Liquid Biofuels and Renewable Hydrogen to 2050

An assessment of the implications of achieving ultra-low carbon road transport

Department for Transport

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Contents

Executive Summary

Climate change is acknowledged as one of the most significant global problems facing us today. The current world energy economy is based on the combustion of fossil fuels, emitting large volumes of carbon dioxide and other greenhouse gases. Transport is a significant user of energy in the UK and a corresponding contributor to emissions of CO_2.

Current technological activity to reduce CO_2 emissions in road transport is centred on improvements to the fuel efficiencies of conventional, fossil fuel-based vehicles. There is considerable scope to reduce CO_2 emissions through such technologies, but as long as vehicles are reliant on fossil fuels for their primary energy, that scope is fundamentally limited.

To go beyond the savings possible through vehicle fuel efficiency, it would be necessary to change the fuel that vehicles use - to 'de-carbon' the fuel. The UK's 2003 Energy White Paper identified two fuels with the potential to achieve such large reductions in transport CO_2: renewable hydrogen and biomass-based fuels. This assessment draws on two commissioned academic studies to consider the overall and long-term energy implications of the large-scale use of these fuels, with a time-horizon of 2050.

From these academic studies, other published reports and stakeholder input, the following broad conclusions are reached:

- It would be possible, by 2050, to reduce total carbon emissions from road transport to very low levels, through significant use of renewable hydrogen or biofuels. This could help the UK to achieve its goal to reduce CO_2 emissions by 60% by 2050.

- Improvements in vehicle efficiency will be essential, but may not be sufficient in themselves to achieve very large carbon savings;

- It is not certain that a hydrogen economy will ever be realised. If it is, the UK could produce enough renewable hydrogen for road transport, but at the expense of renewable energy resource for other sectors.

- If the road transport fleet were fuelled entirely with biofuels by 2050, the UK could grow about one third of the necessary biomass; the rest would have to be imported.

- Both renewable hydrogen and biofuels are likely to be more expensive than today's fuels. But the increased efficiency of hydrogen fuel cell vehicles means that the per km costs of these vehicles could be roughly similar to today's vehicles.

- The large-scale use of either fuel would have numerous local environment, social and economic impacts (positive and negative), all of which would benefit from greater study.

1. Introduction

The Government's Energy White Paper[1], published in February 2003, identified the two major possibilities for non-fossil transport energy as renewably-generated hydrogen used in fuel cells, and biomass-based fuels. The Paper noted that each had major implications for both fuel production and fuel distribution and indicated that the Government would make *'an assessment of the overall energy implications of both a hydrogen economy, and of large scale use of biomass-based fuels,'* (White Paper, paragraph 5.22).

1.1 The challenge of climate change

One of the key drivers behind the Energy White Paper was the need to reduce UK emissions of carbon dioxide (CO_2) and other 'greenhouse gases' that contribute to global warming. The international scientific community is agreed that global warming is a real and present threat to life on Earth and the UK Government is determined to lead the rest of the world in addressing this threat. The UK has a national goal to reduce emissions of CO_2 by 20% by 2010, against a 1990 baseline. In addition, the Energy White Paper set the UK on a path towards a reduction of CO_2 emissions of some 60% by 2050, with real progress by 2020. These goals will be challenging, and will require the UK to make some significant changes in the way that we produce and use energy.

Road transport contributes about one quarter[2] of the UK's emissions of CO_2, and this proportion is expected to rise in the short term. This is the combined result of an absolute increase in emissions from road transport and projected falls in emissions from most other sectors. At present, virtually every vehicle on the road takes its energy from fossil fuels. Fossil fuels contain a large proportion of carbon and, when burned in an internal combustion engine, this carbon reacts with oxygen from the air to form CO_2, which is then emitted from the exhaust pipe. The amount of CO_2 emitted per kilometre driven depends on a number of factors, but vehicle efficiency is the single largest of these. The more efficient a vehicle is, the more kilometres it can be driven on a single litre of fuel, and the less CO_2 it emits per kilometre.

Due to the efforts of the UK Government, the European Union and vehicle manufacturers, as set out in the Government's *Powering Future Vehicles* strategy[3], new vehicles are getting more fuel efficient every year. A new car in the UK today, on average, emits around 10% less CO_2 than in 1995. The EU Voluntary Agreements with European, Japanese and Korean car manufacturers should ensure that, by 2008, European average new car CO_2 emissions will be a full 25% lower than in 1995.

Since 1995, the UK has also experienced significant economic growth, and with that economic growth has come growth in demand for transport and an increase in the number of vehicles on the road. This growth in demand has broadly offset the reductions in CO_2 emissions from individual vehicles; rising demand for transport

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[1] *Energy White Paper*. *Our Energy Future: creating the low carbon economy*, DTI, 2003. (www.dti.gov.uk/energy/whitepaper/index.shtml)

[2] Transport's share of total CO2 emissions depends on the definition used - it varies between 20-25% depending on whether it is defined 'by source' or 'by end user'.

[3] *Powering Future Vehicles: the Government strategy*, DfT, 2002. (www.dft.gov.uk/stellent/groups/dft_roads/documents/page/dft_roads_506885.hcsp)

reflects the priority which people attach to mobility. Transport is and will continue to be a highly-valued commodity.
The Government believes there is scope for further fuel efficiency improvements in conventional vehicles, perhaps by as much as 50% by 2020[4]. The Government will continue to encourage vehicle efficiency improvements through its policies and those of the EU.

A more dramatic and far-reaching change would be to progressively replace transport fossil fuels with something else; to 'de-carbon' the fuel, making large reductions in CO_2 emissions per kilometre driven - to near-zero in some cases.

At present there are two main potential candidates for replacing fossil fuels – renewable hydrogen and biomass-based fuels (biofuels). One form of biofuel - conventional biodiesel - is already available in the UK in relatively small volumes, supported by a growing UK industry. Both renewable hydrogen and biofuels have different benefits and present different challenges; the very large-scale use of either fuel would require significant changes to the way that the transport economy operates today.

If the UK is to reach its long term goal of a 60% reduction in CO_2 emissions by 2050, then such changes are likely to be necessary in the future. This assessment considers the implications of such changes on the overall use of energy in the UK, to ensure that any change can be planned for and managed effectively.

1.2 Additional drivers

Whilst climate change is the primary driver behind the UK interest in renewable hydrogen and biofuels, there are others.

Air quality is a major health and environmental concern, particularly in urban areas. The Air Quality Strategy (January 2003) and first Addendum (February 2003) set health-based objectives for the nine main air pollutants and deadlines for achieving them. The UK also has a legal obligation to achieve EU limit values for a number of air pollutants under the Air Quality Framework Directive and Daughter Directives. Vehicle emissions standards, set at the European level, have reduced emissions substantially, and will continue to do so, but it is possible that these and other measures will not be sufficient to prevent exceedences of the target levels in parts of London and other urban areas. Beyond these short term targets, there may also be increasing pressure in the future to reduce air pollutant levels even further, particularly where geographical and other factors conspire to exacerbate the problem.

The issue of diversity and security of supply of fossil fuels is likely to become of increasing importance as the UK becomes a net importer of oil and gas over the coming decades. This importance was recognised by the Energy White Paper, in which energy reliability was a key theme. A mix of energy sources is desirable, to ensure that the UK is able to maintain an uninterrupted supply of energy to end users. In the much longer term, easily-accessible sources of oil and gas are likely to become exhausted, attention is likely to turn to unconventional reserves and prices to rise.

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[4] *Carbon to Hydrogen Roadmaps: An update report for DfT and DTI*, Ricardo PLC, 2003. (www.dft.gov.uk/stellent/groups/dft_roads/documents/pdf/dft_roads_pdf_026217.pdf)

1.3 Scope of this assessment

The Energy White Paper set a time horizon of 2050, and this assessment follows that same timeframe. Such a long-term view necessarily produces considerable uncertainty, both in the assumptions taken and the results produced. In addition, when looking so far ahead, it must be borne in mind that the state of policy, technology and society may be very different from what is envisaged at present. However, the aim of this assessment is to draw out the implications of the very large-scale use of hydrogen and biofuels; large-scale adoption of these technologies - to a level where they have a very significant share of the market - is only likely to occur decades from now, and the full range of implications only likely to present themselves in a similar timeframe. A transition to renewable transport fuels on this scale would most likely be gradual, and an understanding of the long-term options and their implications can assist in defining and implementing a suitable framework for it.

This assessment does not aim to provide a definitive analysis of all the issues relating to renewable hydrogen, biofuels and their use, nor present a definitive Government view of what the future will be. Instead, it aims to:

- Identify the most promising technologies;
- Provide illustrative scenarios of the role each might play and what the impact would be;
- Summarise the current state of knowledge and identify gaps; and
- Identify key technology and cost issues that future policy choices may have to take into account.

1.4 Process

This assessment has been developed by Government, drawing on a technical analysis, prepared by E4tech (UK) Ltd[5] ('the E4tech analysis'), a study led by the National Society for Clean Air and Environmental Protection (NSCA) and the Institute for European Environmental Policy (IEEP), input from the Fuels working group of the Low Carbon Vehicle Partnership and the views of other stakeholders provided at stakeholder seminars. The E4tech analysis forms the core of the assessment and is described in more detail in the next chapter; the NSCA/IEEP study is described in the chapter 5.

[5] *Liquid biofuels and hydrogen from renewable resources in the UK to 2050: a technical analysis*, E4tech (UK) Ltd, 2003. (www.dti.gov.uk/energy/sepn/futuretransport.shtml)

2. E4tech Technical Analysis

2.1 Introduction

In 2003, the Government commissioned E4tech (UK) Ltd., a specialist energy-environment consultancy, to undertake a technical analysis to inform the overall Assessment of renewable hydrogen and biofuels. The E4tech analysis forms an annex to this assessment and should be read in conjunction with it.

A draft analysis was published in November 2003 and discussed at a stakeholder seminar on 5 December; comments were additionally invited via the DTI Sustainable Energy Policy Network website[6]. The feedback received was taken into consideration by E4tech in drafting the final document, which was published in December 2003.

The E4tech analysis presents the views of the authors rather than the Government. This Assessment is based on the premise that the analysis constitutes best available knowledge in its summaries of fuel and vehicle technologies and its analysis of potential implications of large-scale use of renewable hydrogen and biofuels.

2.2 Aim and scenarios

The analysis had two main objectives:

- To assess the energy requirements for, and the implications of, operating the UK road transport fleet with renewably produced liquid biofuels or hydrogen, to assist with meeting future greenhouse gas emission reductions; and

- To assess the potential for producing renewable hydrogen or liquid biofuels from indigenous resources in the UK.

To achieve the former aim, modelling of both future energy demand and supply was undertaken based on high and low travel demand scenarios and the potential availability of renewable resources.

The modelling generally assumed a high rate of penetration of renewable fuels and highly efficient vehicles, introduced at different times depending on the likely maturity date of the necessary technologies. These fairly extreme scenarios were employed in order to test the limits of large-scale use of renewable hydrogen and biofuels and so yield the full range of implications. The results of the modelling were used to draw out implications for CO_2 emissions, renewable resource requirements and the overall energy system.

A brief analysis was also made of existing and prospective renewable resources in the UK, illustrating the potential for satisfying transport energy from indigenous resources.

The major conclusions on the use of hydrogen and biofuels will be described at the beginning of chapters four and five respectively.

[6] www.dti.gov.uk/energy/sepn/futuretransport.shtml

Full descriptions of the scenarios, the modelling and the base assumptions are set out in the analysis.

It should be noted that the assumptions made for renewable resource availability are fairly bold. These assumptions reflect E4tech's remit to look forward to the distant time horizon of 2050, to take account of future technological developments and determine an upper bound for what might be possible. They also reflect the extent of uncertainty in the future availability and use of renewable resources. Nevertheless, the scale of these assumptions, and the non-energy implications that they carry (e.g. for land-take, biodiversity, public acceptance, capital costs, etc.) should be borne in mind.

