahler-igs.com/news_7.html Accessed on 1st May 2003.

Mann, M.K. (1995a.) Technical and economic assessment of producing hydrogen by reforming syngas from the Battelle indirectly heated biomass gasifier. National Renewable Energy Laboratory Technical Report NREL/TP-431-8143.

Mann, M.K. (1995b.) Technical and economic analyses of hydrogen production via indirectly heated gasification and pyrolysis. In: Proceedings of the 1995 US DOE Hydrogen Program Review, Vol. 1. NREL/CP-430-20036-1. 205-236.

Mann, M.K, Dipietro, J.P., Iannucci, J. and Eyer, J. (1998) Exploring the Technical and Economic Feasibility of Producing Hydrogen from Sunlight and Wind. In: Hydrogen Energy Progress XII, Proceedings of the 12th World Hydrogen Energy Conference, Buenos Aires, 21-26 June 1998.

Marquart, S., Sausen, R., Ponater, M., and Grewe, V., (2000) An estimate of the climate impact of cryoplanes. Abstracts provided for the European workshop "Aviation, Aerosols, Contrails and cirrus clouds" July 3, 2000, collected by Schumann, U.DLR, Institute fu physik der atmosphare [online] Available from: http://www.dlr.de/ipa/aktuelles/veranstaltungen/announcements/a2c3/al_abstr.htm Accessed on: 1st May 2003.

Matsumara, Y and Minowa, T (2003) Fundamental design of a continuos biomass gasification process using a supercritical water fluidized bed. International Journal of Hydrogen Energy. 29, 701-707. Elsevier Science Ltd.

Melaina, M.W. (2003) Initiating hydrogen infrastructures: preliminary analysis of a sufficient number of initial hydrogen stations in the US. International Journal of Hydrogen Energy. 28 (7) 743-755.

Melis, A. (2002) Green alga hydrogen production: progress, challenges and prospects. International Journal of Hydrogen Energy 27, (11-12) 1217-1228.

Mercuri, R., Bauen, A. and Hart,D. (2002) Options for refuelling hydrogen fuel cell vehicles in Italy. Journal of Power Sources. 106. 353-363.

Metcalfe, H (2003) A view from the past - a retrospective view of the future. The Institute of Energy, Dr. W. Idris Jones Memorial Lecture. Cardiff: Cardiff Castle.

Midilli, A., Rzayev,P., Olgun, H., and Ayhan, T., (2000) Solar hydrogen production from hazelnut shells International Journal of Hydrogen Energy, 25, (8) 723-32.

Midilli, A., Dogru,M., Howarth, C.R., and Ayhan, T., (2001) Hydrogen production from hazelnut shell by applying air-blown downdraft gasification technique International Journal of Hydrogen Energy, 26, (1), 29-37.

Midilli, A., Dogru, M., Akay, G., and Howarth, C.R., (2002) Hydrogen production from sewage sludge via a fixed bed gasifier product gas, International Journal of Hydrogen Energy, 27, (10), 1035-1041.

Millennium cell (accessed 2003) Hydrogen on demand fact sheet [online], Available from: http://www.milleniumcell.com/investor/hod.html Accessed 1st May 2003.

Milne, T, Elam, C, Evans, R (2002) Hydrogen from biomass – state of the art and research challenges International Energy Agency report IEA/H2/TR-02/001 [online]. Available from:, http://www.eere.energy.gov/hydrogenandfuelcells/hydrogen/iea/pdfs/hydrogen_biomass.pdf Accessed 1st May 2003.

Mitsugi, C., Harumi, A. and Kenzo, F. (1998) WE-NET Japanese hydrogen program. International Journal of Hydrogen Energy. 23(3) 159-165.

Momirlan, M., and Veziroglu,T., N. (2002) Current status of hydrogen energy International Journal of Hydrogen Energy 6 (1-2), 141-179.

Moore, R.B. and Raman, V. (1998) Hydrogen Infrastructure for Fuel Cell Transportation. International Journal of Hydrogen Energy. 23(7), 617-620.

Mourato, S., Saynor, B and Hart, D. (2003) Greening London's black cabs: a study of driver's preferences for fuel cell taxis. Energy Policy. 32 (5) P685-695.

Mugerwa, M.N. and Blomen, L.J.M.J. (1993) Fuel Cell System Economics. In: Fuel Cell Systems, ed. L. Blomen and M. Mugerwa, Plenum Press, New York, 1993.

Munich (2003) Hydrogen project [online] Available from: http://www.munich-airport.de/EN/Areas/Company/Umwelt/Wasserstoffprojekt/index.html Accessed 1st May 2003.

