# Liquid biofuels and hydrogen from renewable resources in the UK to 2050: a technical analysis

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

carried out for the
**UK Department for Transport**

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# 1 This study

This study has been carried out for the Department for Transport as part of a wider analysis of renewable fuels in the UK. It has been produced by E4tech (UK) Ltd. and does not necessarily represent the views of the Department.

## 1.1 Background

The Energy White Paper (DTI et al., (2003)) identified renewable transport fuels such as hydrogen and biofuels as a potentially important part of meeting greenhouse gas reduction commitments over the long term. The White Paper indicated that Government would produce an assessment of the overall energy implications of a hydrogen economy, and of large-scale use of biomass-based fuels, and develop road maps for the possible transition to these fuels.

As part of this process, the Department for Transport commissioned E4tech, a specialist energy-environment consultancy, to conduct modelling and produce a report to inform this assessment. This report examines the energy and $CO_2$ implications of the use of renewable transport fuel – primarily liquid biofuels and gaseous hydrogen – fuelling the UK fleet under aggressive penetration scenarios. The timescale of the analysis is to 2050, to match the vision of the Energy White Paper.

## 1.2 Caveat

The analysis has been conducted primarily using data from previous studies, but has developed new models for the purpose. Broad assumptions are used throughout, as the purpose is not to *predict* uptake of alternative fuels or vehicles in the UK, nor to *prescribe* the optimal renewable routes to fuel production, but to assess the implications of a large-scale move, *should it be attempted.* Although costs are indicated wherever possible, the timescale to 2050 means that uncertainties are considerable and so all data must be considered in this light.

## 1.3 Introduction to the analysis

The analysis has 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.

The modelling is described in detail in chapter 3 and chapter 4, in which renewable hydrogen and biofuels are modelled, respectively. However, the analysis follows demand scenarios developed in Eyre et al., (2002) for vehicle kilometres driven in the UK to 2050. This analysis is discussed in Annex 1.

Assumptions are then made regarding possible penetration rates of alternative fuel vehicles, their efficiency relative to conventional vehicles, and possible penetration of advanced vehicles using conventional fuels. The latter are used to provide a base case for the analysis.

The allocation of resources is done simply on the basis of quantity and availability over the time period. Because of the high uncertainties regarding costs and technology development, resources are not allocated using a market modelling mechanism. Overall renewable resources in 2050 are also unclear, but model data have been based on a range of previous analyses.

All fuel cost figures in this report, with the exception of current ones, are necessarily speculative. We have based our figures on published reports, including a small profit margin, and excluded tax in all cases. In addition, this study has set out to include the costs of fuels, but not of new technologies. Costs of hybrid vehicles, fuel cell vehicles and other developments are clearly relevant to the future direction of transport, but would only confuse the picture in this assessment.

### 1.4 The process

This analysis is part of a larger piece of work being conducted on future transport fuels by the Department for Transport, much of which can be found online at:

http://www.dti.gov.uk/energy/sepn/futuretransport.shtml

Stakeholder feedback and peer review has formed an important part of the process, both from a workshop and discussions, and the authors would like to thank all the companies and individuals who have taken the time to comment and contribute. As ever, the work here is the responsibility of the authors alone, and does not necessarily represent the views of the Department for Transport.

# 2 Current transport fuels and technologies

- The current transport energy mix is dominated by petrol and diesel, though lower emission alternatives are now entering. Vehicle propulsion technologies are dominated by the internal combustion engine.
- Looking forward, there are a variety of fuel and vehicle technology options which are expected to contribute to significantly reduced vehicle emissions in the coming two decades. These include hybridisation, exhaust gas cleanup and fuel reformulation. They have the potential to make air quality remain a problem in only a limited number of urban 'hotspots'.
- The significant fall in regulated pollutants could be accompanied by strong improvement in fuel efficiency on a per vehicle basis (approximately 45% better compared to 2003 passenger cars), and hence reductions in $CO_2$ emissions. However, this benefit would be outweighed over the longer run by increases in vehicle miles.
- Even with an aggressive penetration of such high efficiency vehicles from today, total $CO_2$ would return to levels similar to today in the period between 2020 and 2050.
- If significant reductions in road transport $CO_2$ are sought, then biofuels and renewably generated hydrogen are two key options which could be pursued. Despite the probable slow uptake of such options, they could lead to very low $CO_2$ emissions from the transport sector in the very long run.
- Biofuels and renewable hydrogen can be produced via a variety of routes. In order to test the limits of large-scale adoption of such fuels, this report uses extreme scenarios and examines their primary resource and $CO_2$ implications for the UK.

Road transport in the UK and elsewhere relies almost exclusively (~98%) on oil for energy. This results in significant emissions of greenhouse gases, which are rising as a function of an increased vehicle fleet and higher annual mileage. Although different grades of fuel are available, almost all fuel used in the UK is either petrol or diesel. Alternative fuels occupy only a small portion of the market (1-2%).

## 2.1 Current fuels and technologies

The main fuels in current use are petrol, diesel, compressed or liquefied natural gas (CNG and LNG) and liquefied petroleum gas (LPG). A small amount of biodiesel is blended with diesel. Hybrid-electric vehicles, using conventional fuels but with highly efficient powertrains, are also available and make up a small proportion of the UK market. A further small number of vehicles are battery-electric (BEV).

The production and use of fuels for road transport leads to emissions that have effects on the local, regional and global environment, impacts on human health and can cause other environmental damage. Table 1 gives a brief summary.

*Table 1: Road transport emissions, production and impacts*

| Emission | Production | Effect |
|---|---|---|
| Carbon dioxide ($CO_2$) | Combustion of hydrocarbon fuels | Global effect - greenhouse gas (GhG) |
| **Regulated pollutants** | | |
| Particulate matter (PM) | Incomplete combustion of hydrocarbon fuels, impurities within the fuels. | Local air pollutant - carcinogenic, linked with respiratory disease |
| Oxides of nitrogen (NOx) | Formed in the high-temperature fuel combustion process from nitrogen in air | Local air pollutants - linked with respiratory disease. Precursor of acid deposition which causes ecosystem damage, damage to buildings. Some GhG effect |
| Sulphur dioxide ($SO_2$) | Combustion of sulphur in the fuel | Local air pollutant – exacerbates respiratory disease. Precursor of acid deposition which causes ecosystem damage, damage to buildings |
| Hydrocarbons (HCs) | Incomplete combustion of hydrocarbon fuels | Local air pollutants - can be carcinogenic or mutagenic. Methane is a GhG |
| Carbon monoxide (CO) | Incomplete combustion of hydrocarbon fuels | Local air pollutant – exacerbates respiratory disease. |

For each fuel, a brief summary of current status is given below.

### 2.1.1 Petrol

**Production:** No worldwide standard exists for petrol, though petrol now sold at the pump is almost a homogeneous product. However, low-sulphur blends, high-performance blends and formulations including detergent are all available.