2.3 Technology assessment

In addition to the modelling outlined above, the E4tech analysis provides detailed descriptions of current and future technologies in hydrogen, biofuels and road vehicles, outlining UK expertise in these areas; and identifies relevant gaps in current knowledge. This assessment will not reproduce that information, but will highlight the overall messages most germane to the development of future policy.

3. Vehicle technologies

3.1 Introduction

It will remain crucially important to continue to improve the average fuel efficiency of vehicles, regardless of what the fuels of the future might be. More efficient vehicles use less energy and therefore require less fuel; providing benefits for both consumers and the environment. Reduced fuel use would also result in less fuel transport on the seas and on our roads, and fewer imports.

Due to the efforts of vehicle manufacturers and governments, the average fuel efficiency of vehicles sold in Europe has been increasing steadily for a number of years. The average fuel efficiency of a new car in the UK in 2003 was around 43mpg, corresponding to average CO_2 emissions of 173g/km (grams of CO_2 emitted per kilometre driven). The higher the vehicle efficiency, the higher the mpg figure and the lower the CO_2 emissions, although the exact relationship varies slightly between petrol and diesel.

Through technical innovation, manufacturers are making more efficient vehicles, which satisfy consumer demands in other areas. Through the support provided by its reforms to company car taxation and Vehicle Excise Duty, and through its Powering Future Vehicles strategy, the Government is encouraging consumers to purchase these vehicles.

3.2 EU Voluntary Agreements

The Voluntary Agreements between the European Commission and the European, Japanese and Korean automotive industry bodies (ACEA, JAMA and KAMA) are one of the key European mechanisms for promoting fuel efficient technologies. They set clear, long-term targets for EU average new car fuel efficiency, but are technology-neutral and flexible, allowing some manufacturers and some segments of the vehicle fleet to deliver greater savings than others.

The targets require the industry bodies to ensure that average CO_2 emissions from new cars sold by their constituent members are reduced to 140g/km by 2008/9. The Voluntary Agreements have already resulted in significant improvements in average new car fuel efficiency, as can be seen from figure 1. Average CO_2 emissions from new passenger cars sold in the EU decreased by 10.8% between 1995 and 2002 and the EU as a whole is on track to meet the targets. As the target is for the new car fleet across the EU, it is EU average performance that is important. In this way, the Voluntary Agreements provide useful flexibility to both individual vehicle manufacturers and EU Member States about how the targets are met.

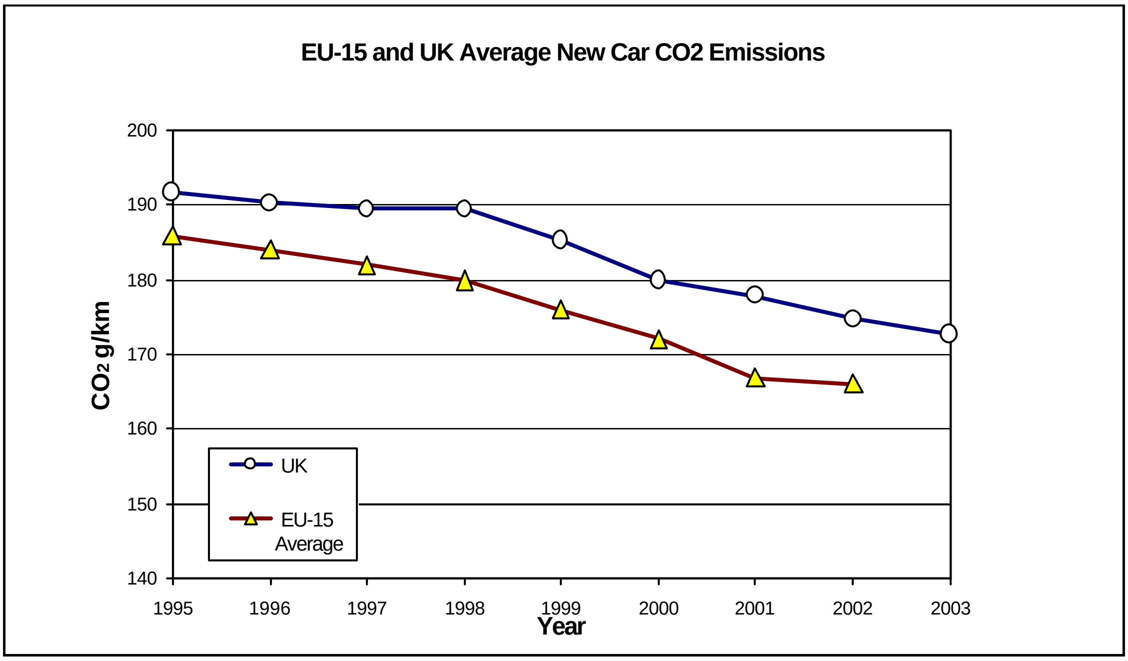

Figure 1: Average CO_2 emissions from new cars sold in (i) the UK (ii) the EU between 1995 and 2003

For a number of reasons, in the UK, there has been a slightly slower, although still significant, rate of improvement; an 8.8% reduction between 1995 and 2002. The UK car market has traditionally been weighted towards larger vehicles, and the UK baseline figure for 1995 was higher than the EU average. In the intervening period, the UK has experienced considerable economic growth, as a result of which consumers have been able to afford generally larger, less efficient vehicles. Further improvements are forecast in the UK average figure by 2008, although on current forecasts it is unlikely that the UK itself will reach the 140 g/km figure by that date. The Government will review what more it can do to increase the rate of improvement, but the carbon savings that the Voluntary Agreements are likely to deliver by 2010 may therefore turn out to be lower than originally forecast in the Climate Change Programme.

The UK Government is actively pressing the European Commission to finalise a new round of Voluntary Agreements with the automotive industry, as it committed to do in the 2003 Energy White Paper. Future targets are likely to focus on long-term fuel efficiency for the period beyond 2008, and are likely to force further technological developments and market changes.

3.3 Further technological developments

In 2002, the Department for Transport and the Department of Trade and Industry commissioned Ricardo Consulting Engineers, a leading automotive engineering consultancy, to develop a feasible route to highly efficient vehicles and, eventually, fuel cell vehicles[7]. In 2003, Ricardo updated this study, based on industry feedback received and technological developments in the interim.

In both reports, Ricardo set out a detailed step-by-step evolution from current vehicles to radically more efficient conventionally-fuelled vehicles and hydrogen fuel

[7] *Carbon to Hydrogen Roadmaps: A report for DfT and DTI*, Ricardo PLC, 2002. (www.dft.gov.uk/stellent/groups/dft_roads/documents/page/dft_roads_507528.pdf)

cell vehicles. This evolution drew on industry input, taking account of future weight savings, aerodynamics, engine design, engine 'downsizing' and, particularly, the use of hybrid electric technology. Ricardo proposed that, by 2020, it would be theoretically possible to produce diesel-powered vehicles that would be around 50% more efficient than a standard 2003 vehicle. There would be a cost associated with this, however, and it is not clear to what extent such ultra-fuel-efficient vehicles could achieve significant market penetration.

Ricardo also noted that battery technology could overcome present technology barriers to become a viable energy storage system for mainstream vehicles. Battery electric vehicles could, in this case, provide the same performance and air quality benefits as a hydrogen fuel cell vehicle, but with greater system efficiency, potentially greater CO_2 savings and without the costs of hydrogen storage and the need for a hydrogen fuel infrastructure. Whether or not battery technology can make this leap remains uncertain; a number of major motor manufacturers are dubious and have abandoned battery electric vehicle (BEV) development, while a number continue to produce BEVs commercially. The current development of hybrid electric vehicles might provide a stimulus to battery development.

3.4 Government support

Whilst more efficient vehicles are desirable to meet environmental aims, their use of new technology can make them more expensive to consumers – even when taking into account fuel cost savings. The Government has therefore put in place a package of measures, providing incentives to consumers to purchase cleaner and more efficient vehicles. These incentives include PowerShift grants towards vehicle purchase costs and CO_2-linked taxation in the form of graduated Vehicle Excise Duty, and Company Car Tax. The Government will continue to keep these policies under review to ensure that they are as effective as possible and is currently consulting on the future of its TransportEnergy grant programmes[8].

The Government also provides funding for the development and demonstration of clean low carbon vehicles, primarily through the New Vehicle Technology Fund (NVTF) and Foresight Vehicle programme. Through the NVTF, six projects have been offered grants under the Ultra Low Carbon Car Challenge to develop highly efficient family-sized vehicles, suitable for mass production. The first demonstration vehicles should be on the road in 2005. A number of proposals have been submitted for the sixth call of the DTI-led Foresight Vehicle programme, aimed at reducing UK fleet average CO_2 emissions. Projects include light weight materials, systems integration for a hybrid city bus, and developing lead acid battery technology for hybrid vehicles.

In formulating its Technology Strategy, the DTI has identified hydrogen technologies as one of the priority areas required to underpin the innovation necessary to achieve industrial growth. Research proposals will be invited in the area of hybrid power systems, including the development and integration of fuel cell technology, for transport application in a call to be launched in April 2004.

In addition, the Government is working with the vehicle and fuel industries, environmental groups and academia to encourage a shift to clean low carbon vehicles through the Low Carbon Vehicle Partnership (LowCVP). The LowCVP has been in operation for over a year, producing during this time some significant outputs including advice to Government on the preparation of this Assessment, through its

[8] Details at www.dft.gov.uk/stellent/groups/dft_roads/documents/page/dft_roads_029321.hcsp

Fuels working group. In 2003, the Bus Working group of the LowCVP made recommendations on ways in which bus companies and operators could work together, with support from Government, to encourage the uptake of low carbon buses. Government responded by launching the Low Carbon Bus Programme, which received an enthusiastic response.

The Government is nearing the final stages for the establishment of a Low Carbon and Fuel Cell technology Centre of Excellence with the aim of co-ordinating UK industrial and academic research, development and demonstration in this area. The centre will be expected to act as an expert resource to catalyse domestic and inward investment and direct organisations that are developing relevant technologies to the most appropriate market, source of advice or funding.

3.5 Fuel Cells

Fuel cells are highly efficient devices that convert the chemical energy of a fuel directly into electrical energy. This process is inherently more efficient than that of the internal combustion engine, so vehicles powered by fuel cells could be substantially more energy efficient than existing vehicles, although that advantage narrows when compared to future hybrid technologies.

Although a number of different types of fuel cell are in development, which could be powered by a number of different fuels, only one type – the Polymer Electrolyte Membrane (PEM) fuel cell – is generally considered suitable for use in vehicles. This type of fuel cell operates optimally on relatively pure hydrogen. It is this potential for high energy efficiency that is partly driving global interest in hydrogen.

Whilst PEM fuel cells require hydrogen as a fuel, this would not necessarily require that fuel cell vehicles be refuelled directly with hydrogen. It is possible to 'reform' other hydrogen-containing fuels, including fossil-fuels, to produce the hydrogen onboard the vehicle. However, this option has significant drawbacks, including weight, cost and air quality, and the vast majority of fuel cell vehicle development is directed towards vehicles fuelled directly with hydrogen.

Hydrogen fuel cell vehicles (FCVs) could also lead to dramatic improvements in local air quality. The hydrogen fuel combines in the fuel cell to produce pure water, which is the only emission from the vehicle. This is a significant advantage, unique, at present, to hydrogen fuel cell and battery electric vehicle technologies.

The most significant barrier to PEM fuel cells is cost. At present, it is estimated that demonstration fuel cell vehicles can cost up to several million pounds each, with the fuel cell costing several thousand pounds. It is thought that these costs could be brought down considerably through mass production.

Hydrogen can also be burned in an internal combustion engine (ICE), but with lower efficiency than could be achieved in a fuel cell. Burning hydrogen in this way also results in some emissions of oxides of nitrogen, an air quality pollutant and indirect greenhouse gas.