Murugesamoorthi, K., Srinivasan, S., and Appleby, A. (1993) Research, development, and demonstration of solid oxide fuel cell systems. In: Fuel Cell Systems, edited by L. Blomen and M. Mugerwa, Plenum Press, New York. 1993.

Myers, N. (1993) Environmental refugees in a globally warmed world. BioScience, 43 (11) 752-760

NATCO (2003)Product profiles: hydrogen generation plant BOC Margam NATCO Group. [online] Available at http://www.natcogroup.com/content.asp?t=margam&ud-no Accessed 1st May 2003.

NAfW (2000a) Local Authority Variation [online] NAfW Available at: http://www.wales.gov.uk/keypubstatisticsforwales/content/publication/social/2001/sb13-2001/contents.htm Accessed 1st May 2003.

NAfW (2000b) Wales: changing climate challenging choices. The impact of climate change in Wales from now to 2080 [online]. National Assembly for Wales. Available at: www.bangor.ac.uk/ies/walesen.pdf Accessed 1st May 2003

NAfW (2001a) Transport [online] NAfW Available at: www.wales.gov.uk/keypubstatisticsforwalesfigures/content/transport/transport1 accessed 1st May 2003.

NAfW (2001b) Housing [online] NAfW Available at: www.wales.gov.uk/keypubstatisticsforwalesfigures/content/publication/compendia/2001/sb49-2001. Accessed 1st May 2003.

NAfW (2001c) The Transport Framework for Wales: (A Consultation Paper) March 2001, Annex 5-Maps [online]. Available from:, http://www.wales.gov.uk/subitransport/content/framework/index.htm Accessed 1st May 2003

NAfW (2002a) Review of Energy Policy in Wales Part 1: Renewable Energy. Cardiff: Economic Development Committee. ISBN: 0 7504 2898 8. [online]. National Assembly for Wales. Available at: http://www.wales.gov.uk/keypubassemecodev/content/energy/home-e.htm Accessed 1st May 2003

NAfW (2002b) Statistics for Wales: Welsh Transport statistics – latest information, [online] NAfW Available at: www.wales.gov.uk/keypubstatisticsforwalesfigures/content/publication/transport/2002/wts2002/wts2002-ntro.e.htm Accessed 1st May 2003.

NAfW (2003a) Environment: Land [online] NAfW Available at: www.wales.gov.uk/keypubstatisticsforwalesfigures/content/environment/land. Accessed 1st May 2003.

NAfW (2003b) Review of Energy Policy in Wales: Renewable Energy - Final Report. Cardiff: Economic Development Committee, National Assembly for Wales ISBN: 07504 3087 7. [online]. National Assembly for Wales. Available at: http://www.wales.gov.uk/keypubassemecodev/content/energy/homee.htm Accessed 1st May 2003

NafW (2003d) Press release: First Minister's media briefing, Tuesday 25 February 2003 [online] NAfW. Available at: www.wales.gov.uk/servlet/firstministersmediabriefings/ Accessed 1st May 2003.

NAfW (2003e) National Assembly for Wales web site [online] Available at: http://www.wales.gov.uk/themessustainabledev/index.htm Accessed 1st May 2003

NafW (2004) Tan 8 Consultation Document. Available [online] from: www.wales.gov.uk/index.htm Accessed 1st September 2004.

NASA (1997) Safety standards for hydrogen and hydrogen systems, Office of Safety and Mission Assurance, Washington DC.

National Grid Company. (2002) NGC seven year statement and updates. [online] Available at: www.nationalgrid.2002com/uk/ Accessed 1st May 2003.

National Trust. (2001) Valuing our environment: economic impact of the environment of Wales. [online] Available at: http://www.nationaltrust.org.uk Accessed 1st May 2003.

Neath-Port Talbot County Borough Council (2002) Air quality reports. Summaries of routine air quality monitoring conducted by the Council 1998-2001. [online] Available at: http://www.neathporttalbot.gov.uk/html/environment/pollution/pollution_frame.html Accessed 1st May 2003

Newborough, M (2004) A report on electrolysers, future markets and the prospects for ITM Power Ltd's electrolyser technology, February 2004, distributed via H2Net meeting, September 2004.