**Use and availability:** Petrol is the most common fuel for light vehicles in the UK, with petrol vehicles making up 79% of cars and light goods vehicles in circulation, and nearly all motorcycles, scooters and mopeds.

**Cost**: the pre-tax price of petrol at the pump is around 18 pence per litre. The pump price of petrol is related to several factors including the price of crude oil; this price corresponds with an oil price of around \$25 per barrel. As a guide, a \$2 per barrel increase in the crude price will lead to a 1p/litre petrol price increase at a constant exchange rate.

**Emissions:** The average $CO_2$ emissions of a new petrol engine car in 2002 were 178 g/km. This is higher than for any other fuel, but has decreased by 6% over the last five years (SMMT, 2003). Many modifications to the internal combustion engine, including variable valve timing, multi-valve cylinder heads, lean-burn closed loop control, direct petrol injection and electronic engine management have reduced emissions and increased efficiency. Reductions in local pollutant emissions from petrol vehicles since the 1970s have been considerable, and progress is still being made, with continually tightening European standards for petrol and diesel illustrated in Figure 1. 'End-of-pipe' emissions reduction technologies, including catalytic converters, are highly sophisticated and under intensive development.

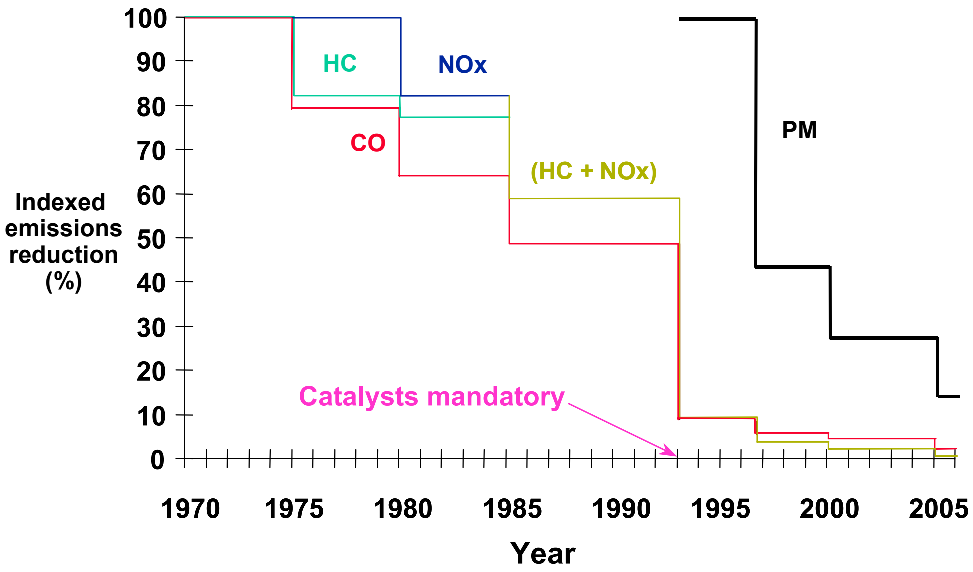

*Figure 1: Evolution of EU petrol and diesel emissions standards for light duty vehicles*

### 2.1.2 Diesel

**Production:** Like petrol, diesel is a broadly homogenous product, though recently there has been more emphasis on its development, as a result of increased use in the car market.

**Use and availability:** Diesel is the predominant fuel for heavy vehicles, including lorries and buses, and fuels around 20% of light vehicles. In 2002 diesel penetration of the UK new car market reached 23.5% (SMMT, 2003), and this is expected to continue to increase, potentially to 30% by 2004 and possibly 40% by 2008 if the current tax regime is maintained.

**Cost**: The pre-tax price of diesel at the pump is around 20 pence per litre. The price of diesel also varies with the underlying price of crude oil, though varies less than the petrol price. The price above again corresponds with an oil price of around $25 per barrel.

**Emissions:** $CO_2$ emissions from diesel vehicles are lower than those from equivalent petrol vehicles, thanks to a more efficient combustion process. In 2002, the average $CO_2$ emissions for a new diesel car were 162 g/km – a decrease of 13% over the last five years. However, emissions of local air pollutants such as $NO_x$ and particulates are higher for diesel vehicles than for petrol. These can be reduced by exhaust gas catalysis, and in larger vehicles by technologies such as particulate traps and $NO_x$ scrubbing. Low sulphur diesel (<50ppm) is essential to prevent poisoning of the exhaust catalyst.

### 2.1.3 LPG

**Production:** LPG consists of a mixture of hydrocarbons, primarily propane and butane, with some propylene and butylenes. The gas is a by-product of oil and gas extraction, and of oil refining. LPG is gaseous at standard temperature and pressure, but can be liquefied at pressures of 6-8 bar, and is normally stored and transported in liquid form.

**Use:** LPG can be used in modified petrol or diesel engines. LPG is most popular for cars and light vans, either with dedicated LPG engines, or through retrofitting of conventional (usually petrol) engines. Bi-fuel vehicles that carry petrol and LPG and can switch between them are also available.

**Availability:** Many LPG vehicles are in use worldwide, though the amount is still small in comparison with conventional fuels. 800,000 vehicles run on LPG in Italy, and more than 500,000 in Japan, where taxis are often converted to use the gas. In the UK, LPG is now available nationwide, with over 1,300 refuelling points, and around 100,000 LPG cars are in use in the UK.

**Emissions** of regulated pollutants from LPG are comparable to a petrol engine conforming to Euro 4 standards. However, the best results are usually derived from the use of dedicated LPG engines, as a poor retrofit to a conventional engine can actually cause emissions to rise. $CO_2$ emissions of LPG vehicles are generally around 10-15% lower, but can be up to 30% lower than Euro IV standard petrol vehicles. However, there are negligible $CO_2$ emissions benefits when compared with diesel. $CO_2$ emissions from dedicated LPG vehicles are expected to decrease by 8-10% with improved vehicle technology.

**Cost:** A litre of LPG costs around 29.5/litre. However, a litre of LPG allows a vehicle to travel only 80% of the distance it could travel on a litre of petrol. Using LPG therefore saves around 40% of fuel costs. The cost of converting a petrol car to run on LPG is around £1,500, and the premium for a new LPG vehicle between £1,500 and £2,000, before Powershift grants.

### 2.1.4 CNG/LNG

**Production:** Natural gas (NG) is primarily composed of methane, with the amount varying with different geographies and NG sources, from 80% to 95% by volume. Other main constituents can include ethane, nitrogen and $CO_2$. NG is gaseous at standard temperature and pressure, and is used in vehicles in compressed or liquefied form. Methane can also be produced from biomass sources, when it is commonly called biogas or biomethane.

**Use:** Compressed natural gas (CNG) can be used in converted spark ignition engines with small modifications to engine timing and fuel injection. A narrow range of OEM-produced engines and vehicles is also available. NG engines can be dedicated for NG alone, bi-fuel petrol/NG where either fuel may be used, or dual fuel where compression ignition occurs using a small quantity of diesel fuel as a pilot to burn NG. Liquefied natural gas (LNG) is used as an alternative to CNG, in part because it requires less storage volume, and also because the liquefaction process removes many of the impurities present in natural gas. This can provide both better vehicle range and fuel combustion characteristics.