3.6 Biofuels use

Conventional biofuels, bioethanol and biodiesel, are used today as part substitutions for petrol and diesel respectively, but they have different compositions to standard fuels, different viscosities and different combustion characteristics. All major vehicle manufacturers have warranted their engines for use with blends of bioethanol and biodiesel with standard petrol and diesel up to a maximum of 5% by volume[9]. It has been suggested that blends at this level can marginally improve the combustion qualities of the fuel and the power output of the engine, due to the oxygenate properties of biofuels. If conventional biodiesel blends were to be used beyond this proportion, many engines would require modification to prevent damage to interior surfaces and allow optimal engine operation.

Flex-fuel vehicles have been developed to allow consumers to switch between high percentage conventional blends and standard fuel, allowing drivers to use whichever fuel is available to them. This technology is currently used in Sweden and the US, where high percentage bioethanol blends are available in certain areas (up to 85%, known as E85).

Advanced biofuels technologies, produced from woody crops, grasses, and organic residues and wastes, could be processed to have chemical compositions much closer to those of standard petrol and diesel, and might in time obviate the need for vehicle modifications or specialist vehicles. Some of these technologies are described in more detail in chapter 5.

3.7 E4tech analysis

The importance of efficient vehicles was highlighted by the E4tech analysis, which took, as the base case for all scenarios, a rapid introduction of highly efficient petrol and diesel vehicles from 2004, with efficiencies 45% greater than the 2003 average. The modelling showed that, despite an initial decrease in emissions due to the early and aggressive penetration of these radically more efficient vehicles, in a very high-demand scenario, increasing transport demand could see total CO_2 emissions return to current levels between 2020 and 2050, as demonstrated in Figure 2.

The likely time of introduction, rate of penetration and the total efficiency of possible high efficiency vehicles remains uncertain. It is likely, for example, that such vehicles would be introduced gradually, gaining an increasing foothold in the marketplace as consumer acceptance increased and costs fell. A small number of very high efficiency vehicles are available in the UK at present, but at this early stage, they service only a niche market. Future transport energy demand is equally uncertain, depending as it does on the demand for personal travel, impact of UK Government and EU measures and economic growth. Therefore, long-term predictions of future CO_2 emissions from transport can only be indicative.

What is clear from the analysis though, is that to considerably reduce CO_2 emissions from transport, it may be necessary not only to continue to encourage vehicle efficiency increases, but also to engineer at least a partial switch to lower carbon fuels.

[9] Where quoted, all biofuel blend proportions are by volume.

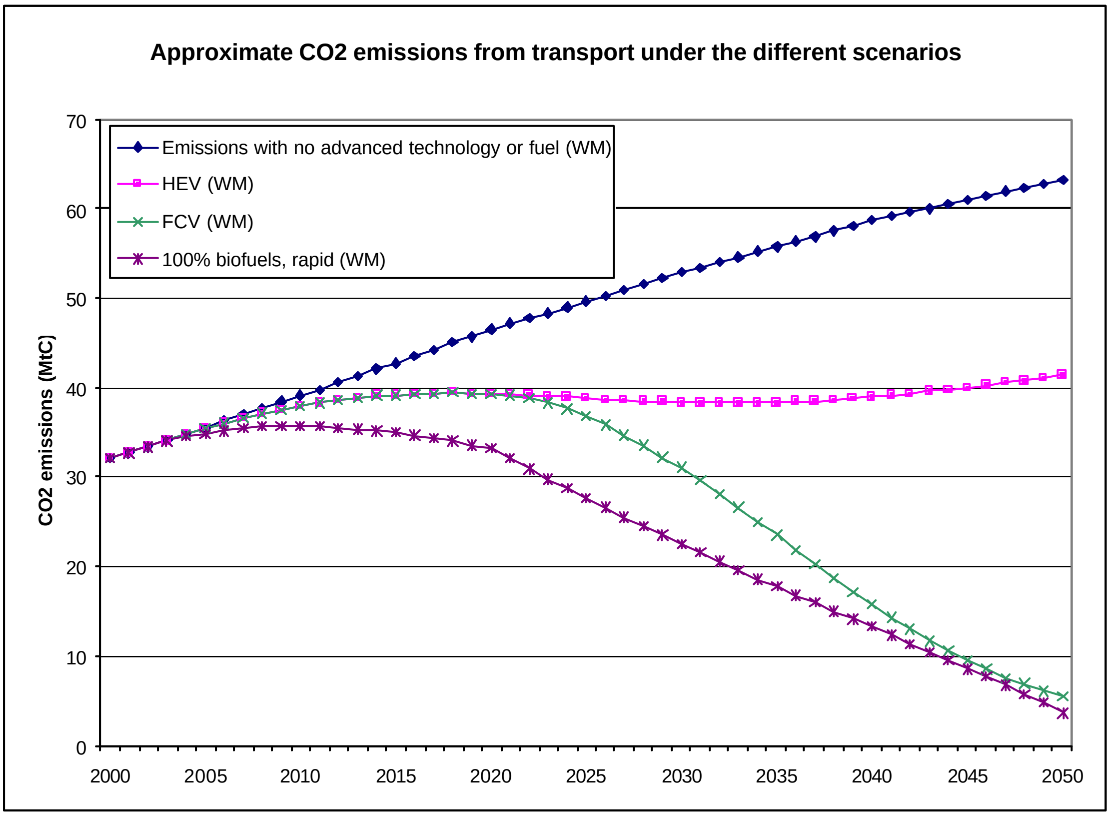

Figure 2: Approximate CO_2 emissions reductions to 2050 through introduction of HEVs using conventional fuels, HEVs using 100% biofuels, or FCVs using renewable hydrogen, under the World Markets (high demand) scenario[10]

[10] *Liquid biofuels and hydrogen from renewable resources in the UK to 2050: a technical analysis*, E4tech (UK) Ltd, 2003. (www.dti.gov.uk/energy/sepn/futuretransport.shtml)

4. Hydrogen

4.1 Introduction

Hydrogen is not an energy source like oil, natural gas, solar or wind, but an energy vector, like electricity; in fact electricity provides the best analogy. The great potential value of hydrogen, just like that of electricity, is in its ability to transfer energy from one place to another so that it can be made to do useful work. Again, like electricity, hydrogen can be produced using almost any primary energy source, but where it has a benefit over even electricity is in its potential to effectively store that energy until the hydrogen is used.

Hydrogen is an extremely abundant element in compound form, making up two thirds of all the water molecules on earth. 'Renewable' hydrogen can be generated via a number of different processes, as described in the E4tech analysis. These production processes fall roughly into three types:

- The use of renewable electricity, from wind power, solar power, wave power, geothermal, etc., to electrolyse water;
- The conversion of biomass – energy crops, agricultural wastes, organic household waste – to hydrogen; and
- Novel methods still at the research stage, such as the use of solar energy, heat or organisms to split water into hydrogen and oxygen.

All of these generation routes can offer very low lifecycle CO_2 emissions. The variety of possible production methods also provides an excellent potential diversity of supply.

An alternative low carbon, but not renewable, route could be achieved by hydrogen generation from fossil fuels combined with the capture and storage of the CO_2 released in the process. However, this option is not explored in any detail as the focus of this assessment is on hydrogen from truly renewable resources.

4.2 E4tech conclusions

4.2.1 CO2 emissions

The E4tech modelling demonstrates that CO_2 emissions from transport could be reduced dramatically by the use of renewable hydrogen in either internal combustion engine or fuel cell vehicles. It is assumed that there is a near-zero carbon penalty attached to renewable hydrogen. Therefore, as renewable hydrogen penetrates the transport sector, CO_2 emissions fall proportionally. However, in practice carbon emissions resulting from renewable hydrogen may vary substantially, depending on the methods of production and transportation and the overall level of non-renewable energy inputs to the hydrogen supply chain.

4.2.2 UK production

Under the hydrogen scenarios modelled, there would be sufficient hydrogen from UK renewable resources available to power the entire transport fleet if it were composed of efficient fuel cell vehicles. Under the lowest demand scenarios, there would also be renewable energy sufficient to meet about half of the UK's energy requirements for heat and power. Under the high demand scenario, however, that available energy is reduced to just one quarter of heat and power requirements. It should be borne in mind that these are not absolute limits; renewable electricity availability was modelled on the basis of reasonable cost, rather than finite resource. The potential for electricity generation from wind, wave, tidal and solar energy is limited principally by its cost; beyond the levels modelled, the costs to the UK would be extremely high.

Due to their lower efficiency, the introduction of hydrogen-fuelled internal combustion engine vehicles would require approximately one quarter more energy than fuel cell vehicles by 2050. Under the high demand scenario, use of ICEs would require imports of renewable hydrogen from around 2030, once the UK renewable resource base is utilised.

It is projected that the most efficient method of producing renewable hydrogen in the mid-term would be the gasification of short rotation coppice (such as willow and other fast-growing woody crops). It is estimated that this process could yield hydrogen at an indicative end-user cost of around £8 per GJ (Gigajoule – or 10^9J), compared with the current pump price of petrol of £5.2 per GJ (excluding taxes). It is highly unlikely that all UK hydrogen would be produced via this process, nor would it be totally desirable, particularly from a diversity of supply perspective. A possible weighted average hydrogen cost across all production methods was estimated as £12.6 per GJ by 2050. This cost would equate to around 1.8p per kilometre driven in a fuel cell vehicle (because of the greater efficiency afforded by fuel cell technology), or 1.9p/km in an ICE; the current petrol cost is around 1.2p/km. All costs are quoted at today's prices, exclude fuel duty and, in view of the large number of variables and the long time-frame, are subject to considerable uncertainty.

4.3 Power generation

Beyond technical considerations, there is a more important question about whether the limited renewable resources that will be available should be used to generate hydrogen or be directed elsewhere. The Government has set challenging targets for renewable electricity generation in the UK. The Renewables Obligation requires electricity suppliers to obtain 10% of their electricity from renewable sources by 2010-11. In addition, the Energy White Paper stated the Government's aspiration to provide 20% of UK electricity from renewable resources in 2020 (roughly 20GW).

The Tripartite Report[11] concluded that greater CO_2 benefits could be had from the use of renewable resources for heat and grid electricity generation than from the production of hydrogen, until such time as renewables or high efficiency CHP gas technologies were the dominant electricity generation technologies. The authors suggested that, to maximise CO_2 benefits, only surplus renewable electricity (such as available at times of low electricity demand) should be used for transport; they did not foresee such a surplus in the short-term. A recent joint study by CONCAWE/EUCAR/JRC[12] similarly concluded that renewable resources may be more efficiently used in power generation.

Nevertheless, there are other potential synergies between hydrogen and electricity generation that might improve the carbon balance. The ability to convert electricity to hydrogen and vice-versa, can be used to effectively 'store' electricity, to provide a buffer to intermittent renewable electricity sources. In such an application,

[11] *Fuelling road transport: Implications for energy policy*, Energy Saving Trust, Institute for European Environmental Policy, National Society for Clean Air, 2002.
[12] *Well-to-wheels analysis of future automotive fuels and powertrains in the European context*, CONCAWE, EUCAR and JRC, 2003. (http://ies.jrc.cec.eu.int/Download/eh/33)

renewable, but intermittent, electricity resources, such as wind and wave, could be used to generate hydrogen during periods of high resource availability, but low electricity demand. This hydrogen could be stored and either sold on for transport or other use, or converted back into electricity, to provide additional power during times of peak demand. Another possible synergy is in 'polygeneration' using future gasification technologies. Gasification of biomass (high-temperature conversion into gaseous products in a low oxygen environment) can generate a mixture of products, which could include hydrogen, heat, power, biofuels, and chemical precursors. If such processes can be co-ordinated sufficiently with relevant markets, they could help optimise resource use and a range of potentially valuable products.

4.4 Non-renewable hydrogen

The ideal scenario for low carbon hydrogen production and use is one based on renewable hydrogen, in which the full carbon and air quality benefits of hydrogen may be obtained. In view of other demands on renewable resources, and the potentially greater carbon benefits of directing these resources to other uses, it is quite possible that insufficient renewable hydrogen will be available to satisfy transport demand. In such a scenario, other options are available that might serve to meet the same aims, as outlined in section 4.1 and described more fully below.