Newsholm G (2003) Fuel Cells: understanding the hazards, controlling the risks, HSE, first draft, 1 July 2003

Newson, E., Haueter, Th., Hottinger, P., Von Roth, F. Scherer, G.W. and Schucan, T. H. (1998) Seasonal storage of hydrogen in stationary systems with liquid organic hydrides. International Journal of Hydrogen Energy, 23(10). 905-909

NHA (2002a) Hydrogen safety codes and standards workshop proceedings, [online] available at http://www.hydrogensafety.info/articles/02-oct-04.asp

NHA (2002b) Developing international hydrogen standards gets more complicated, [online] available at http://www.hydrogensaftey.info/articles/02-jan-05.asp

NHA (2003) Hydrogen safety fact sheet [online]. Available at http://www.hydrogenus.com/nha.asp Accessed November 2004

Odum, H.T. (1998) Environmental Accounting, Emergy and Decision Making. John Wiley, NY, pp370. Office of Science and Technology. (2001) Report of the Chief Scientific Adviser's energy research review group. [online] Available at: www.ost.gov.uk/policy/issues/csa_errg/main_rep.pdf

Office Of Science And Technology. (2002) Chief Scientific Adviser's energy research review group: Report of the Group [online]. Available at: http://www.ost.gov.uk/policy/issues/csa_errg/ Accessed 1st May 2003

Ogawa M (2003) Nuclear production of hydrogen. Available [online] at: www.iea.org/dbtw-wpd/textbase/ work/2003/hydrogen/sessionii/Nuclear.pdf. Accessed 20/10/04

Ogden, J.M, Steinbugler, M. and Kreutz, T. (1995) Hydrogen as a fuel for fuel cell vehicles: a technical and economic comparison. In: Proceedings of the Eighth Annual Conference of the National Hydrogen Association, Arlington, Virginia, USA. March 11-13, 1997.

Ogden, J., (1999) Developing and infrastructure for hydrogen vehicles: a Southern California case study, International Journal of Hydrogen Energy, 24, (8) 709-730.

Ogden, J.M. (2002) Modeling infrastructure for a fossil hydrogen energy system with CO_2 sequestration. In: Proceedings of the Sixth International Conference on Greenhouse Gas Control Technologies, October 2002, Kyoto, Japan.

Ogden, J. M., Williams, R.H. and Larson, E.D. (2003) Societal lifecycle costs of cars with alternative fuels / engines. Energy Policy. 32 (1) P7-27

Ohi, J (2002) Hydrogen Codes and Standards, Proceedings of the 2002 U.S. Hydrogen Programme Review, NREL/CP-610-32405. Oilnergy.com. NYMEX Henry-Hub Natural Gas Price [online]. Available from: http://www.oilnergy.com/1gnymex.htm Accessed 1st May 2003

Oilnergy.com. (2004) NYMEX Henry-Hub Natural Gas Price. [online] Available at: http://www.oilnergy.com/1gnymex.htm Accessed 3rd November 2004

Oney, F., Veziroglu, T.N. and Dulger, Z. (1994) Evaluation of pipeline transportation of hydrogen and natural gas mixtures. International Journal of Hydrogen Energy. 19 (10), 813-822.

Oy, N. (1992) New Hydrogen Technologies Project Report: Evaluation of Techniques (cited in Amos 1998)

Padro, C.E.G. and Putsche, V., (1999) Survey of the economics of hydrogen technologies. National Renewable Energy Laboratory Technical Report NREL/TP-570-27079.

Patterson, S (2003) Private communication, Welsh Development Agency.

Pehr K (1995) Aspects of safety and acceptance of LH2 tank system in passenger cars. , International Journal of Hydrogen Energy. 21 (5) 387-395. Elsevier Science Ltd.

Penn State (2002) Obstacles fall to feasibility of hybrid fuel cell vehicles [online], Available from: www.sciencedaily.com/releases/2002/08/020820072006.htm Accessed 1st May 2003.

Perez Sainz, A. (2003) Toward hydrogen: a vision of European Union. Presented at the International Energy Agency Conference, Paris, March 3rd 2003.

Performance and Innovation Unit. (2001) Renewable energy in the UK. [online] Available at: www.piu.gov.uk/2001/energy/Renewener.shtml Accessed 1st May 2003.

Performance and Innovation Unit. (2002) Energy review. [online] Available at: www.cabinetoffice.gov.uk/innovation/2002/energy/report/index.htm Accessed 1st May 2003.

Petroplus. (2003) Security of supply and benefits for Wales. [online] Available at: http://www.energyforwales.co.uk/security_of_supply.html Accessed 1st May 2003

Pettifer, J. and Turner, N. (1984) Automania : man and the motor car. Little Brown. Boston.

Pidmore, A., and Bristow, A., (2002) The role of hydrogen in powering road transport,. Tyndall Centre for Climate Change, UK. Working paper 19.