**Availability:** More than 1 million CNG vehicles are in use worldwide, with a large number operating in Italy and in Argentina. There are around 850 NG vehicles in the UK, both dedicated vehicles and conversions. Bi-fuel vehicles, which can switch between petrol and NG operation, and dual fuel vehicles, running on a mixture of diesel and NG are also available. Although there is not a very high penetration of LNG vehicles into the global parc, it is considered a good fuel for heavy-duty vehicles and some long-distance haulage vehicles use LNG, in addition to its use in a number of refuse vehicle fleets. The majority of NG vehicles in the UK are heavy vehicles such as lorries and buses, generally with a refuelling point at the depot. There are also around 20 CNG and 8 LNG refuelling stations with public access in the UK.

**Emissions:** NG engines have low PM emissions; NOx emissions are around 80% lower than diesel; CO emissions around 75% lower than petrol or diesel and non-methane hydrocarbon emissions are very low. However, emissions of methane itself tend to be higher, as it can escape complete combustion and pass through the engine. $CO_2$ emission from NG vehicles are very similar to those of equivalent diesel vehicles. It is argued that NG engines are significantly less developed and so have more room for improvement. Emissions from LNG vehicles are similar to those from CNG vehicles, though fuel cycle emissions of $CO_2$ may be slightly higher than from CNG, as additional energy is required to liquefy the gas. NG engines also tend to be 50-75% quieter than diesel engines as they are spark-ignition and not compression ignition engines. The use of biomethane can bring significant fuel cycle $CO_2$ emissions reductions in comparison with NG.

The **cost** of LNG and CNG is around 41 p/kg,. This is equivalent to around 28 pence per litre of petrol equivalent. The additional cost of buying a new dedicated natural gas truck can be between £20,000 and £40,000, or about £3-4,000 for cars and vans. Converting an existing heavy-duty vehicle to bi-fuel may cost between £10,000 and £25,000.

### 2.1.5 Biodiesel blended with diesel

**Production:** Biodiesel is currently produced by esterification of oil-rich crops such as rapeseed, or waste oils. A very small amount (around 5.4 Ml/year) is currently produced in the UK from waste oils, but new capacity coming on stream in 2004 will bring the total to 230 Ml/yr. Production in the EU has grown strongly to 3 Bl/year, predominantly in Germany.

**Use:** Biodiesel can be used without blending, but this would result in loss of engine performance, and require new infrastructure. Therefore it is most commonly used as a blend. Blends of up to 20% may be able to be used in almost all diesel engines and are compatible with most storage and distribution equipment, however blends of up to 5% are all that is sanctioned by the motor manufacturers at present. Biodiesel is an oxygenate, and therefore blending can actually improve engine performance.

**Availability:** 5% biodiesel blends are available from around 110 sites in the UK, with 20% blends and 95-100% blends also available from a very small number of sites.

**Emissions** from biodiesel blends are generally slightly lower than from diesel, except for NOx emissions, which can be slightly higher than for ultra-low sulphur diesel (ULSD). Improved engine performance leads to lower emissions of particulates.

The current production **cost** of biodiesel is around 44p/l, and it is eligible for a 20p/l fuel duty reduction under current transport fuel taxation policy (Woods and Bauen, (2003)).

### 2.1.6 Ethanol blended with petrol

**Production:** Bioethanol is produced commercially from the fermentation of sugar and hydrolysis of starch crops such as sugarcane, corn, sugar beet and wheat. There is currently no bioethanol for fuel production in the UK.

**Use:** Large quantities of bioethanol for blending with petrol are produced in Brazil and the US. Total bioethanol for fuel production was approximately 25.5 Bl/yr in 2002. The largest producers are Brazil with about 12.5 Bl/yr, the US with about 8 Bl/yr and the EU with about 2.2 Bl/yr (2001). Bioethanol is usually blended with petrol. The share of bioethanol is generally below 5%, but blends in Brazil contain 20 to 24% ethanol. Flexible fuel vehicles (FFVs) are commercially available that accept variable bioethanol blends. Bioethanol can also be used neat (generally in hydrous form, containing 2-3% water) in dedicated engines. ETBE is used as an octane enhancer in a number of countries, such as the US, France and Spain.

**Availability:** Bioethanol fuel, blended or neat, is currently not available in the UK.

**Emissions** from bioethanol blends are generally slightly lower than from petrol, except for NOx emissions, which may be slightly higher because of the higher combustion temperature of oxygenated fuels. Hydrocarbon evaporation from the fuel system may be higher with ethanol blends. ETBE is also increasingly used as an octane enhancer in the place of MTBE, which is a reason of concern because of its toxicity.

### 2.1.7 Battery-electric

**Production:** Battery electric vehicles (BEVs) use electricity from the grid to recharge batteries on board.

**Use and availability:** Few BEVs have been successfully introduced worldwide. A common problem is that battery technology has not advanced as much as was once anticipated, and BEVs thus suffer from severely diminished range in comparison with conventional vehicles. They are therefore most suitable for city based cars and vans with set routes, and there have been trials in buses.

**Emissions:** Because no combustion process takes place and there are few moving parts, BEVs are quiet and on-board emissions of all pollutants are zero. However, emissions do arise from the electricity generated to charge the vehicles, both of regulated pollutants and of greenhouse gases. These emissions depend heavily on the source of the electricity (though partly on the vehicle drive-cycle).

**Costs:** The few available BEVs cost approximately £5,000 more than the petrol equivalent, before Powershift grants. Batteries are often leased, rather than purchased outright, at a cost of around £60-100 per month. Running costs are estimated to be about a tenth of those of petrol vehicles, at around 1 p/mile.

### 2.1.8 Hybrid-electric

**Production**: Hybrids employ an engine and batteries in a variety of configurations to drive the vehicle. They are refuelled with petrol or diesel, though some other fuels/engines have been proposed. Hybrids offer the opportunity to operate the engine at constant load close to its most efficient point, enabling greater efficiency. They may also be able to run on batteries alone, offering zero emissions at point of use. There are two main approaches: series hybrids in which the engine/alternator acts solely as a charger for the batteries which in turn drive electric motors; and parallel hybrids in which engine and/or electric drive can be applied.

**Use and availability**: Hybrid vehicles have only recently been introduced commercially, however, their use is expected to increase as their performance approaches that of conventional engine vehicles and efficiency improves further. Experimental heavy duty vehicle hybrids have been demonstrated, but the main focus is light duty vehicles at present.

**Emissions**: Hybrids offer lower emissions of $CO_2$ and other pollutants, compared to equivalent performance vehicles. The most efficient vehicle on sale in the UK is a hybrid – the Honda Insight - that emits 80g of $CO_2$/km – less than half of the UK average.