Hydrogen can be produced relatively cheaply from fossil fuels, either by chemical reformation or partial oxidation of the fuel, or by burning to generate electricity, then using that electricity to generate hydrogen. Either route currently leads to the emission of significant quantities of CO_2, which are vented to the atmosphere. To prevent these emissions, it may be possible to capture the CO_2 before it is vented, then store the gas securely for an indefinite period. Options for storage include injection into geological formations including deep saline aquifers and in the voids left by the removal of oil and natural gas. CO_2 is already routinely used in North America to enhance oil recovery from mature oil fields; 1 Mt/yr (million tonnes per year) is committed to aquifer storage from Norway's Sleipner natural gas field in the North Sea. Carbon capture technologies currently in development are suited to large scale operations and could in principle be applied to existing power stations and other significant CO_2 emitters, or future hydrogen generation plants.

The DTI's Cleaner Fossil Fuels Unit has recently completed a review of the feasibility of carbon dioxide capture and storage in the UK[13]. This concluded that the technology had a potentially important role in reducing emissions from both power generation and road transport, with large-scale deployment commencing around 2020-2030. A new Carbon Abatement Technologies strategy is now being developed to take this forward, covering authorisation, regulation and monitoring methods as well as technology development.

At present, hydrogen is produced largely through industrial steam reformation of natural gas. This is an efficient process, but results in substantial emissions of CO_2. One option often proposed for the early introduction of hydrogen is to extend this process more widely, using reformers fed from the natural gas grid centrally, in filling stations, workplaces or domestic homes to produce hydrogen for vehicular and other uses. Just as production of renewable hydrogen would be dependent on distributed production to be economically viable, so would a natural-gas fed system. Such a distributed system would most likely be incompatible with economic carbon capture and storage technologies. Nevertheless, it has been suggested that, if combined

[13] *Review of the Feasibility of Carbon Dioxide Capture and Storage in the UK*, DTI, 2003. (http://www.dti.gov.uk/energy/coal/cfft/co2capture/index.shtml)

with the use of highly efficient FCVs, this process might still yield lower overall CO_2 emissions than conventional fossil fuels and vehicles. These CO_2 savings would be very much dependent on the successful and early introduction of FCVs, operating towards the upper end of their predicted efficiencies.

The CONCAWE/EUCAR/JRC study concluded that hydrogen generated from natural gas, without carbon capture, could only yield CO_2 emissions savings if it were used in fuel cell vehicles, and then at a cost of around €1300 per ton of CO_2 saved. In contrast, the use of this natural gas in dedicated compressed natural gas (CNG) vehicles could lead to carbon savings at around €300 per ton. Producing hydrogen from natural gas was found to lead to lower overall CO_2 emissions than from electrolysis of water using EU-mix electricity. CO_2 emissions from hydrogen used in ICEs were found to be higher than for conventional vehicles or from the use of natural gas in CNG vehicles. These routes could provide, at best, incremental CO_2 reductions; none could offer the very large CO_2 reductions provided by truly renewable hydrogen and biomass-based fuels.

4.5 Technology and knowledge gaps

The principles behind fuel cell automotive powertrains have been well proven; the challenge facing industry now is to resolve outstanding technical issues, with the overall goal of reducing costs towards those of conventional powertrains. At present, it is thought that fuel cell costs are around two orders of magnitude greater than would be required for them to compete with standard ICEs on a cost per kilowatt basis. In addition, it will be necessary for manufacturers of FCVs to demonstrate their reliability and durability; consumers have exacting demands of their vehicles and it will be important that commercially-available FCVs can meet these demands and maintain consumer confidence.

Onboard hydrogen storage, whether in liquid or compressed form, has yet to be addressed satisfactorily, though this is an area of considerable global investment. No current technology satisfies all the requirements of vehicle manufacturers or consumers, such as weight, volume, capacity, cost, manufacture and safety. Incremental improvements continue with existing technologies (largely based on liquid or gaseous storage), along with research into more advanced solutions, such as solid state storage with lightweight metal hydrides, liquid-state storage in chemical hydrides, or the use of more complex materials, such as carbon nanotubes.

A number of hydrogen refuelling projects are underway, though these largely use tanker-delivered hydrogen for private depot-based fleets. Some countries have announced ambitious plans to establish substantial public refuelling infrastructures across large areas. Currently though, the use of hydrogen as a fuel is negligible. Industrial production of hydrogen for industrial use is commonplace, largely through the reformation of natural gas, rather than from renewable resources.

Whilst refuelling trials are vital, there remains a larger question of the most cost- and carbon- efficient methods of generating and distributing hydrogen to the end user. When considering renewable hydrogen production in the UK, the greatest limiting factors are the availability of the renewable resource and the high cost of transportation. Renewable resources tend to be widely distributed geographically. While it may be best to use biomass resources close to their point of origin, renewable electricity could be transported via the grid to produce hydrogen close to or at its end-use location. Transportation is problematic due to the low energy density of hydrogen gas, the high energy and monetary cost of liquefaction and the resulting low efficiency of road transport. To transport the energy equivalent of one petrol tanker could require around ten to twelve hydrogen gas tankers.

If the UK were to import renewable hydrogen or renewable resources, a number of problems would have to be solved. If the policy aim of introducing hydrogen were to reduce carbon emissions, this would present the question of how the emissions attached to the import would be measured and verified. The carbon emissions from biomass-produced hydrogen could vary considerably according to the agricultural methods, the processes for transporting the biomass and converting it to hydrogen and the method of hydrogen transportation. Not all renewable hydrogen would be as carbon-free as the best.

Uncertainties in the cost of developing a hydrogen infrastructure in the UK are large, whether the hydrogen is assumed to come from renewable sources or otherwise. Estimates of the cost of developing a distribution system and network of filling stations across the UK range up to hundreds of billions of pounds. Current international activity, such as the recent Californian 'Hydrogen Highways' initiative[14], should help to develop understanding of the economic impact of hydrogen infrastructure - both on industry and the public sector.

4.6 Current support for technologies

The Department of Trade and Industry (DTI) has been supporting industrial research on fuel cells since 1992 under its Advanced Fuel Cell Programme. During its lifetime, the focus of the programme has changed from supporting studies designed to inform the DTI and the industry regarding the prospects for fuel cells to work to supporting the development of UK capabilities. Since its inception, the programme has supported a total of 156 projects involving total DTI expenditure of £12.4m. Currently the programme is funded at about £2m per annum. In addition, DTI, EPSRC and the Carbon Trust are working together to produce an integrated support programme for fuel cells in the UK.

The DTI is currently developing a strategic framework for hydrogen energy activity and support in the UK. As the first stage of this, DTI has commissioned a study to provide recommendations, which is due to report in November 2004.

The DTI's New and Renewable Energy programme is focused on high quality, innovative industrial R&D projects in renewable technologies including biofuels and fuel cells. These projects must offer the prospect of reduced cost and/or improved performance of renewable energy. The goal is to improve the competitiveness of both renewable energy and the UK industry or understanding of the prospects for renewable energy.

With support from Government, Fuel Cells UK was established last May as an umbrella organisation for the UK fuel cell industry. Fuel Cells UK provides a focus for this growing industry and works to foster that growth through:

- raising the profile of the industry both in the UK and overseas;
- acting as a central liaison point for national and international contact;
- catalysing partnering opportunities between UK and overseas organisations;
- improving the positioning of the UK fuel cell industry in the international arena; and
- developing a pan-industry perspective on key issues.

[14] www.hydrogenhighway.ca.gov/

Since its formation, Fuel Cells UK has developed a guide[15] to the UK fuel cell industry and produced a UK Fuel Cell vision[16], which was launched in London last September at the Grove Fuel Cell Symposium.

One of the key tasks of the Low Carbon Vehicle Partnership is to provide advice on their 2020 vision for the UK car market and for the UK industry and Government's role in this. The Partnership has prepared a draft version of this vision, and are due to submit their final version to the Government later this year.

The proposed national Centre of Excellence for Low Carbon and Fuel Cell Technologies, supported by Government, developed by the LowCVP and referred to in more detail in section 3.4, will include hydrogen and fuel cell technologies for transport within its scope.

The UK Energy Research Centre is currently being established, and will undertake and co-ordinate interdisciplinary research on sustainable energy issues, with crucial importance to the development of renewable hydrogen technologies.

The UK is involved in a number of international initiatives on hydrogen. These are the Hydrogen and Fuel Cells Implementing Agreements of the International Energy Agency (IEA), and the recently established IEA Hydrogen Co-ordination Group; the EC Hydrogen and Fuel Cells Technology Platform and the International Partnership for the Hydrogen Economy (IPHE). The IEA Implementing Agreements are frameworks for international collaborative research. The IEA Hydrogen Co-ordination Group is a higher level committee designed to co-ordinate the activities of the relevant Implementing Agreements – which include the Greenhouse Gases and Advanced Motor Fuels agreements in addition to those previously mentioned. The EC Hydrogen and Fuel Cells Technology Platform was established in January 2004 following the recommendations of a high level group appointed by the Commission. It will be a partnership involving collaborative projects (including those funded under the EC Framework Programmes) and information exchange. The International Partnership for the Hydrogen Economy is a US initiative launched in Washington last year. Fifteen countries including the UK were invited to join. The IPHE will act as a mechanism for international collaborative research and also as a forum for advancing policies which will accelerate the cost effective transition to the hydrogen economy.

4.7 Vehicles

Hydrogen use in road transport would be optimised by Fuel Cell Vehicles (FCVs), from climate change, energy conservation, consumer fuel cost and air quality perspectives. Therefore, whilst the use of hydrogen is not contingent upon their successful commercial introduction, should FCVs fail to become viable, there would be a greatly reduced benefit in the adoption of hydrogen for transport use.

Considerable effort and funding is being directed at the development of FCVs, by industry, academia and governments. This effort is expended in the full expectation that FCVs will succeed, with commercial introduction from around 2020 to 2030. A number of global vehicle manufacturers have started, or intend to start in the next few years, to lease small numbers of FCVs and others expect to begin commercial sales within the next decade.

[15] www.fuelcellsuk.org/team/Library/CapabilityGuideWithCovers100903.pdf
[16] www.fuelcellsuk.org/team/Library/Visionwithcovers100903.pdf

Fuel cell technology is also being demonstrated in a number of trials of public vehicles. The EU's Clean Urban Transport for Europe (CUTE) project involves the trial of fuel cell buses in nine major European cities; with Government support, three buses have been in service in London since January 2004. One of the specific aims of this project is to develop working knowledge of the vehicle and refuelling technology in regular operation, and produce reliable data to feed back into the technology development process.

Although FCVs would optimise a renewable hydrogen transport energy chain, hydrogen ICEs might have a place in the early stages of a hydrogen economy, particularly if they could be produced at relatively low cost and could serve to usher in the necessary hydrogen infrastructure. A number of major vehicle manufacturers are investing in the development of hydrogen ICEs, though few are giving these the same profile as FCVs. Hydrogen could also be combined with natural gas to form 'hythane' mixtures, which could potentially be used in Compressed Natural Gas vehicles or hydrogen ICEs, providing another early market for hydrogen.

4.8 Fuel infrastructure

As noted in section 4.2.3, hydrogen delivery and refuelling infrastructures are a current knowledge gap, with particular uncertainties around relative cost and carbon efficiencies. Several demonstrations of hydrogen refuelling technologies are underway in a number of different countries, which will serve to reduce this knowledge gap to an extent. Since April 2002, expenditure on new plant and machinery installed in the UK to refuel vehicles with hydrogen fuel can qualify for 100% first year capital allowances. The refuelling station does not need to be open to the public, or used for cars; fleet-based infrastructure can also be eligible.

The Health and Safety Executive (HSE) is currently investigating the possibility of creating a joint industry project to develop a recognised code for installation of hydrogen fuel cells in domestic and transport situations, paralleling the existing CORGI codes for gas. The development of a recognised code for the installation of hydrogen devices in domestic and commercial situations would represent the removal of a major obstacle to, and facilitate the more rapid deployment of, innovative technology. In the longer term, common EU standards for hydrogen technology will be developed; it will be important that, in the development of a UK code, the EU dimension is taken into consideration.