Planet Ark (2001) London council first buyer of fuel cell vehicle (May 24, 2001) [online] Available at: www.planetark.org/dailynewsstory.cfm/newsid/ 10940/newsDate/24-May-2001/story.htm Accessed 1st May 2003

Plug Power, (1999) “Flint energies partners with GE fuel cell systems to market fuel cells in Georgia.” Press release June 23, [online]. Available at: http://www.plugpower.com/press.html. Accessed 1st May 2003

Ponater, M., and Klug, H.G., (2000) Impact of hydrogen fuelled aircraft upon the atmosphere – state of knowledge and current activities. Abstracts provided for the European workshop “Aviation, Aerosols, Contrails and cirrus clouds” July 3, 2000, collected by Schumann, U.DLR, Institute fu physik der atmosphare [online] Available from: http://www.dlr.de/ipa/aktuelles/veranstaltungen/announcements/a2c3/al_abstr.htm Accessed on: 1st May 2003.

POSTNOTE (2002) Prospects for a hydrogen economy. London: Parliamentary Office of Science and Technology 1-4186.

Puzach S V (2002) Some features of formation of local combustible hydrogen-air mixtures during continuous release of hydrogen in a room. International Journal of Hydrogen Energy. 28, 1019-1026. Elsevier Science Ltd

Randerson, P. (2003) Private communication, Cardiff University.

Raton B (2004) CRC Handbook of Chemistry and Physics: A ready reference book of Chemical and Physical data, London ISBN 22813160

RCEP (2000) 22nd Report: Energy - The Changing Climate [online] Royal Commission on Environmental Pollution. Available at: www.rcep.org.uk/newenergy.html Accessed 1st May 2003

Rehm W and Wang B L (2002) Fire protection and explosion prevention for hydrogen safety technology. Forschungszentrum Jülich (FZJ) Jülich, Germany.

Ricardo Consulting Engineering Ltd. (2002) Carbon to hydrogen: roadmap for passenger cars: a study for DfT and DTI. [online] Available at: www.roads.dft.gov.uk/cv/power/carbon/index.htm Accessed 1st May 2003.

Rifkin, J. (2003) The hydrogen economy: after oil, clean energy from a fuel cell driven global hydrogen web. Extracted from The hydrogen economy: the creation of the worldwide energy web and the redistribution of power on earth. Tarcher Putnam.

Roe, B., Teisl, M.F., Levy, A. and Russell, M. (2001) US consumers willingness to pay for green electricity. Energy Policy.29, 917-925

Ross A, Hanley I, Dupont V, Jones J, Twigg M, Brydson R (2003) Development of unmixed reforming for production of hydrogen from vegetable oil. Pare presented at the European Hydrogen Energy Conference , 2003. Grenoble, France.

Ryskamp, J (2003) Hydrogen production from nuclear energy, Available [online] at: nuclear.inel.gov/papers-presentations/ nuclear_hydrogen_3-3-03.pdf. Accessed 21/10/04

Sandrock, G. (1997) State-of-the-art review of hydrogen storage in reversible metal hydrides for military fuel cell applications. Final Report, prepared for Department of the US Navy, Office of Naval Research. Contract N00014-97-M-0001, July.

Sarkar, A and Banerjee, R (2004) A quantitative method for characterization of carbon nanotubes for hydrogen storage. International Journal of Hydrogen Energy. 29, 1487-1491. Elsevier Science Ltd

Sato, T., Hamada, A. and Kitamura, K. (1998) A feasibility study of conceptual design for international clean energy network using hydrogen conversion technology. WE-Net Technical papers 1998 [online]. Available on: http://www.enaa.or.jp/WE-NET/ronbun/1998/04/0498.htm Accessed 1st May 2003

Schwarz, J. and Amankwah, K. (1993) Hydrogen storage systems. In: The Future of Energy Gases, U.S. Geological Survey Professional Paper 1570. United States Government Printing Offices, Washington D.C.

Scott. D.S (1995) Whales and Whiskey Barrels. International Journal of Hydrogen Energy. 20 (12) 939-943

Sebastian, P (2002) Mexican Participation in IEA program on production, storage and utilisation of hydrogen, International Journal of Hydrogen Energy, 28, (6), 595-595.

Simbeck, D.R. and Chang, E., (2002) Hydrogen Supply: Cost estimate for hydrogen pathways – scoping analysis. NREL/SR-540-32525.

Skulason, J.B and Peterson. B. (2003) Hydrogen plan of Iceland. Presented at the IEA Renewable Energy Working Party Seminar3 March, 2003 International Energy Agency 9 rue de la Fédération, Paris.