**Costs**: Only three hybrid models are currently on sale in the UK costing £3000-4000 more than their petrol equivalent. They qualify for Powershift grants and congestion-charging exemption making them broadly competitive with conventional vehicles, though the driving experience is not completely equivalent.

### 2.1.9 Summary

*Table 2 Characteristics of current conventional and alternative fuels and technologies*

| **Fuel** | **Carbon content [g C/MJ]** | **Well-to-wheels $CO_2$ emissions** | **Local pollutant emissions** | **Availability (UK)** | **Suitability** |
|---|---|---|---|---|---|
| ***Petrol (Euro III)*** | ***18.9*** | ***Baseline for fuels below*** | ***Baseline for fuels below*** | ***Widespread*** | ***Light vehicles*** |
| **LPG** | 17.2 | 10-15% lower<br>25-30% for dedicated vehicles | 20-30% lower NOx | 1300 sites | Light vehicles |
| **Bioethanol** | | ~3% lower | Marginally reduced CO emissions, increased NOx | Nil | Light vehicles |
| **Battery** | zero | As electricity generation | As electricity generation | Generally at owner site | Light vehicles |
| **Hybrid** | As petrol/ diesel | 42% reduction (for new Toyota Prius) | 90% reduction in CO, HC and NOx (for new Toyota Prius) | Widespread | All vehicles |
| ***Diesel (Euro III)*** | ***20.2*** | ***Baseline for fuels below*** *10-20% lower than petrol* | ***Baseline for fuels below*** *Higher PM and NOx than petrol* | ***Widespread*** | ***All vehicles*** |
| **CNG** | 15.3 | ~7% lower | 10-15% lower NOx, small CO reduction | Depots plus 20 public sites | All vehicles |
| **LNG** | 15.3 | ~10% higher | 10-15% lower NOx, small CO reduction | 8 sites | All vehicles |
| **Biodiesel 5% blend** | | ~2.5% lower | Marginal increase in NOx, decrease in PM and CO | 110 sites | All vehicles |

## 2.2 Prospects for improvements in petrol and diesel vehicles

Internal combustion engine technology has improved massively since its introduction in the late 19th Century. Improvements are still being made, but these are now more incremental than revolutionary. However, increased use of advanced electronic controls and hybridisation of vehicles will continue to improve ICEs, though trade-offs between vehicle performance (e.g. top speed) and efficiency may be necessary. Some additional improvements in emissions reductions can be obtained from developments in exhaust gas clean up technology and fuel reformulation.

### 2.2.1 Engine and vehicle technology changes

A wide range of electronic control technologies, multiple valves and improved internal combustion engines (ICE) designs have improved power output, efficiency and emissions performance of ICEs, and will continue to do so. Some of these benefits have been counteracted by a continuing trend towards increasing vehicle weight, though this has been projected to slow, and potentially decrease after 2015 (Owen and Gordon, (2003)).

However, these improvements are incremental and have only a limited impact on the $CO_2$ emissions of the total vehicle parc. Hybridisation of ICE vehicles could have a more significant impact, as it can greatly improve efficiency over a drive cycle, while using a conventional fuel infrastructure.

A study carried out by Ricardo (Owen and Gordon, (2003)) gives a detailed analysis of possible pathways from conventional fuels to the use of hydrogen in mid-range cars. The analysis includes industry input on future weight, efficiency, power and other options for conventional cars, and the potential for fuel cell cars. Results suggest that very significant benefits – of up to a 50% reduction in $CO_2$ emissions – can be obtained from improvements in conventional vehicles. These include downsizing, lightweighting, aerodynamic improvements and engine design improvements. A major component of this gain is the use of hybridisation to improve drive cycle efficiency.

### 2.2.2 Hybridisation

Hybrid electric vehicles use an energy storage device (usually a battery) and electric motor as well as the internal combustion engine. A variety of classifications of hybrid vehicle exist, but the most relevant in this case are those that can shut off the engine when stationary (e.g. at traffic lights), can use regenerative braking and can use a smaller internal combustion engine than in a conventional vehicle of similar performance. These are sometimes termed ‘mild’ hybrids. A ‘full’ hybrid can also drive on only electric power, for example to allow zero emissions in urban areas.

As suggested by Ricardo, the introduction of hybrids into the passenger car sector, with additional vehicle weight reductions, could improve efficiency by up to 50% in certain vehicle sectors in the UK, and reduce $CO_2$ emissions by a related amount, if the type of fuel used is kept constant[1]. These vehicles will inevitably be slightly more expensive (about 10% is estimated) than conventional vehicles, as they have two sets of some components.

Having achieved such an efficiency gain, however, further improvement becomes very difficult. Lightweight materials, better aerodynamics and other vehicle body and chassis refinements can help, but benefits will continue to be incremental. Meanwhile, vehicle kilometres (vkm) are rising, and this trend seems likely to continue, negating much of the benefits from improved vehicle efficiency.

### 2.2.3 Exhaust gas clean up technology

This is in continual development, to achieve demanding EU emissions standards at the lowest possible cost. For petrol vehicles, the principal technology is the three way catalyst, which reduces emissions of hydrocarbons, CO and NO. Technologies being

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[1] Different fuels (e.g. petrol, CNG) have different carbon content and so the efficiency gain and $CO_2$ reduction will differ if fuel switching takes place.

introduced for diesel vehicles include continuously regenerating particle traps and, potentially, selective catalytic reduction of $NO_x$ using urea.

These technologies are expected to lead to considerable reductions in exhaust emissions, to the point where regulated emissions reductions are no longer one of the primary drivers for alternative fuels. EU Auto Oil programme projections suggest that by 2015 emissions of all regulated pollutants will have fallen to below 20% of their 1990 levels.

However, zones of poor airflow, especially in cities, mean even lower emissions levels are required if local air quality standards are not to be exceeded. In addition, many emissions (e.g. formaldehyde, benzo(a)pyrene) are currently unregulated and might still be of concern (Lloyd, (2000)). Alternative fuels and enhanced clean-up technologies are therefore still of interest for air quality.

### 2.2.4 Fuel reformulation

To reduce regulated pollutant emissions, fuel composition can be changed by reformulation. Methods include oxygenation, desulphurisation and blending with alcohols.

**Petrol**. Oxygenation involves increasing the oxygen proportion of the fuel to improve its combustion properties, leading to reductions in emissions of HC and CO. Oxygenates include additives such as ethyl tertiary butyl ether (ETBE), commonly made from ethanol. Blends of petrol and ethanol or methanol, with alcohol ratios ranging between 5% and 85%, have also been used, with some success in reducing emissions. Desulphurisation improves exhaust catalysis, and reduces $SO_2$ and particulate emissions. From 2005, all petrol in the EU must have below 50 ppm sulphur, though in the UK the majority of petrol already meets this specification.

**Diesel**. Methods include desulphurisation and blends with biodiesel. As for petrol, sulphur levels in diesel have been reduced significantly to allow improved exhaust gas catalysis.