The development of standards and refuelling technologies are important, but the most significant barriers to the production of hydrogen from renewables are economic, since renewable energy resources are usually more expensive than fossil fuels. While there have been no demonstrations of renewable hydrogen production of any significant scale in the UK, this is not the case elsewhere. The EU Clean Urban Transport for Europe (CUTE) project, to trial hydrogen fuel cell buses in cities across Europe (including London, as described later in this chapter), will compare the production of hydrogen via a number of routes, some of them renewable. There are also a number of actual or prospective projects involving hydrogen generation from renewables for island communities.

Relatively high transportation costs suggest that distributed hydrogen production might be the most economic route, perhaps using renewable electricity for electrolysis. For this to be feasible, development of suitably small-scale, efficient electrolysis equipment would be necessary, for use near population centres or on fuel station forecourts.

Large-scale production could be viable where there is a greater concentration of renewable resource, for example a large wind farm. The problem of transportation would still remain, though this could be addressed through the use of pipelines, or even a national hydrogen grid. Overall, a mix of solutions is suggested as the most likely result, combining small-scale production, close to the point of use and large scale production and transportation.

Production from imported resources would require careful analysis of the optimal configuration. Hydrogen could be produced at the point of entry and distributed by surface transport, or pipeline, much as oil is refined and distributed from the point of entry today. Alternatively, the renewable resource itself could be transported to local plants for conversion to hydrogen and subsequent local distribution. If the renewable resource were electricity, it could be fed into the grid and used in centralised generation, or perhaps the kind of distributed infrastructure described above.

4.9 Hydrogen as a greenhouse gas

The Intergovernmental Panel on Climate Change recognises hydrogen as an indirect greenhouse gas. A study under Defra's Climate Change Research Programme on the global warming effect of hydrogen concluded that the presence of hydrogen in the atmosphere changes the build up of methane and ozone, which are both greenhouse gases, making hydrogen an indirect greenhouse gas with a global warming potential (GWP) of 5.8 (in comparison carbon dioxide has a GWP of 1; and methane has a GWP of 21)[17,18].

The global warming consequences of a hydrogen economy would be affected by the leakage rates for hydrogen manufacture, storage and distribution systems. The Defra study estimated that if the entire current fossil-fuel based energy system were replaced by hydrogen (produced from sources with no carbon dioxide emissions), and 1% hydrogen leakage was assumed, it would have 0.6% of the climate impact the fossil-fuel system – a reduction of over 99%. If only transport fossil fuels were replaced by hydrogen, then the reduction in greenhouse emissions may not be directly proportional, as transport fuel may have higher leakage rates; however, there would still be considerable benefits over fossil fuels.

4.10 The future

It has been estimated that the global market for fuel cells could be worth $30bn (USD) by 2011, with growth to 2021 being in the range 10-50% pa. It will be important for UK industry to secure a strong position in this market, building on existing academic and industrial strengths.

Renewable hydrogen, used in highly efficient fuel cell vehicles, is an attractive fuel for many reasons. It can be generated from numerous renewable energy sources and its use in fuel cell vehicles could lead to highly efficient transport energy use. However, if renewable hydrogen is to become a mainstream transport fuel and used on a large scale, then it will have to overcome a number of hurdles.

On-board vehicle hydrogen storage is currently a technological hurdle, but efforts to overcome this are significant. Costs of renewable hydrogen and issues around its

[17] *Global warming consequences of a future hydrogen economy*, Derwent, R.G., 2004, Transport and the Environment. Issues in Environmental Science and Technology, Volume 20, Royal Society of Chemistry, Cambridge, UK. In Press.
[18] There is not absolute scientific consensus on this value.

generation and distribution are dependent on a greater number of factors and reducing the uncertainty around them is likely to be a medium- to long-term challenge.

Whilst it is not possible to identify at the present moment all of the potential factors relevant to the success of renewable hydrogen, a number of them, both positive and negative, are set out in Table 1.

Factors that could encourage renewable hydrogen uptake	Factors that could hinder renewable hydrogen uptake
Economic • Costs of FCVs fall considerably in the medium term • Price of future hydrogen production looks promising • Biofuels costs fail to fall significantly • Overall costs of crude oil increase significantly	**Economic** • Hydrogen costs do not fall to viable levels • Costs of fuel cell vehicles do not fall to viable levels • Cost of hydrogen infrastructure proves prohibitive • Biofuels costs fall, leading to high availability and consumer uptake
Technical • Storage and distribution issues resolved • Mismatch between renewable electricity supply and demand • Agreements on international hydrogen vehicle and fuel standards • Carbon sequestration route starts to look promising. • Advanced biomass conversion technologies fail to be proven • Hydrogen trials in the UK and elsewhere in the world give promising results	**Technical** • Insufficient renewable electricity or biomass available • Storage and distribution technical issues not resolved • Hydrogen trials in the UK and elsewhere in the world are unsuccessful • FCVs do not prove reliable enough for consumer demands • A breakthrough in battery electric vehicles makes them viable
Consumer • Consumer awareness of climate change increases • FCVs offer motorists driving advantages over conventional vehicles • Consumers not accepting of biofuels	**Consumer** • A serious FCV accident dents public confidence • The public not accepting of FCV technology
Political • The EU pushes the agenda strongly • Major non-EU international partners push the agenda strongly • High desire to reduce dependency on imported oil • Pressure grows on transport to increase rate of CO_2 reductions	**Political** • Priority for renewable resources given to heat and power for domestic/industrial use • Loss of interest from key global players

Table 1: Factors that may help or hinder the uptake of renewable hydrogen as a major transport fuel.

5. Biomass-based fuels

5.1 Introduction

Biomass-based fuels (or biofuels) are fuels with similar physical characteristics to existing mineral fuels, but are produced from chemically processed plant material or other organic matter. As biomass grows, CO_2 is absorbed from the atmosphere and converted into sugars to fuel growth. When a crop is harvested, converted into biofuels and then burned, the CO_2 released through combustion is equal to that originally absorbed during growth. This process is not currently zero-carbon, as chemical fertilisers, agricultural machinery, collection of waste and residues, transport and processing all lead to CO_2 emissions. However, biofuels can currently offer CO_2 savings in the range of 40-60%[19,20] over mineral fuels and, in theory, could in the future provide much higher savings, if sensitive agricultural practices and renewable energy sources are used at each stage.

The term 'biofuels' essentially refers to any fuel synthesised from biomass material. At present, only two biofuels are commercially available for transport use in any significant volumes: biodiesel (from vegetable oils) and bioethanol, which can substitute for mineral diesel and petrol respectively. Biodiesel and bioethanol are often termed 'conventional biofuels'. In principle, biofuels could be made from a variety of biomass material, ranging from oil seed rape and sugar beet as at present, to organic municipal waste, grasses and woodchip in the future; such future biofuels technologies may be termed 'advanced biofuels'. A range of different types and sources of biofuels are set out in detail with their relative costs and benefits in Chapter 4 of the E4tech analysis.

Biofuels have a crucial advantage as low carbon fuels in that their use does not require a new fuel distribution and retail infrastructure, nor major changes to existing vehicle technology. Conventional biofuels are not chemically identical to their mineral counterparts and their use in proportions beyond 5% blends with mineral fuels might require modifications to some vehicle and fuelling infrastructure components, as discussed in section 3.6. Nevertheless, they are similar to petrol and diesel in key respects: they are transported, stored and dispensed as liquids; they are held as liquids in plastic vehicle fuel tanks; they are burned by internal combustion engines in standard processes. Existing infrastructure for mineral fuels could be gradually developed for increasing conventional biofuels use at relatively low cost. Advanced biofuels technologies may yield biofuels that are chemically much closer to petrol and diesel, allowing straight substitution in vehicles and the fuelling infrastructure.

Only biodiesel is produced in the UK at present, made from waste vegetable oils or food-grade oil yielding crops. These sources, and particularly the use of waste oils, can provide significant carbon savings, but at a relatively high monetary cost. The potential to reduce conventional biodiesel costs through improvements to crop yields, processing methods etc. needs to be established. Advanced biofuels technologies could allow the conversion of cheaper feedstocks, such as straw, grasses, forestry and agricultural residues and woody crops, which hold the promise of lower cost

[19] *Evaluation of the Comparative Energy, Global Warming and Socio-economic costs and benefits of Biodiesel*, Sheffield Hallam University, 2003.
[20] *Well-to-wheels analysis of future automotive fuels and powertrains in the European context*, CONCAWE, EUCAR and JRC, 2003.

biofuels. However, these technologies largely remain at the research and small-scale demonstration scale and are yet to be proven commercially.

In 2002, the Government introduced a 20p/l duty differential for biodiesel (the same incentive for bioethanol is due to take effect from January 2005), which stimulated rapid growth in sales. Sales currently stand at around two million litres per month; sales of mineral diesel are around 1700 million litres per month. It is expected that the introduction of the bioethanol duty differential in 2005 will stimulate sales of bioethanol, though perhaps to a lesser extent than was achieved for biodiesel.

Some outstanding technical difficulties remain with the blending of bioethanol with petrol. Blending of bioethanol can significantly affect the physical properties of the resulting fuel, even at relatively low concentrations. Blending 5% bioethanol with standard petrol can raise the vapour pressure of the resulting fuel above the level specified by European fuel standards. There are also concerns about the impact of the high water solubility of bioethanol on its distribution in existing infrastructure. It is expected that both of these issues will be resolved in due course.

The Energy White Paper noted the contribution that biofuels could make to a future low carbon transport economy. It predicted that 5% penetration of biofuels might be possible by 2020, which, at this level, could deliver carbon savings up to 1 MtC (million tonnes of carbon) per year.

5.2 E4tech conclusions

5.2.1 CO2 emissions

The modelling of the biofuels scenarios showed that their use could reduce transport CO_2 emissions to very low levels; halving 2000 emissions by 2035 and 2045 under the rapid and slow uptake scenarios respectively. In the analysis, the complete replacement of fossil fuels with biofuels would not reduce CO_2 emissions to the same final level as for replacement with renewable hydrogen, due to the CO_2-emitting processes described in section 6.1. However, this is not an absolute limit; lower carbon agricultural methods, transportation and the use of biomass material to provide power for processing (such as the burning of co-products like straw) could reduce CO_2 emissions further, perhaps to a similar level to that assumed for renewable hydrogen for 100% biofuels use.

5.2.2 UK Production

Biofuels demand could in theory be satisfied to 2020 by UK-sourced biofuels under both high and low demand scenarios, with both slow and rapid uptake of biofuels. Beyond 2020 this would not be the case under the high demand scenario with rapid uptake, and imports would be required. For all scenarios, under slow and rapid take up, imports would be required from around 2035 at the latest. Indigenous resources could supply a maximum of around 500PJ (petajoules - 1×10^{15} joules) of energy in the form of transport fuels. Total energy consumption by UK road transport in 2002 was around 1700PJ. By 2050, complete substitution of petrol and diesel could require approximately two thirds of the total biofuel demand to be met by imports[22].

Mid-range projected costs for advanced biofuels technologies suggest that they could be produced at around two to three times the current untaxed cost of petrol and

[22] The assumptions leading to this result are spelled out in full in the E4Tech analysis.

diesel, ignoring co-product value. Co-products can have significant value, with uses including bio-chemicals, animal feed, oils, or straw for heat and power generation. Indeed it is possible that, in the future, fuels may become the co-products of other potentially higher-value primary products, such as bio-chemicals. There is therefore considerable uncertainty about the future markets for, and values of, co-products, and estimating their value into the future is not simple. For example, if biofuel crops are increasingly grown in the UK and the market for co-products does not expand to the same extent, it might serve only to inflate the co-product supply, thereby reducing co-product value and perhaps shifting the economic balance.

The lowest projected biofuel costs, excluding co-products, are for processes using lignocellulosic crops, such as short rotation coppice, wood and straw, rather than existing biofuel crops such as oil seed rape, sugar beet and wheat. Because of their cost and carbon advantage, the E4tech analysis makes the assumption that the production of biofuels from lignocellulosic resources will dominate by 2030.