Slater, S. (2002) Hydrogen from sunlight: sustainable hydrogen in Cambridge and Sweden. Presentation given at the Generation H Conference 19 April 2002. [online] Available at: www.forumforthefuture.org.uk/ uploadstore/GenH_Slater.pdf Accessed 1st May 2003

Sørenson. B and Sorenson, F. (2000) Hydrogen energy progress XIII. Procedings of the 13th World Hydrogen Energy Conference, Beijing China, 12-15 June 2000: p35.

Sørensen, B. (2001) Hydrogen as an energy carrier - scenarios for future use of hydrogen in the Danish energy system. A project carried out 1999-2001 by Roskilde University, Risø National Laboratories, Danish National Oil and Gas Company, Elkraft Systems and Energy E2 for the Danish Energy Agency under contract 1763/99-0001

Sørensen, B. (2002) Handling fluctuating renewable energy production by hydrogen scenarios [online] Energy subsidies in the EU parliament, workshop available from: mmf.ruc.dk/energy/Montreal2002.PDF. Accessed 1st May 2003.

Spath, P. and Mann, M. (1998) Technoeconomic Assessment of Four Biomass-to-Hydrogen Conversion Technologies. In: Hydrogen Energy Progress XII, Proceedings of the 12th World Hydrogen Energy Conference, Buenos Aires, 21-26 June 1998.

Staunton G (2003) Personal communication, The Carbon Trust, UK.
Steinberg, M. and Cheng, H.C. (1989) Modern and prospective technologies for hydrogen production from fossil fuels. International Journal of Hydrogen Energy. 14 (11), 797-820.

STILL (2002) Proton Motors, Still and Linde promotional brochure advertising their Forkilft tuck with PEM fuel cell. Available from: STILL GmbH, Berzeliusstrabe 10, D-22113 Hamburg, Germany.

Sustainable Development Commission (2002) Low carbon spaces, area-based carbon emission reduction scoping study. [online] Available from: www.sd-commision.gov.uk/pubs/lowcarbonspaces/04.htm Accessed 1st May 2003.

Sustainable Development Commission. (2003) UK climate change programme: a policy audit. [online] Avaialble at: www.sd-commission.gov.uk/pubs/ccp/sdc/ Accessed 1st May 2003

Sustainable Energy Ltd (2001) Strategic study of renewable energy resources in Wales, draft report.[online] Available at: www.sustainable-enegy.co.uk Accessed 1st May 2003.

Swain, (2001) Fuel leak simulation, coe proceedings 2001, US Department of Energy, Washington DC [online] Available from: http://www.eere.energy.gov/hydrogenandfuelcells/pdfs/30535be.pdf Accessed 1st May 2003

Swain M R, Filoso P, Grilliot E S and Swain M N (2002) Hydrogen leakage into simple geometric enclosures. International Journal of Hydrogen Energy. 28, 229-248. Elsevier Science Ltd

Syred, N. (2003) A view from the past – a rerospective view of the future, The Institute of Energy, Thirteenth Dr.W.Idris Jones Memorial Lecture. Cardiff: Cardiff Castle, 28th February 2003.

Tavoulareas, E. S and Charpentier, J.P. (1995) Clean coal technologies for developing countries. World Bank Technical Paper No. 286, Energy Series, July.

Tanisho S. (1996) Feasibility study of biological hydrogen production from sugar cane by fermentation. Proc 11th World Energy Congress, Hydrogen Energy Progress XI, Stuttgart Eds. Veziroglu TN, Basselt C J and Kreysa G, pp 2601-2606.

Taylor, J., Alderson, J., Kalyanam, K., Lyle, A. and Phillips, L. (1986) Technical and economic assessment of methods for the storage of large quantities of hydrogen. International Journal of Hydrogen Energy. 11(1) 5

Texaco Ovonics (2003) Texaco Ovonics hydrogen systems [online], Available from: http://www.texaco.com Accessed 1st May 2003.

Thomas, C. E., James, B., Lomax, Jr., F. and Kuhn, J.R. (1998) Integrated analysis of hydrogen passenger vehicle transportation pathways. Draft Final Report, National Renewable Energy Laboratory, Subcontract AXE-6-16685-01, March.

Thomas, C. E., James, B.D. and Lomax, F.D.Jr. (2000) Analysis of residential fuel cell systems and PNGV fuel cell vehicles. Directed Technologies, Inc. In: Proceedings of the 2000 DOE Hydrogen Program Review NREL/CP-570-28890

Thomas, D., (2001a) Strategic Study of Renewable Energy Resources in Wales, Draft Report. Cardiff: Sustainable Energy Ltd.

Thomas, C.E., Reardon, J.P., Franklin, D.L, Pinyan, J. and Kuhn, I.F. (2001b) Distributed hydrogen fuelling systems analysis. Proceedings of the 2001 DOE Hydrogen Program Review.