### 2.2.5 Summary and comments

If all of the improvements mentioned above were introduced into the vehicle fleet, the emissions of regulated pollutants would be at a level where many sources other than vehicles would play a major part in causing air quality problems. Some pollution ‘hotspots’ caused by poor airflow or unusual microclimatic conditions would continue to exist, but the majority of vehicles would not be significant contributors.

From a $CO_2$ perspective the picture is different. Figure 2 below, projected to 2050, indicates that even with an aggressive introduction of high efficiency vehicles (HEVs) emitting 45% less $CO_2$ than 2003 vehicles into the UK vehicle stock, emissions only dip slightly around 2020. However, they then begin to rise as the number of vehicle miles travelled continues to increase. This chart follows Energy Paper 68 (EP68) projections to 2020, and then extrapolates the same trend to 2050. It should be noted that this is not a prediction, but merely serves to illustrate the limited emissions reductions available purely through efficiency measures.

On the same chart is a projection of a slower uptake of renewable fuels (via fuel cell vehicles using hydrogen) into the UK transport sector, *but without the 45% improvement in conventional technology*. These are assumed to emit zero carbon. It can be seen that the short term benefits of concentrating purely on new technologies and fuels is limited (partly by the turnover of the vehicle stock), but the long term benefits can be very great. The lowest emission option in the short term shown on the chart is immediate rapid introduction of biofuels in HEVs. Of course, in reality a compound scenario is more likely, as will be developed later in this report.

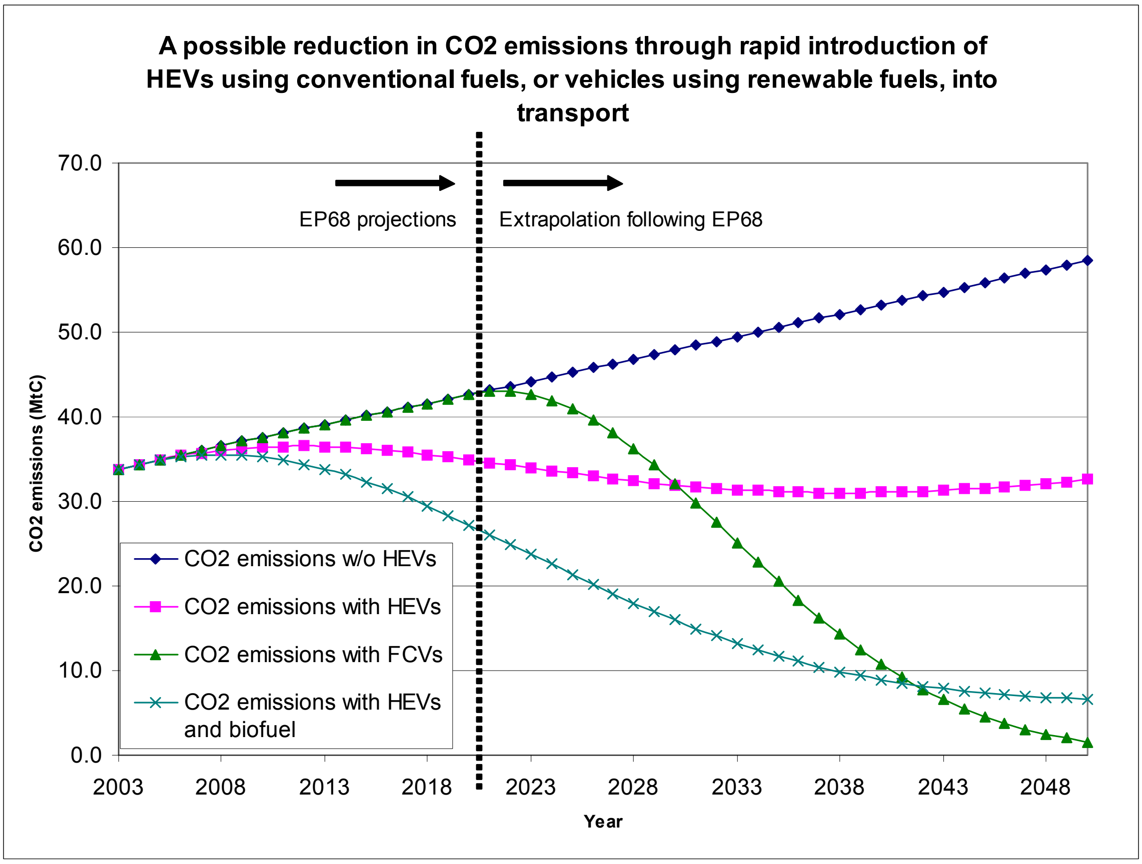

*Figure 2: Illustrative $CO_2$ emissions reductions to 2050 through introduction of HEVs using conventional fuels, HEVs using biofuels, or FCVs using renewable hydrogen*

Note: The projections shown here are purely illustrative of the difference between technology improvement and fuel switching. In practice, neither will happen in isolation.

If transport emissions of greenhouse gases are to be reduced significantly, it appears that improved conventional technologies will be an important part of the development, but that fuel switching will be essential.

## 2.3 Future fuels

The summarised information above suggests strongly that an aggressive introduction of alternative fuels into the UK transport fleet may be required to meet long-term policy targets on $CO_2$ emissions. The alternative fuels described above, with the exception of renewable electricity in BEVs, cannot offer the substantial $CO_2$ reductions required, while BEVs still require major technical development in batteries if they are to become successful in a wide market. These have not so far been forthcoming, and several automotive manufacturers have stopped developing BEVs. Other factors must also be considered with respect to future fuels, and all of these are summarised below:

**Deeper cuts in carbon emissions.** The progressive reductions in $CO_2$ emissions described above are unlikely to be sufficient to achieve long-term reduction goals, especially given projected increases in global vehicle numbers and distance travelled. Whilst technologies such as HEVs could give significant emissions reductions, there is a limit to these improvements when the fuel itself is a high-carbon content fossil fuel.

**Diversity and security of supply.** All of the main alternative fuels listed are derived from oil and gas. Unreliable supply is a risk in the short term, as a possible result of geopolitical instability, terrorism, major technical problems or extreme weather conditions, and potentially in the long term, as the UK becomes a net importer of energy over the next two decades. It is for these reasons that the Energy White Paper stresses the importance of using a diverse mix of fuel types and sources. In the longer term, reserves of oil and gas will diminish, with increased scarcity and the need to exploit poorer quality unconventional reserves expected to lead to higher prices.

**Local air quality improvement and noise reduction.** Achieving local air quality targets, particularly in congested urban areas, will require considerable further reduction in emissions from road transport. Although the majority of this reduction will come from the increasingly stringent Euro standards, this may not be enough in some air quality 'hotspots'. Measures taken may also increase fuel consumption, and therefore $CO_2$ emissions. Currently unregulated emissions such as formaldehyde may become a problem in the long term.