Biomethane is considered by the E4tech analysis, but was thought to be generally confined to short to medium term use in niche gas-powered vehicles. Beyond this timeframe, it was assumed that the organic fraction of wastes (which is where the majority of accessible biomethane would originate) would be reclaimed before landfill and used for producing liquid biofuels or hydrogen.

5.3 NSCA & IEEP study

In 2003, the Department for Transport and the BOC Foundation commissioned the Cleaner Transport Forum (CTF) to co-ordinate a study into the wider environmental and social impacts of biofuels production and use in the UK. The study was published in March 2004.

The study was developed in two strands:

- An assessment of the global impacts of biofuels, including a description of a range of methodological issues in undertaking lifecycle or 'Well to Wheels' assessments of greenhouse gas (GHG) emissions and their importance in interpreting some recent fuel cycle analyses of greenhouse gas emissions from biofuels[23]; and
- An assessment of the local impacts of biofuels, such as land use, biodiversity, regional development and agricultural practices[24].

The National Society for Clean Air and Environmental Protection (NSCA) and the Institute for European Environmental Policy (IEEP) facilitated an expert/stakeholder consultation with academics and independent experts to address the former strand. The IEEP facilitated the latter via a separate expert/stakeholder consultation process.

Sub-section 5.3.3 sets out some of the relevant Government measures already in place to ensure that possible local impacts of energy crops are avoided, or managed effectively. The section also highlights research showing the positive impacts of energy crops on biodiversity.

[23] *Expert Paper on the Global Impacts of Road Transport Biofuels*, IEEP and NSCA, 2004. (www.nsca.org.uk/assets/Biofuelsexperts.pdf)
[24] *The Potential Environmental and Rural Impacts of Biofuel Production in the UK*, IEEP and NSCA, 2004. (www.nsca.org.uk/assets/Biofuelsimpacts.pdf)

5.3.1 Global impacts

The key messages from the study are split into three sections: what we know; what we need to understand better; and policy implications. The latter two are most relevant in the context of the long-term view of this Assessment.

What we need to understand better

- Different methods for allocating GHG gas emissions between biofuels and their co-products can have a substantial impact on the estimated greenhouse benefits of the biofuel component. A better understanding is required of how co-product and by-product use might evolve in the event of large-scale biofuels production, particularly in relation to the most appropriate allocation methodology for different circumstances.

- The GHG impact of alternative agricultural practices is not completely understood. Should such practices be employed in the production of biofuels, these impacts would have to be explored in greater depth.

- The technical and economic potential of biofuels produced via hydrolysis and gasification processes needs to be better understood.

- Significant uncertainties exist in the potential for UK biomass production and the carbon balance between different uses of biomass resources.

- GHG impacts of imported biofuels are not automatically better or worse than indigenous sources and must be analysed on a case-by-case basis. In addition, imports may well present other environmental, social and economic issues that will have to be taken into account.

Policy Implications

- The significant uncertainties and methodological issues involved in undertaking lifecycle assessments of biofuel GHG emissions have a substantial bearing on their environmental benefits in different circumstances. It is important that these complexities are understood by policymakers in order to ensure that the specific results of lifecycle assessments address the policy questions posed. It would therefore be useful if simple and robust approaches could be developed to allow comparison of biofuel production chains on their environmental impacts.

- The authors suggest that in the long term it would be advantageous to move to tax incentives based on full fuel cycle GHG emissions, but note that this might not be sufficient to encourage a significant UK market or production industry. Novel production methods, being currently at the research and demonstration stage, would almost certainly require additional support to reach commercialisation.

- Some of the most favourable GHG assessments of conventional biofuels assume non-standard production methods such as the use of co-products to fuel the process. These methods are perhaps unlikely to be adopted without additional Government support.

5.3.2 Local impacts

The consultation focused on the environmental impacts of expanded biofuel crop production in the UK, particularly those on the quality and character of the countryside. A distinction was made between the impacts of conventional agricultural crops, specifically oil seed rape, sugar beet and wheat, and those arising from more novel crops, such as short rotation coppice and grasses.

Issues relating to the use of conventional crops included:

- A general perspective that a modest expansion in existing crops, particularly rape and wheat, would not raise substantive new environmental issues.

- This would not necessarily be the case if GM varieties were to be planted; large scale opposition might result, both to the specific crops and to biofuels in general.

- There was some concern that industrial crops might reduce the scope for less intensive systems, including organic, and potentially affect land availability for alternative uses such as nature conservation.

- The principal biofuels crops all have local environmental costs, including those linked to issues around crop rotation, habitat provision and the level of inputs required; the latter two are of particular concern for wheat . An enlarged area of oilseed rape would have a variety of impacts, depending on the crops it displaced.

- There was a specific concern that growing a larger area of industrial crops on set-aside land would be a step backwards in terms of biodiversity.

- The ploughing of permanent grassland for arable cropping would be damaging for biodiversity and landscape interests in many but not all locations.

Issues relating to the use of novel crops included:

- It was thought that short rotation coppice could have biodiversity benefits if well managed, but there is relatively little experience of commercial production in the UK.

- The landscape effects of planting coppice would be positive in some locations but negative in others, depending on the precise siting. Rigorous Environmental Impact Assessments and strategic environmental assessment would be required for growth on a significant scale.

- One of the principal concerns about certain new crops, particularly SRC, is their heavy water demand and potential impact on aquatic systems. This topic needs further investigation.

- Less is known about the potential impact of miscanthus, a fast-growing tropical grass, which is currently grown in limited locations.

- The report states that appropriate soil management will be necessary for both conventional, annual crops and novel, more permanent biofuel crops. The latter offer advantages over conventional arable crops in reducing soil disturbance and erosion, but there is some concern about damage during winter harvesting.

- Economic effects were generally seen as being positive, but uncertain, being highly dependent on a number of factors including the level of imports, the level of EU and domestic financial support provided, the type of crops grown and the location of growth. It was expected that a stronger market for wood products would bring new revenues and employment in both new and existing woodlands. It was thought that the flexibility provided by processing plants capable of handling a variety of different feedstocks would be important.

5.3.3 Existing Government measures

In the short term, Defra expects energy crops to complement organic farming and other England Rural Development Programme (ERDP) schemes as elements of a sustainable farming and food policy. It is likely that conventional crops destined for transport fuels would mainly replace similar crops currently grown for food. Therefore, little change in agronomy is envisaged. Some use is likely to be made of set-aside land for energy crops, but there is no guarantee that set-aside will remain as a feature of the Common Agricultural Policy (CAP) in the longer term. CAP reform arrangements ensure only limited potential for ploughing of permanent pasture for arable cropping. Environmental assessments including landscape impacts are already in place as part of the ECS application assessment process. For planting of short rotation coppice (SRC) or miscanthus on a large scale, a strategic environmental assessment would be required. Best practice guidance is available for siting and growing of energy crops supported under the Defra scheme.

In the longer term, enlarging the area of oilseed rape grown could have a variety of impacts, depending on the crops it displaced. Replacing autumn-sown cereals such as wheat with oilseed rape for example could lead to biodiversity benefits. The Secretary of State for Environment, Food and Rural Affairs made clear in her statement on GM policy that there is no case for a blanket ban on GMO's[25]. However, she stated that each request for authorisation must receive a comprehensive prior assessment of any potential risk to human health or the environment.

Miscanthus has been grown in the UK for around 10 years and is now being grown commercially. Research has shown that it can enhance biodiversity for a range of wildlife including for certain reed nesting birds, earthworms, spiders and mammals compared with growing winter-sown cereals[26, 27]. The positive biodiversity impacts of SRC willow are also well documented[28, 29]. Reductions in soil disturbance and erosion can be achieved from growing miscanthus or SRC willow compared with conventional arable crops. A recent study suggests that SRC willow could have a positive impact within a catchment in localised flood reduction[30]. Appropriate soil

[25] Secretary of State's statement on GM: Hansard, 9 March 2004, Column: 1382.
[26] Jodl, S, Eppel-Hotz A and Marzini K (1998) *Examination of the ecological value of miscanthus expanses – faunistic studies*. In: Biomass for Energy and Industry; Proc 10th EU Bioenergy Conference, Wuzburg, Germany Carmen Publishers, Rimpar, Germany pp 48-53.
[27] Christian D G , Bullard M J and Wilkins C (1997) *The agronomy of some herbaceous crops grown for energy in Southern England*. Aspects of Applied Biology. 49 Biomass and Energy crops. pp41-51.
[28] Cunningham, MD, Bishop, JD, McKay, HV and Sage, RB (2004) *Ecology of Short Rotation Coppice - ARBRE Monitoring*. New Energy Solutions B/U1/00627/REP. Commissioned by the DTI through NES.
[29] Sage & Tucker (1998) *Integrating crop management of SRC plantations to maximize crop value, wildlife benefits and other added value opportunities*. Report of the Energy Technology Support Unit, DTI.
[30] Stephens, W, Hess, T.M. and Knox, J.W. (2001) *The effect of energy crops on hydrology*. Aspects of Applied biology 65. Biomass and Bioenergy Crops II.

management will be expected of all receiving single farm payments from January 2005.

5.4 Alternative uses

As discussed in section 4.6, the Government has set targets for the generation of renewable electricity in the UK, and placed obligations on electricity suppliers to meet these. This existing programme could place significant demands on the finite UK biomass resources, reducing the availability of these resources for biofuels production; future programmes would be likely to further increase these demands. Government will then be faced with a choice as to where the biomass resource should be employed to achieve the greatest benefit. This choice will have to consider relative costs, carbon savings, relevant domestic and European targets and future benefits.

In the E4tech analysis, it was assumed that a maximum of 4Mha of land would be available for the growing of energy crops; this represents about 25% of current UK agricultural land and was acknowledged as an ambitious assumption, in line with others in the analysis. At present, there is some 0.6Mha of set-aside land not currently employed in agricultural production, though this would not necessarily be suitable for growing energy crops. To grow novel energy crops on 4Mha of land might therefore require the change of use of some 3.4Mha of land, and perhaps major changes in agricultural practices. The growing of short rotation coppice is markedly different to growing wheat or oilseed rape. Whilst such a change might be practicable, the agricultural community would need to be strongly engaged. The growth of conventional crops for biofuels on such an area might not require any significant changes, as these are already grown for food production.

5.5 Technology and Knowledge Gaps

Conventional biofuels are expensive in comparison to petrol and diesel, despite support provided by the Government's fuel duty differential. Many vehicle manufacturers will not at present warrant the use of blends of these biofuels beyond 5%. Development is underway of an alternative near-term processing route to existing post-refinery blending, with the potential to address both of these issues to some extent. This is the introduction of biomass material into conventional mineral oil refinery processes, to produce fuels that perform very similarly to conventional fuels. Research and development activity on this option to date has focussed on rapeseed oil and other vegetable oils to produce diesel. The products of this 'mainstreaming' process would be chemically indistinguishable from conventional diesel or petrol, but inputs to the process would be a mixture of mineral and bio-products.

Potentially, this could have a number of advantages. It could give many of the benefits of conventional biofuels without the cost and complication of separate fuel blending and distribution arrangements. It could avoid the current need for vehicles to be adapted to run safely on higher blends of conventional biofuels; and it would avoid the possible fuel quality concerns associated with small-scale independent production. It would also allow considerable economies of scale.

There is work to be done on assessing the viability of this option, and particularly in improving understanding of the carbon benefits and the limits to the level of biomass incorporated. In parallel, the UK Government is investigating how it might make fiscal arrangements to deal with such an input-based production technology.

A similar option exists for using bioethanol and biomethanol in the refining of petrol by converting it to ethyl tertiary-butyl ether (ETBE), a petrol extender and oxygenate. However, the UK's 20 pence per litre duty derogation for bioethanol, due to come into effect in January 2005, would not currently extend to a bioethanol component of ETBE. The Government is carrying out further work on the environmental, health and safety implications of the use of bio-ETBE as a road fuel.