Tindall, B and Crews, A (1999) Alternative technologies to steam methane reforming, Hydrocarbon Processing, November 1995, 75-82.

Toshiaki, A.B.E. (2003) Japan's hydrogen vision. Presentation given at the IEA Renewable Energy Working Party Seminar, 3rd March 2003, Paris, France. [online] Available at: www.iea.org/workshop/2003/hydrogen/keynotes/japan.pdf Accessed 1st May 2003

Trade and Industry Committee. (2002) Security of Energy Supply. [online] Available at: www.parliament.the-stationery-office.co.uk/pa/cm200102/cmselect/cmtrdind/364/36402.htm Accessed 1st May 2003.

Tso, C., and Chang, S., (2002) A viable niche market – fuel cell scooters in Taiwan. International Journal of Hydrogen Energy. 28 (7) 757-762.

UKSHEC (2003). UKSHEC website [online] Available at: http://www.ukshec.org/ Accessed 5th November 2004.

UNDP-GEF (2003) Project reports [online] United Nations Development Programme (UNDP) Global Environment Facility (GEF) Available at: http://cfapp2.undp.org/gef/site/

UNFCCC. (2002a) United Nations framework convention on climate change. New York 1992. Climate Change Secretariat [online]. United Nations Framework Convention On Climate Change Available at: http://unfccc.int/resource/convkp.html Accessed 1st May 2003

UNFCCC. (2002b) A guide to the climate change convention and its Kyoto protocol. Climate Change Secretariat [online]. United Nations Framework Convention On Climate Change Available at: http://unfccc.int/resource/convkp.html Accessed 1st May 2003

University of Glamorgan (2004). Public perceptions of hydrogen as an energy source in Wales. A report prepared by People, Science and Policy Ltd. for Hydrogen Research Unit, University of Glamorgan, October 2004. (Unpublished).

UKPIA/IP (2002) UK retail marketing survey 2002. [online] Available at: http://www.petroleum.co.uk Accessed 1st May 2003

US DoE (1999) Report to Congress on the Status and Progress of the DOE Hydrogen Program. [online] United States Department Of Energy. Available at: http://www.eere.energy.gov/hydrogenandfuelcells/pdfs/bk28423.pdf Accessed 1st May 2003

US DoE (2002a) National hydrogen energy roadmap: toward a more secure and cleaner energy future for America. United States Department Of Energy.

US DoE (2002b) A national vision of America's transition to a hydrogen economy – to 2030 and beyond. United States Department Of Energy.

US DOE (2003) Safety, Codes & Standards Basics, [online] available at http://www.eere.energy.gov/hydrogenanfuelcells/codes

US DoE (2003a) Just the Basics: Fuel Cells [online]. Available from: http://www.eere.energy.gov/hydrogenandfuelcells/fuelcells/generalinfo.html Accessed 1st May 2003.

US DoE (2003b) US Department of Energy hydrogen page [online] Available from: http://www.eere.energy.gov/re/hydrogen Accessed 1st May 2003.

US DoE (2003c) Storage – Hydrogen storage Technologies [online], Department of Energy, Available from: http://www.eere.energy.gov/hydrogenandfuelcells/hydrogen/storage.html Accessed 1st May 2003.

US DoE (2003d) Safety, Codes & Standards Basics [online]. Available from: www.eere.energy.gov/hydrogenanfuelcells/codes Accessed 1st May 2003.

US DoE (2003e) Global climate change policy book. [online] United States Department Of Energy [online]. Available at: http://www.usgcrp.gov/usgcrp/Library/gcinitiative2002/gccstorybook.htm Accessed 1st May 2003

US DoE (2003f) Energy News Briefs (3/13/03). [online] United States Department Of Energy. Available at: http://www.rebuild.org/sectors/newsdetail.asp?newsid=1634&mktid=2 Accessed 1st May 2003

Valoen, L. O., (2001) Hydrogen storage in carbon materials, Norwegian University of Science and Technology, Preliminary literature study [online], Norwegian University of Technology: Facility of Natural sciences and Technology. Global Watch Electrochemistry 2001Available from: www.chembio.ntnu.no/users/lov/ Accessed 1st May 2003.

Van Niel, E. W. J., Budde, M. A. W., de Haas G. G., van der Wal, F. J., Claassen, P. A. M. and Stams A. J. M. (2002) Distinctive properties of high hydrogen producing extreme thermophiles *Caldicellulosirupter Saccharolyticus* and *Thermotoga* elfii. International Journal of Hydrogen Energy, 27, (11-12) 1391-1398.