**Fuelling new vehicle technologies**. Fuel cell vehicles, under intensive development by the major automotive manufacturers, may offer customers a new experience and hence be an attractive marketing opportunity for the automotive companies. They are, therefore, expected to be introduced at some time in the future. However, the present state-of-the-art suggests that fuel cells will require non-conventional on board energy carriers, such as hydrogen.

**Reduced environmental impact of fuel production and supply.** Consideration of the full fuel chain, from resource extraction to final use, is increasingly important. Environmental impacts at every stage of the chain must be considered and, where possible, minimised. Alternative fuel sources can help to mitigate these impacts.

Future transport solutions will have to include not only changes in vehicle technology, leading to more efficient vehicles, and demand side management measures, but also alternative transport fuels. This report focuses specifically on hydrogen and biofuels, which are considered to be the most likely long-term options for very low carbon road transport. A brief description is given below; more detail is given in Chapters 3 and 4.

***Hydrogen*** can be used in internal combustion engine vehicles, or in fuel cell vehicles, resulting in very low or zero tailpipe emissions. Hydrogen can be produced from a very wide range of sources, including fossil fuels, biomass and renewable electricity, enhancing diversity and security of energy supplies. If it is produced renewably, or with carbon sequestration, vehicles using hydrogen could have very low or zero well-to-wheels CO2 emissions. Fuel cell vehicles also have increased efficiency (lower overall energy and hence fuel requirements), much lower regulated pollutant emissions, and reduced noise compared with internal combustion engine vehicles. However, hydrogen is not currently used as a fuel outside demonstrations, and its introduction would be a major shift.

***Biofuels,*** such as bioethanol and biodiesel, are produced from biomass crops and wastes. A wide range of feedstocks can be used, including agricultural and forestry wastes, energy crops and organic municipal wastes. Biofuels can be used with existing vehicle technologies, including as blends with conventional fuels, and can therefore in most cases be easily integrated into the existing fuel infrastructure. Use of biofuels in vehicles can lead to very low carbon emissions, as the $CO_2$ released when the fuel is burned has been absorbed from the atmosphere during plant growth. However, fuel chain analysis is complex, as issues such as fertiliser energy inputs must be included. The introduction of biofuels could also help to achieve other policy goals, such as increased rural diversification and waste management.

It is important to consider the production of transport fuels in the wider context of UK energy production. Local production of transport fuels has many benefits, but the resources dedicated to this could have alternative energy uses. For example, biomass crops and wastes can be used to produce heat and power, as well as biofuels. Renewable electricity could be used to produce hydrogen, by electrolysis, or could be put directly into the electricity network. Each use will have varying levels of benefit in terms of avoided carbon emissions, avoided pollutant emissions and increased energy security.

## 2.4 Scenarios for future fuels

To understand the possible reductions in emissions brought about by the introduction of different fuels, plausible scenarios for their uptake are required. However, it is also valuable to consider extreme scenarios, to explore the boundaries of possible future solutions. Questions for consideration include whether enough renewable fuels could theoretically be produced to fuel *all* of the UK transport fleet, and what possible mix of technologies could provide this. If not, imports of renewable fuels may be equally effective.

The primary objective of this study is therefore to understand the implications for fuel supply and emissions of a large renewable fuel requirement in the UK: hydrogen, biofuels or a combination. Modelling has been conducted using the same vehicle kilometre demand scenarios generated for similar work for the UK Government and described in detail in Eyre et al., (2002); IAG, (2002); Marsh et al., (2002), which consider issues such as behavioural changes and modal switching in future demand for transport. The implications of providing fuel for the vehicle energy demand modelled using these scenarios have been examined in detail. Modelling to 2050 is carried out, to match the limit of the emissions reductions discussed in the Energy White Paper.

Several scenarios have been chosen. Each is superimposed on an underlying ‘base case’ scenario, in which we assume conventional technology develops aggressively. This is represented by a penetration of vehicles that are 45% more efficient than existing ones.

Two extreme cases are then used to understand the limits of the possible requirements for fuel over the period to 2050. One deals with the introduction only of renewable hydrogen, the second with only biofuels other than hydrogen. The final scenario represents a mix of hydrogen and biofuels. For each scenario, one or more supply cases are used to test their implications. These are detailed in the following section.

The implications for renewable energy are then modelled – the amount of hydrogen and biofuels likely to be produced from different sources; resources remaining for other uses such as stationary power production; an indication of transmission distances and requirements – in addition to the effects on $CO_2$ emissions from road transport.

### 2.4.1 Scenario development

For the demand scenarios the projections developed in the ‘tripartite’ report are retained, expressed in billion vehicle kilometres (bvkm). However, penetration rates for different types of vehicle are then developed, to enable the modelling of their energy, fuel and ultimately resource requirements. The vehicles themselves are not specified in detail, though information is taken both from a report conducted by (Eyre et al., (2002)) and Owen and Gordon, (2003). Instead, compound key characteristics of the vehicles (efficiency, emissions, etc.) are represented in the model. These characteristics are estimated over the period to 2050, and are therefore subject to considerable uncertainty.

Eyre et al., (2002) analysed the implications for UK $CO_2$ emissions of a mix of energy scenarios in which renewable energy was used in transport fuel production, in heat and power production, or in a mixture of the two. Using very aggressive technology scenarios (e.g. a 65% efficiency improvement over 2002 vehicles from future fuel cell vehicles), they suggested that a considerable proportion of UK fuel could be produced from indigenous renewables. However, for maximum $CO_2$ emissions reduction from the UK energy system the report suggested that renewable electricity should first be used to displace fossil fuelled power plants. Only with a surplus of renewable electricity should transport fuel, e.g. hydrogen, be produced. Further discussion of this report can be found in Annex 1.

This analysis takes estimates from a range of reports to provide the input data, and sets out scenarios to assess the implications for both $CO_2$ reductions and resource use of a rapid move towards renewable fuels in the UK. The scenarios are represented below in tabular format. Table 3 represents the different scenarios, while Table 4 gives the underlying assumptions in more detail. We have used a 45% efficiency improvement for conventional vehicle technology as an aggressive target. This is close to the maximum suggested by Owen and Gordon, (2003) and takes into account the fact that some vehicle classes will not achieve the full improvement. Other analyses (e.g. CONCAWE et al., (2003)) are less optimistic about the potential for hybrid vehicles, though they admit not having analysed their potential in such detail.