In the longer term, sustainable use of biofuels will be reliant on significant cost reductions in existing production chains, or the successful introduction of more cost competitive biomass sources and production methods. Advanced biofuels, produced from potentially cheaper non-food crops, wastes and residues, have the potential to achieve this. The development of integrated gasification and gas to liquids technologies for the conversion of biomass to gaseous and liquid fuels is likely to be important in this context. In addition, there are a number of other potential biomass processing routes, such as pyrolysis (high-temperature decomposition) and anaerobic digestion by micro-organisms, with similar potential for efficient conversion of low-cost biomass feedstocks. At present, gasification and other advanced conversion technologies are at the research and demonstration stage, but are widely expected to be the dominant in the future.

There is a great deal of research into the crop-to-fuel side of biofuels production, but greater uncertainties remain on the agricultural side, particularly for more advanced biomass technologies using dedicated energy crops such as short rotation coppice, or fast-growing grasses. Profitability will be of prime importance to the agricultural sector, but there is little experience with, and information available about, wood and grass crop yields, capital and running costs, alternative markets, prices and price evolution over time. Nor is there comprehensive information about the practicalities of growing these crops on the varied types of existing agricultural land in the UK. In addition, greater understanding is required of the value chain of biofuels production, in comparison with the value chain for biomass heat and power generation. Until these factors are better understood, the adoption of energy crops would pose a considerable financial risk to the farmer.

5.6 Current support for technologies

Regional support grants for capital investment in biofuel production plants are available through the Regional Development Agencies (RDAs). It is largely a matter for the RDAs about how these are spent, but a number are interested in the regional benefits that may be provided by investment in the industry. Following the agreement for reform of the Common Agricultural Policy, payments of €45 per hectare will also be available to UK farmers growing energy crops on non set-aside land.

The Department of Trade and Industry's New and Renewable Energy programme includes biofuels projects as a priority.

As mentioned previously, a 20p/l fuel duty incentive has been in place for biodiesel since 2002 and a similar incentive will come into effect for bioethanol on 1 January 2005. Budget 2004 confirmed that the duty differentials for biodiesel and bioethanol will be maintained at 20 pence per litre until at least 2007. This incentive has prompted a rapid increase in sales of biodiesel to some two million litres per month. At this rate, Government support amounts to almost £5m per year in revenue forgone. In Budget 2004, the Government also committed to exploring with stakeholders how the use of Enhanced Capital Allowances might support investment in the most environmentally beneficial biofuels production technologies.

The UK Energy Research Centre (UKERC) will be established shortly and will provide leadership in energy research and assist in giving coherence and co-ordination to the UK energy research agenda. It will have responsibility for co-ordinating a network of environmental, engineering, economic and social scientists, and acting as the "hub" of a National Energy Research Network that links other centres of excellence, research institutes etc. In addition to its role in co-ordinating the National Energy Research Network, UKERC will also be expected to be a centre of research excellence in its own right and to undertake an interdisciplinary programme of research that underpins the quest for sustainable energy solutions. UKERC will provide a significant resource to address many of the wide-ranging and interdisciplinary issues of key importance to the development of biofuels and renewable hydrogen technologies and to the growth of a low-carbon transport economy.

5.7 EU Biofuels Directive

The 2003 EU Biofuels Directive[31] requires Member States to set indicative targets for biofuels sales for 2005 and 2010, and to introduce a specific labelling requirement at sales points for biofuel blends in excess of 5 per cent. In setting their targets, the Directive requires member states to take account of reference values set out in the Directive.

The Department for Transport published a consultation paper, 'Towards a Biofuels Strategy for the UK'[32] on implementation of the Directive in April 2004. This sought views on what more the Government might do to encourage the development and use of biofuels, and on the levels of biofuels sales targets that might be set for 2005 and 2010.

The consultation emphasised the balance to be struck between the costs of today's conventional biofuels and the benefits that they can offer, outlining some possible options for biofuels support in the UK.

The Government will continue to develop its strategy in light of consultation and the expanding area of research dedicated to biofuels and other renewable fuels. This Assessment forms part of that process, but its focus is on long term considerations, which need not necessarily be constrained by short term factors.

5.8 Air Quality

When biofuels are burned in an internal combustion engine, the process emits not only the CO_2 that was absorbed as the feedstock crop grew, but also pollutants including nitrogen oxides, hydrocarbons and particulates. Emissions of these pollutants by vehicles is subject to strict EU standards. Modern vehicles are engineered to meet these standards with standard mineral fuels, through the use of technologies such as engine management and catalytic converters. Consistency of air quality performance is assured by EU-wide standards for the crucial performance parameters of petrol and diesel.

[31] Directive 2003/30/EC
[32] www.dft.gov.uk/roads/biofuelsconsultation

Currently, biofuel blends must meet these same EU standards in order to ensure the same air quality performance. Blends available at present generally contain around 5% conventional biofuel, and meeting fuel standards does not pose a problem. Research undertaken for the Department for Transport demonstrated that current biodiesel blends of up to 5% have a negligible effect on the level of emissions from standard diesel vehicles, provided the biodiesel meets appropriate quality standards[33].

However, if higher percentage conventional biofuel blends were introduced, it might prove challenging to ensure that the resulting blended fuel could still meet existing EU fuel standards, and therefore to ensure that vehicles would meet EU emissions standards when running on such fuel.

Advanced biofuels technologies and mainstreaming refinery technologies might present a more favourable option as they could be formulated to burn cleanly in unmodified petrol or diesel engines. In any event, air quality is an issue that the Government will have to address in partnership with the fuel and vehicle industries.

5.9 The future

Some studies have estimated the impacts of a UK domestic biofuels industry, in terms of value added to the UK economy, cost to the Exchequer and rural employment. These have naturally focussed on the short term impacts, rather than the timescale considered in the Assessment. Nevertheless, it has been estimated that a large bioethanol plant might create up to 1000 jobs[34]; clearly, there is potential for economic benefit to be had from a UK biofuels industry. Realising this benefit out to the long-term future will be a challenge for both the industry and Government.

Biofuels are attractive low carbon transport fuels for many reasons, with the potential to greatly reduce transport CO_2 emissions in the long term. They can be produced from a variety of biomass material and have the significant advantage of general compatibility with existing liquid fuel infrastructures and vehicles. However, if biofuels are to become mainstream transport fuels, used on a large scale, then a number of obstacles will have to be overcome.

The ability of standard vehicles to handle existing high percentage conventional biofuels blends is currently an issue, but it is likely that this will be overcome within the short to medium term by a combination of new biofuel technologies, and technical developments in successive vehicle generations. The potential availability of biomass resources for biofuels, overall costs and other issues around biofuels production are dependent on a greater number of factors; addressing these and the uncertainty around them is likely to be a medium- to long-term challenge.

Whilst it is not possible at the present moment to identify all of potential factors relevant to the success of biofuels, a number of them, both positive and negative, are set out in Table 2.

[33] *DfT Biofuels Evaluation - Final Report of Test Programme to Evaluate Emissions Performance of Vegetable Oil Fuel on Two Light Duty Diesel Vehicles*, Ricardo PLC, 2003.(www.dft.gov.uk/stellent/groups/dft_roads/documents/page/dft_roads_027622.pdf)
[34] *The Impacts of Creating a Domestic UK Bioethanol Industry*, Ecofys UK Ltd, 2003

Factors that could encourage biofuels uptake	Factors that could hinder biofuels uptake
Economic • Overall costs of crude oil increase significantly • Feedstock costs rapidly fall • Healthy markets for biofuels co-products • Biomass crops rapidly adopted by agricultural sector • Hydrogen/infrastructure/FCV costs do not fall to viable levels	**Economic** • Hydrogen costs rapidly fall to viable levels • Costs of fuel cell vehicles rapidly fall to viable levels • Low profitability or high capital costs means agricultural sector unwilling to adopt novel biomass crops • Higher prices for crops/biomass in other markets limits supply
Technical • Advanced biofuels technologies rapidly come to maturity • The adoption of mainstream refinery technologies by oil majors • Hydrogen distribution and storage issues not resolved	**Technical** • Vehicles difficult to adapt to run on higher conventional biofuel blends • A breakthrough in battery electric vehicles makes them viable • Difficulty in guaranteeing air quality standards • Renewable biomass used more cost-effectively in heat and power production • Production of novel biomass crops proves problematic • Advanced biofuels technologies fail to be successfully proven • Poor environmental standards of some potential imports
Consumer • Agreement on, and application of, international standards. • Consistent high quality of biofuels • Public rejection of hydrogen	**Consumer** • The public not accepting of biomass refineries • Bad consumer experiences with poor quality biofuels • Public embrace hydrogen technologies
Political • The EU pushes the agenda strongly • Engagement from key global players • Pressure grows on transport sector to increase rate of CO_2 reductions • High desire to reduce dependency on imported oil • Consumer awareness of climate change increases	**Political** • Lack of international agreement on future biofuels standards • Lack of engagement from key global players • Uncertainty regarding CAP reform and effects on UK agriculture

Table 2: Factors that may help or hinder the uptake of biofuels as major transport fuels.

6. Summary and conclusions

6.1 The challenge

Reducing CO_2 emissions and improving security of supply were two of the main policy goals underpinning the Energy White Paper. Renewable hydrogen and biofuels can contribute towards both of these aims, but they are very different fuels, with different requirements for infrastructure and vehicle technologies.

The Government does not favour any one particular technology; what is important is the clean, low carbon transport outcome. Hydrogen and biofuels have been considered in this assessment because they currently look like the most promising low carbon fuel options. That is not to say that other, more cost or carbon-efficient options will not present themselves in the future; as mentioned previously, it is possible that battery technology might make a significant breakthrough and become viable as a mainstream technology. Other technologies, of which we have no knowledge at present, may also emerge.

For this reason, the Government will continue to support the development, demonstration and uptake of a variety of technologies that have the potential to meet its long term objectives.

6.2 The context

The objectives of the Energy White Paper also framed the context for the UK's energy future. Within this overall framework sits the Powering Future Vehicles strategy, which sets out the Government's policy to reduce transport air quality and CO_2 emissions with a shift to clean, low carbon transport.

The long term vision of the Powering Future Vehicles strategy is that of a very low carbon transport economy, contributing to the UK's long term aspiration to significantly reduce CO_2 emissions. The Energy White Paper described many of the other measures that will also contribute to this aspiration, noting a particular role for renewable heat and power generation. Meeting the desire for low carbon energy production will require the availability of substantial primary energy sources. E4tech's modelling of possible UK renewable resources to 2050 suggested that up to some 4000PJ of raw resource might be available by this time. The amount available to the end user will depend on the efficiencies of conversion for each individual use. As discussed in Chapters 4 and 5, large-scale use of renewable hydrogen or biofuels could require the dedication of a significant proportion of this resource.

Table 3 sets out possible UK energy use (in PJ) in 2050, excluding road transport, under the same high and low demand scenarios modelled by E4tech.

Sector	Scenario	
	WM	**GS**
Domestic	2074	1534
Service	1184	767
Non-road transport	2740	994
Industry	1296	868
Total	**7284**	**4162**

Table 3: Possible energy use in PJ in the UK in 2050 under different scenarios (without road transport)[35]

6.3 Summary

6.3.1 Vehicles

Increasing vehicle efficiency is of central importance under any future scenario. Regardless of what the fuels of the future might be, it will be crucial that they can optimise the available energy; to reduce emissions of CO_2 and air quality pollutants and also to manage energy demand. The Government will continue to encourage the use of cleaner, low carbon vehicles through its purchase grant and fiscal regimes, through supporting research and development activity, and through the pursuit of supportive activity by the EU.

Vehicle manufacturers and governments will continue to invest in hydrogen fuel cell technology for the foreseeable future. It is hoped that the steps that have been taken by the UK Government will ensure that UK industry is able to play a significant part in this. However, it is far from certain that the cost and technical barriers associated with hydrogen FCVs will be surmounted to the point where they become commercially viable. Because of the energy efficiency and zero-emission capability that they provide, the viability of a hydrogen economy will depend to some extent on the successful introduction of FCVs.