Vellone, R. (2003) The Italian Hydrogen National Programs: strategies, resources, perspectives. Presented at the IEA Renewable Energy Working Party Seminar3 March, 2003 International Energy Agency 9 rue de la Fédération, Paris

Veziroglu, T. N. (1997) Hydrogen movement and the next action: fossil fuels industry and sustainability economics. International Journal of Hydrogen Energy. 22(6) 551-556.

Veziroglu, T and Barbir, F. (1998) Hydrogen Energy Technologies Emerging Technology Series, prepared for the United Nations Industrial Development Organization, Vienna, 1998.

Waleswatch (2000). Objective One guest opinion - Richard Harris (European Regional Affairs – ERA Wales) [online] Available at: http://www.waleswatch.welshnet.co.uk/assembly/objera.htm Accessed 1st May 2003.

Wang, M.Q. (1999) GREET 1.5—transportation fuel-cycle model: 1. Methodology, development, use and results. Report ANL/ESD-39 from Center for Transportation Research, Argonne National Laboratory for Office of Transportation Technologies, US Department of Energy.

Wautelet, V (2001) An Urban Integrated Solar to Hydrogen Renewable Energy Demonstration NNE5/2001/332, USHER, [online] Available from: http://www.europeanislands.net/projects/view.php?projectId=4 Accessed 1st May 2003.

Welsh Development Agency (2003) WDA Energy Policy, August 2003. [online] Available at: http://www.wda.co.uk/index.cfm/wda_home/board_management/september_2002/en285 Accessed 5th November 2004.

WE-NET (2003) WE-NET [online] Available from: WWW.enaa.or.jp/WE-NET Accessed 1st May 2003.

Whitton, P (2003) Private communication, PROGRESSIVE ENERGY LTD.

Williams, L.O. (1980) Hydrogen power: an introduction to hydrogen energy and its applications. Pergamon Press.

Winebrake, J. J and Creswick, B.P. (2003) The future of hydrogen fueling systems for transportation: an application of perspective-based scenario analysis using the analytic hierarchy process Technological forcasting and social change 70 (4) P359-384

Woking (2003) Woking Borough Council [online] Available from: http://www.gov.uk/news/archive/sustainablewoking Accessed 1st May 2003.

World Chlorine Council, (2002) Turning Salt into Chlorine and Caustic Soda: The Chloralkali Manufacturing Process [online] Available from: http://worldchlorine.com/publications/index.html Accessed 1st May 2003

World Chlorine (2003) Chlorine Chemistry's role in our daily lives [online]. Available from:, www.worldchlorine.com. Accessed 1st May 2003.

WHO (2000a) Air pollution: including WHO's guidelines for air pollution control. Fact sheet no.187. [online] World Health Organization Available at: http://www.who.int/inf-fs/en/fact187.html Accessed 1st May 2003

WHO (2000b) AIR POLLUTION, Fact Sheet N° 187. [online] World Health Organization Available at: http://www.who.int/inf-fs/en/fact187.html Accessed 1st May 2003

Wurster, R. 2004. "Hydrogen road vehicles and their refuelling infrastructure: Strategic considerations and the European situation in regulations and standards." Paper presented to the Italian Hydrogen Association, Milan 16thApril 2004.

Ye, J., Zou, Z., Arakawa, H. (2003) A novel series of water splitting photocatalyst NiM2O6 (M = Mb, Ta) active under visible light. International Journal of Hydrogen Energy, 28, (6) 651-655.

Zittel, W. (2002) The prospects for a hydrogen economy based on renewable energy, Ireland's Transition to Renewable Energy, November 1st, 2002 Thurles, Tipperary, Ireland [online]. Available from: http://www.hydrogen.org/Knowledge/ireland2002.html Accessed 1st May 2003

Zou, Z., Ye, J. and Arakawa, H. (2003) Photocatalyic water splitting into hydrogen and /or O_2 under UV and Visible Light irradiation with a semiconductor photocatalyst. International Journal of Hydrogen Energy, 28, (6) 663 – 669.