*Table 3: Scenarios modelled*

| | | |
|---|---|---|
| **Base case** | **Hydrogen** | ICE |
| | | Fuel cells |
| | **Biofuels** | Slow uptake |
| | | Rapid uptake |
| | **Hydrogen and biofuels** | Slow biofuels uptake |
| | | Rapid biofuels uptake |

*Table 4: assumptions underlying scenarios*

| Scenario | Vehicle and fuel uptake |
|---|---|
| **Base case** | Uptake of HEVs from 2004 with 45% efficiency improvement for cars and LDVs, with 25% improvement for PSVs and 15% improvement for HGVs |
| **Hydrogen ICE** | Base case +<br>ICEs introduced from 2006, reach 10% of new vehicles in 2015, and all vehicles in 2050 |
| **Hydrogen FCV** | Base case +<br>FCs introduced in 2020 (2030 for HGVs), reach 10% of vehicles in 2025, 33% in 2030 and all vehicles in 2050 |
| **Biofuels Slow uptake** | Base case +<br>3%[1] by 2010 and 5% by 2020. Then all fuel in 2050. |
| **Biofuels Rapid uptake** | Base case +<br>10% by 2010 and 20% by 2020 and all fuel in 2050 |
| **Hydrogen and slow biofuels uptake** | Base case +<br>FCV uptake as FCV scenario<br>Biofuels uptake as slow biofuels uptake scenario |
| **Hydrogen and rapid biofuels uptake** | Base case +<br>FCV uptake as FCV scenario<br>Biofuels uptake as rapid biofuels uptake scenario |

[1] All by energy content

These scenarios are in no way intended to be either a recommendation or a prediction of the future. They are constructed primarily to develop an understanding of the potential implications of a transition to renewable transport fuels and so that areas of uncertainty around renewable transport fuels can be examined. The scenarios also try to bring together the large amounts of good but disparate information on UK renewable resources and their potential for fuel production.

Prices, technologies and even societal behaviour will change radically over the period to 2050. Step changes in technology can be imagined – such as a shift from internal combustion engines to fuel cells – but the exact nature and effects of these changes cannot be predicted. At the same time, incremental but potentially highly significant changes may take place in existing technologies. The use of composite materials and fabrication techniques could make conventional vehicles significantly lighter and safer, while also improving handling and reducing energy use. The introduction of the highly efficient yet uncompromised ‘hypercar’ concept vehicle, for example, would allow this progress. There is also uncertainty over the development of technologies for the production of renewable transport fuels, advanced biofuels in particular, and the biomass resources that would be available in practice for fuel production.

# 3 Renewable hydrogen

**Future energy resource requirement**

- Two main scenarios have been used to drive the demand for vehicles and road travel, and therefore vehicle energy. Under the Global Sustainability scenario, total vehicle distance increases earlier in the period, but flattens towards 2050. Under a World Markets scenario, vehicle distance driven increases throughout the period to a level that is 50% higher than under Global Sustainability.
- Under the base case, high efficiency conventional vehicles (with 45% higher efficiency) are assumed to penetrate the vehicle parc from 2004.
- The availability of hydrogen and fuel cell technologies is currently limited and intensive development efforts are ongoing. In the modelling fuel cell cars, buses and light duty vehicles are assumed to penetrate the vehicle parc from 2020 and heavy duty goods vehicles from 2030.
- Hydrogen internal combustion engines could be introduced earlier and penetration starts from 2006 in the modelling.

**Prospective UK supply**

- As well as deriving hydrogen from hydrocarbons, hydrogen can be produced via a range of fuel chains which produce little or no $CO_2$, such as electrolysis using renewable energy and biomass conversion. The overall efficiency of each chain is different.
- The gross UK renewable energy resource to 2050 is forecast to be very large from some chains, in particular offshore wind and energy crops. However, the modelling does not assume that any of this resource is reserved for other energy needs.
- If fuel cell vehicles penetrate the vehicle parc from 2020 and displace all other vehicle types by 2050, then the UK could meet all of its hydrogen fuel needs from indigenous renewable resources. Under the Global Sustainability scenario in 2050 approximately half of the resource would be available for other applications, whilst under a World Markets scenario the remaining resource would be around a quarter.
- If hydrogen internal combustion engines were to penetrate the vehicle parc from 2006 then a different picture emerges. Under the Global Sustainability scenario in 2050 a little over a quarter of the resource would be available for other applications, whilst under a World Markets scenario a small amount of imported hydrogen would be required to meet the total requirement from around 2030.
- For comparison, under the lowest energy demand scenarios for road transport and other energy use, the remaining renewable resource after fuelling all of road transport with hydrogen could meet almost half of energy requirements for heat and power.
- $CO_2$ emissions drop largely in line with the displacement of conventionally-fuelled vehicles by hydrogen fuelled ones, though hydrogen internal combustion engine vehicles are slower to produce a $CO_2$ benefit compared with fuel cell vehicles.

**Hydrogen fuel issues**

- Hydrogen remains a technically challenging fuel due to its physical properties, making it difficult to store in particular.
- Estimates of renewable hydrogen production costs to 2020 shows that some routes could approach the current pump price of hydrocarbon fuels, though future technology cost and performance is uncertain in many fuel chains
- The UK is not a leader in hydrogen energy, though some global players are based in the UK and there are pockets of world class R&D.

As the number of vehicles on the roads increases, in conjunction with the annual mileage driven by each vehicle, even much higher fuel efficiency will not serve to reduce $CO_2$ emissions to within policy targets. Switching to fuels containing less carbon, or recycled carbon, will be essential.

One fuel under strong consideration, in large part because of its link with the developing technology of fuel cells, is hydrogen. Hydrogen produced from renewable sources is especially interesting in the long term, as it may provide a means of solving not only problems related to $CO_2$ emissions, but also assist with improving air quality and reducing dependence on single energy sources. Hydrogen can also potentially be produced with low or zero carbon emissions from fossil fuels with carbon capture and storage, or from nuclear power. However, these are outside the scope of this analysis.

### 3.1 Introduction to hydrogen

Hydrogen is a colourless, odourless, non-toxic flammable gas, with no local pollutant effects. It is not a greenhouse gas, but is only found in useful quantities on earth in compound forms, such as water or hydrocarbons. Hydrogen can be used as a transport fuel, in internal combustion engine (ICE) or fuel cell (FC) vehicles. Hydrogen must be produced using primary energy, then stored and transmitted before it can be converted to an energy service in an end-use technology such as a vehicle.

Hydrogen is commonly produced from conventional hydrocarbons such as gas, oil and coal, or from the electrolysis of water. Removal of impurities may then be necessary before the hydrogen can be used in an energy application. Storage of hydrogen normally takes the form of compressed gas, though liquefaction is also common, and alternative storage methods are being developed. Transport is by tanker, barge or train in compressed or liquid form, or as a gas by pipeline when large amounts are required for a long period of time.

Emissions from hydrogen systems depend mainly on the primary energy source used to produce the hydrogen, but also on the transport and end-use technologies.

Hydrogen is necessarily more expensive *per unit of energy* than the source from which it is produced, but if it can be used more efficiently then the overall cost of the *service* (e.g. miles driven) may not differ greatly from conventional fuels. As a highly simplified example, hydrogen produced from natural gas might cost about twice as much as the natural gas itself. However, burning the natural gas at 20% efficiency in a standard car engine would still be more expensive than using the hydrogen in a fuel cell, if the fuel cell has a 50% efficiency. The greater efficiency of the fuel cell in this example more than cancels out the loss of efficiency in the production process.