The use of increasing concentrations of conventional biofuels may require modifications to engine and fuel delivery systems, unless the input material can be processed through modified conventional refinery processes as described in section 5.5 to create fuels with identical properties to petrol and diesel. Advanced biofuels may circumvent this problem, as it might be possible to adopt processes that can yield high quality fuels that are entirely compatible with petrol and diesel, but have superior performance.

6.3.2 Fuels

Both renewable hydrogen and biofuels look promising as solutions to the low carbon transport question and it is likely that neither renewable hydrogen nor biofuels will be used in isolation. Indeed, optimal CO_2 benefits are likely to be provided by a mix of both fuels whilst conventional vehicles are still on the roads. Under any scenario, the domination of the UK fleet by hydrogen FCVs is very much a long-term prospect. In their analysis, E4tech assumed an aggressive penetration rate for FCVs, with the entire fleet being replaced by 2050. Even with such a rate, there would still be some conventional ICE vehicles in the market up until 2050, with a concomitant demand for

[35] *The Energy Review*, Performance and Innovation Unit, Cabinet Office, 2002.

suitable fuels. Biofuels could satisfy at least part of that demand, whilst delivering CO_2 savings.

Although renewable hydrogen offers many considerable benefits including CO_2 reductions, energy efficiency, air quality and diversity of supply, it remains unclear whether a hydrogen economy will develop to the extent where it dominates the transport sector. Many technical and economic hurdles must be overcome for the hydrogen economy to achieve its potential. The E4tech analysis showed that, under some circumstances, it might be possible for the UK to produce sufficient renewable electricity and biomass to generate the hydrogen required by a FCV fleet. However, such a scenario would require that a significant proportion of the UK's potential renewable resources be employed in the transport sector. As discussed in previous chapters, greatly reduced resources would therefore be available for the generation of heat and power. It is unlikely that, in the short term, this would be the most cost-efficient use of the UK's renewable resources, and, as the Tripartite report concluded, it would not generally be the most carbon-efficient use.

Renewable hydrogen generation and distribution infrastructures would be required to service end users. The optimal configuration for these remain unclear, as do the likely establishment costs.

Biofuels are already a reality on a small scale and clearly present a strong option in the short to medium term and possibly beyond. Their use can both provide direct CO_2 benefits by replacing fossil fuels and also help to develop technologies in biomass conversion and infrastructure that would be applicable to a renewable hydrogen economy. Biofuels have a significant strength in their similarity to existing liquid fuels and their potential for assimilation into existing vehicles and the fuel infrastructure; advanced biofuels in particular hold great promise. However, biofuels use is not without its problems: fuel quality, economic viability, agricultural considerations, land requirements and air quality are all closely dependent on the production processes and delivery methods employed and all will require close monitoring. As with hydrogen, there are also likely to be issues of resource availability and competition with other, possibly more carbon-efficient renewable energy demands, especially heat and power generation.

Short rotation coppice (SRC), miscanthus and other novel perennial crops look extremely promising as renewable resources for both renewable hydrogen and biofuels. But there are a number of potential problems with their growth on a significant scale. There is very limited agricultural experience of these crops and currently a lack of appetite within the farming community for growing them. Further technical developments are still required to bring the processing technologies to commercialisation.

The link between agriculture and transport fuels, and the development of a biomass and biofuels distribution system will be common to production of both conventional and advanced biofuels. Beyond these common factors, however, the technologies diverge somewhat. Conventional biofuels are produced from conventional crops, and processed using existing technologies. Advanced biofuels are likely to be produced from novel crops, requiring different agricultural practices and favouring different growing conditions. These crops would then be processed using advanced technologies. It will be important that the agricultural and processing technology differences between these two approaches are taken into consideration in managing any strategic shift between them.

Table 4 provides a brief overview of the potential fuel technology options available, their CO_2 benefits and other impacts.

	Time of introduction	Estimated WTT CO2 emissions[1]	Resource Costs	Prospective Consumer Cost[2]	Other impacts
Conventional biofuels technologies	Current	Potentially low to medium, but vary widely depending on inputs and technology used (waste oil – 1.9-16.1 kg/GJ; sugar beet – 30-90kg/GJ)	Medium. From waste oils to high-grade food crops. Dependent on value of co-products	Medium (3-7p/km)	- Biodiversity questions. - Landscape impacts? - Land use for fuels vs heat/power? - Benefits to rural econom y? - Imports required? - Quality issues?
Advanced biofuels technologies	From 2010 - 2020?	Potentially very low to medium, but vary widely depending on inputs and technology used (FT-diesel from SRC – 2.4-29kg/GJ; Bioethanol from SRC – 4-90 kg/GJ)	Could be low from SRC or wastes. Dependent on value of co-products.	Low to medium (2-5p/km)	- Use for fuels vs. heat and power? - Agricultural uncertainty? - Water requirements? - Landscape impacts? - Winter harvesting problems? - Benefits to rural economy? - Imports required? - Quality issues?
Hydrogen (renewable electricity)	From 2020-2030? Electrolysis technology available today	Potentially very low; dependent on source, and hydrogen transport.	Strongly dependent on cost of renewable electricity	Low to high (1.8-14p/km)[3]	- Sufficient renewable electricity? - Landscape impacts? - Imports required? - Significant local air quality benefits.
Hydrogen (biomass)	From 2020 - 2030?	Potentially very low to medium; dependent on feedstock and transport.	Dependent on price of feedstock – could be low from SRC or wastes. Also dependent on value of co-products	Low (1.2-1.4p/km)[4]	- Use for transport vs. heat and power? - Agricultural uncertainty? - Water requirements? - Winter harvesting problems? - Benefits to rural economy? - Imports required? - Significant local air quality benefits.

[1]Where quoted, figures are in kg CO_2 equivalent per GJ of fuel produced
[2]Prospective end-user costs per km driven, excluding taxation, co-products value and subsidies
[3]Based on hydrogen use in FCVs
[4]Based on hydrogen use in FCVs

Table 4: Matrix of low carbon fuel options: timescale, CO_2 emissions, cost and other impacts (figures taken from E4tech analysis).

Current estimates of costs for both renewable hydrogen and biofuels are in terms of wide ranges, reflecting not only the diversity of biomass sources, processing technologies, energy inputs and GHG allocation methodologies, but also the uncertainty in the future availability of feedstocks and other inputs, efficiencies of conversion, cost of enabling technologies and demand for the fuel and co-products. Changes in each of these factors might have significant bearing on the final product cost and hence its financial viability. As UK and international experience builds, these uncertainties and hence the cost ranges should decrease. It will therefore be important for the Government to monitor these costs, to ensure that analysis can be based on current values and that valid comparisons can be made with carbon-abatement costs and efficiencies in other sectors.

Overall, it is possible that transport will become more expensive in the future – future hydrogen costs could be around 50% higher than current fossil fuels and biofuels could be around two to three times higher. In the long term, as oil reserves fall significantly, it is possible that the price of oil will increase, perhaps to the point where it is equivalent to the price of renewable hydrogen and biofuels. At this stage, there would be a much greater incentive for consumers to adopt these fuels and it is possible that additional Governmental support would not be necessary. In addition, were FCVs to achieve efficiencies towards the upper end of the predicted ranges, this efficiency benefit over other vehicle types might offset to some extent the extra fuel cost.

6.3.3 Key uncertainties

Throughout the Assessment, a number of areas of uncertainty have been identified, where greater understanding is likely to be important in making future policy decisions. The UK Government will consider how best to develop this understanding by commissioning research, participating in partnerships with industry or other Governments, or by monitoring existing activity in the UK or abroad. The uncertainties are summarised in Table 5.

Uncertainty	Description
The most cost- and carbon-efficient means of generating and distributing hydrogen	There are many different options for renewably generating hydrogen and distributing that hydrogen to end-users. Different options will all have different economic, social, environmental and safety implications. Greater understanding of these implications will be important in making sound decisions about which option, or options, might be adopted.
The future consumer cost of FCVs	The consumer cost of FCVs will be a significant factor in their viability and, to an extent, that of renewable hydrogen as a transport fuel. Vehicle manufacturers are confident of reducing costs considerably, to the point where FCVs would be roughly competitive with ICEs, but it remains to be seen how quickly this can be achieved.
Future consumer costs of renewable hydrogen	The E4tech analysis set out a range of possible costs for renewable hydrogen. Eventual consumer costs will be dependent on a large number of factors, including the costs of plant, renewable electricity, biomass and distribution, competition for these resources
Future consumer costs of biofuels	Future costs of biofuels will be influenced by similar factors to those affecting renewable hydrogen, but, as biofuels are entirely reliant on biomass and other organic material as feedstocks, their costs will be even more closely linked to the market price of these commodities, and values of co- and by-products

Advanced biomass conversion technologies	Advanced biofuels technologies are entirely reliant on the successful development of processing technologies to convert the biomass material to useful fuel. The E4tech analysis suggested that biomass might be the most economic source of renewable hydrogen, so that too is reliant on these technologies, though to a lesser extent. A number of research, development and demonstration projects are currently underway to try to prove the relevant technologies. These, and more like them will be important in developing technologies to the stage where their viability can be thoroughly assessed.
Environmental impacts of large-scale growing of novel energy crops	Although a great deal is known about conventional crop growing, it is less clear what the impacts might be of growing novel crops on a significant scale, particularly if there will be additional demand for biomass for heat and power generation.
Environmental benefits of imports	In a future global market in renewable hydrogen, renewable electricity, biomass or biofuels, it will be vital for the UK's climate change goals that the expected CO_2 savings from such commodities are realised. Equally, it will be important that the production of these commodities does not lead to other negative effects, in accordance with the principles of sustainable development.
Land availability for growing biomass crops	There is currently much disagreement about the amount of land that might be available, and suitable, for growing biomass crops. Part of this disagreement stems from the lack of comprehensive data about soil type, topography, local climate etc. across the UK.
Future economic benefits of UK biofuels industry	It is clear that there could be economic benefits from a future biofuels industry. However, the scale and distribution of these benefits is unclear, resting as it does on a host of interrelating and external factors, such as the siting of biomass crops and biofuels plants, the level of imports, the development of advanced biofuels technologies, the future price of biofuels and so on.
Air quality impacts	The use of increasing levels of conventional biofuel blends, and even advanced biofuels, may impact on vehicle air quality emissions. The Government will need to continue to monitor any air quality impacts and engage with industry to implement appropriate solutions as required.
Emergence of competing technologies	Although renewable hydrogen and biofuels appear the best options for ultra-low carbon road transport at present, it is possible that alternatives will be developed in the period between now and 2050. Battery technology has already been mentioned as a possibility, but there may well be others which have not yet emerged. It will be important for Government and industry to remain open to such alternatives and alert to technological developments.
UK's strategic framework for renewable energy use	This Assessment has clearly highlighted the importance of the relative economic costs and carbon balances of the numerous different options for the use of the UK's renewable resources. Rigorous analysis of these costs and benefits will be required. Moreover, it will be for Government to draw on such analyses and set a strategic framework for use of UK renewable energy resources and the part the transport will play within that.

Table 5: Key uncertainties in the development of renewable hydrogen and biofuels towards large-scale transport use

6.4 Conclusions

From these academic studies, other published reports and stakeholder input, the following broad conclusions are reached:

- It would be possible, by 2050, to reduce total carbon emissions from road transport to very low levels, through significant use of renewable hydrogen or biofuels. This could help the UK to achieve its goal to reduce CO_2 emissions by 60% by 2050.

- Improvements in vehicle efficiency will be essential, but may not be sufficient in themselves to achieve very large carbon savings;

- It is not certain that a hydrogen economy will ever be realised. If it is, the UK could produce enough renewable hydrogen for road transport, but at the expense of renewable energy resource for other sectors.

- If the road transport fleet were fuelled entirely with biofuels by 2050, the UK could grow about one third of the necessary biomass; the rest would have to be imported.

- Both renewable hydrogen and biofuels are likely to be more expensive than today's fuels. But the increased efficiency of hydrogen fuel cell vehicles means that the per km costs of these vehicles could be roughly similar to today's vehicles.

- The large-scale use of either fuel would have numerous local environment, social and economic impacts (positive and negative), all of which would benefit from greater study.