Zhou,L, Zhou, Y and Sun, Y (2004) A comparative study of hydrogen absorption on superactivated carbon verses carbon nanotubes. International Journal of Hydrogen Energy. 29, 475-479. Elsevier Science Ltd

Appendix I

Physical and Chemical Properties of Hydrogen

Molecular formula	H_2	[2]
Molecular weight	2.014	[2]
Phase as standard	Gas	[2]
Appearance	Colourless	[2]
Odour	Odourless	[2]
pH	N/A	[2]
Boiling point	-253.39C / 20.39K	
Freezing/Boiling point	-259 C / 14K	
Auto Ignition Temperature	560 C / 833K	
Explosion limits, lower	4% vol	[1]
Explosion limits, higher	75%vol	[1]
Stability in water	1.6mg/l	
Specific gravity/density	0.07	
Lower Heating Value (LHV)	119.9MJ/kg	[1]
Higher Heating Value (HHV)	141.86 MJ/kg	
Density (liquid hydrogen)	70.79kg/m^2	[1]
Density (gaseous hydrogen)	0.083kg/m^2	
Detonation limits in air, lower	18.3% vol	
Detonation limits in air, higher	59.0% vol	
Diffusion coefficient	0.61cm^2/s	
Specific heat capacity, C_p	14,199J/kg/K	
Specific heat capacity, C_v	10,074 J/kg/K	
Stoichiometric mixture in air	29.53%vol	[1]
Flame temperature in air	2,318 K	[1]

[1] Barbir.F, (2003), [2] Raton B. (2004)

EU labeling in accordance with EU directives (CGH2)

Hazard symbol:	F+
Risk phrase:	R12 Extremely Flammable
Safety Phrases:	S9 – Keep container in a well ventilated place
	S16 - Keep away from ignition sources, No Smoking
	S33- Take precautionary measures against static discharge

Energy Equivalences

1l LH_2	0.27 l gasoline
1kg LH_2	2.75kg gasoline

Both based on the lower heating value

Appendix 2

Examples of US H_2 Activity (taken from European Hydrogen Energy Conference in Grenoble, France 2 – 5 October 2003)

US H_2 Vehicle Standards Activity

Crashworthiness	NHTSA
Emissions	EPA
Fuel cell vehicle systems	SAE
Fuel delivery systems	SAE
Containers	CSA
Reformers	SAE
Emissions	SAE
Recycling	SAE
Service and Repair	SAE

Fuel Delivery, Storage

Composite cylinders	ASME, CSA,CGA,NFPA
Piplelines	ASME,API,CGA,AGA
Equipment	ASME, API, CGA, AGA
Fuel transfer	NFPA, API

General

Fuel specifications	SAE, ASTM, API
Weights and mesures	NIST, API, ASME
Fueling/defueling	SAE
Sensors and Detectors	UL,NFPA, SAE, CSA
Connectors	SAE, API, CSA
Communications	SAE, UL, CSA, API, IEEE

Fueling service parking facility

Storage tanks	ASME, CSA, CGA, NFPA, API
Piping	ASME, CSA, CGA, NFPA
Dispensing	CSA, UL, NFPA
On site H_2 production	CSA, UL, CGA, API
Built environment codes	ICC, NFPA

Appendix 3

Glossary

AGA	American Gas Association
API	American Petrolium Institute
ASME	The American Society of Mechanical Engineering
ASTM	American Society for Testing and Materials
BCGA	The British Compressed Gas Association
BNQ	Bureau de Normalisation du Québec
BSI	British Standards Institution
CEC	Commission for Environmental Cooperation / Californian Energy Commision
CEN	Comité Europeén de Normalisation
CENELEC	European Committee for Electrotechnical Standardization
CGA	The Compressed Gas Association
CORGI	The Council for Registered Gas Installers
CSA	Canadian Standards Association
DIN	Deutsches Institut für Normung e. V.
DOE	US Department of Energy
DSEAR	Dangerous Substances and Explosive Atmospheres Regulation 2002
DTI	Department of Trade and Industry
ECE	The Economic Commission for Europe
EIGA	The European Industrial Gases Association
EIHP	European Integrated Hydrogen Project
ETSI	European Telecommunications Standards Institute
FAR	Federal Acquisition Regulation
HSC	Health and Safety Commission
HSE	Health and Safety Executive
HSL	Health and Safety Laboratory
ICC	International Chamber of Commerce
IEC	International Electrotechnical Commission
IEEE	Institute of Electrical and Electronics Engineering
IMDG	International Marine Transport
ISA	The Instrument Society of America
ISO	International Standards Organization
JASIC	Japan Automobile Standards Internationalization Centre
JEVA	Japanese Electric Vehicle Association
NASA	National Arenautics and Space Administration
NFPA	National Fire Protection Agency
NHA	National Hydrogen Association

NHTSA	National Highway Traffic Safety Administration
NIST	National Institute of Standards and Technology
NREL	National Renewables Energy Laboratory
OHS	Occupational Health and Safety
PATH	The Partnership for Advancing the Transition to Hydrogen
SAE	Society of Automotive Engineers
TAN	Technical Advice Note
TC 197	Technical Committee 197
TCI	Total Capital Investment
UL	Underwriters Laboratory
WTO	World Trade Organisation