## 3.2 Renewable hydrogen

While hydrogen used in vehicles produces no tailpipe carbon dioxide emissions, the production of hydrogen can result in carbon dioxide and potentially other pollutant emissions. Although fuel cycle emissions from the use of fossil-fuel derived hydrogen vehicles can be lower than those from petrol and diesel vehicles (CONCAWE et al., (2003); General Motors et al., (2002)), emissions could be reduced even more significantly by the use of hydrogen produced using renewable energy.

### 3.2.1 Renewable hydrogen production methods

Hydrogen can be produced by electrolysis, splitting water into hydrogen and oxygen. The electricity needed for this process can be provided from renewable sources such as wind, tidal, wave, hydro, or solar energy, and so hydrogen can be produced with zero carbon dioxide emissions. Thermal decomposition of water is possible in principle, though it requires very high temperatures.

Hydrogen can also be produced directly from biomass products, through fermentation, gasification and/or digestion, followed by a series of chemical reactions to strip out the hydrogen. Carbon dioxide is released in this process, but this is offset by the carbon dioxide absorbed in replacement biomass growth. Other production routes are the photo-biological splitting of water using bacteria and algae via a natural photosynthetic process.

Although hydrogen can be produced using any renewable energy source, some are not especially relevant in the UK context (e.g. geothermal energy) and so this analysis will be restricted to production of renewable electricity using the means below, and to relevant biomass production routes. These are indicated in Figure *3*.

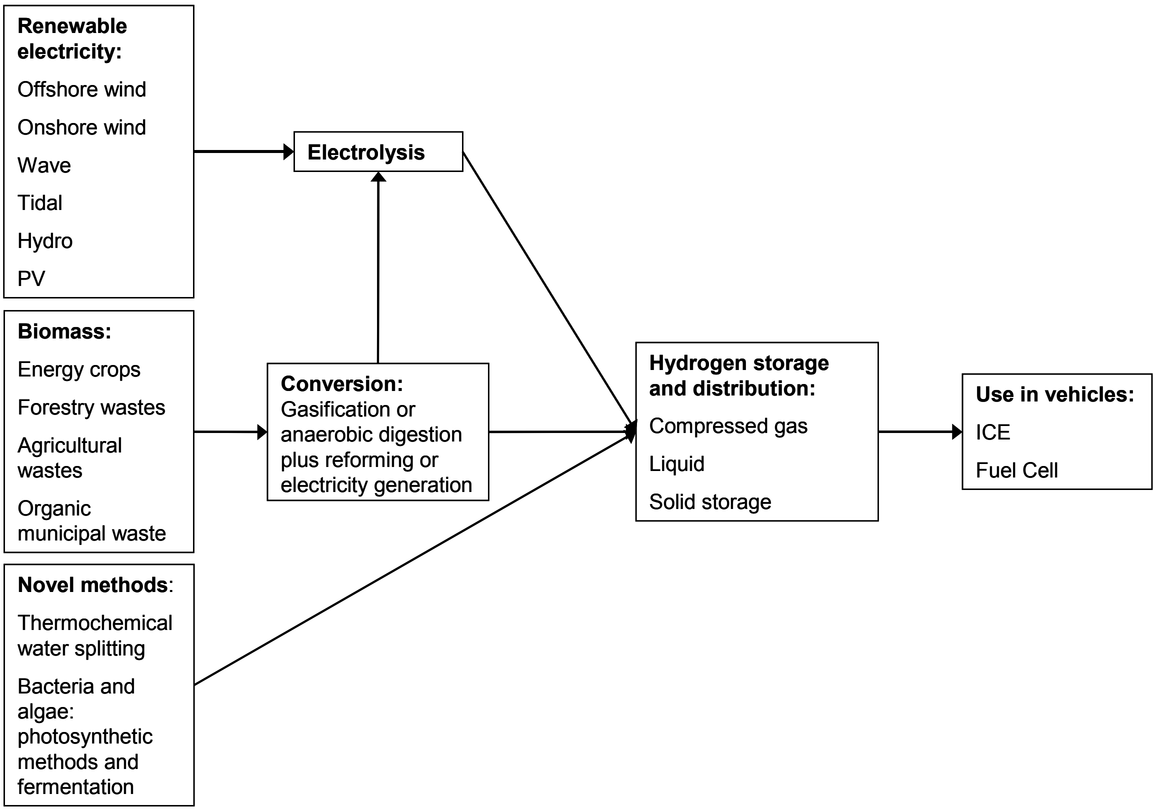

*Figure* 3*: Fuel chains for renewable hydrogen production*

Hydrogen production from renewables could vary widely in terms of scale of production installations and geographic distribution. The choice of a particular hydrogen supply chain will depend on economies of scale of equipment, alternative options and costs for the distribution of the inputs to hydrogen production (e.g. electricity for electrolysis and biomass), and options and costs for hydrogen transport and distribution.

In this analysis, however, the specific detail cannot be evaluated. Instead, for each applicable renewable energy resource a brief description is given. The expected economics are summarised along with, for the biomass routes, carbon implications. The potential UK resource is then discussed. Gaseous hydrogen only is considered, for simplicity. Liquefaction is discussed later in the chapter.

### 3.2.2 Production from renewable electricity

Water electrolysis is the electrochemical splitting of water into hydrogen and oxygen. Originally developed in 1800, it is a well-understood industrial process and large commercial plants achieve efficiencies of 70-75%. Two main electrolyser types exist: liquid alkaline electrolyte electrolysers and proton exchange membrane (PEM) electrolysers. Alkaline electrolysers are used for most applications, while PEM electrolysis units are under development. High temperature and high pressure electrolysers are also being developed, with the long term potential for efficiencies closer to 85-90% (Martinez-Frias et al., (2003)).

Once the hydrogen gas has been produced, it is typically compressed for storage and distribution. Compression requires energy, but electrochemical compression in the electrolyser is considerably more efficient than mechanical compression, and prototype electrolyser units producing up to 13 MPa are undergoing development and testing. To pressurise hydrogen to a typical vehicle storage pressure of 35 MPa requires the equivalent of between 5% and 12% of the energy in the hydrogen, depending on the input pressure.

Hydrogen from electrolysis is typically very pure, containing only small amounts of water vapour and oxygen. For the majority of applications, no further clean-up is required.

For hydrogen produced from renewable electricity, the location of production will be an important consideration in the real design of systems. Production close to the point of demand is ideal, as transportation of hydrogen is typically inefficient and expensive. However, for the purposes of this analysis the primary consideration is of resource potential. Once the hydrogen production potential has been calculated to fit the anticipated demand, the implications for the resource, including location, will be discussed.

The greenhouse gas emissions of hydrogen produced from renewably generated electricity are negligible, arising solely from e.g. diesel-based transport of the fuel (General Motors et al., (2002)). For the purposes of this analysis they will be considered to be zero, as we assume that all transport modes will also use hydrogen.

### 3.2.3 Production from biomass

Biomass is another potential hydrogen source. Biomass energy crops, such as short rotation coppice (SRC) and miscanthus were identified as being one of the major potential renewable energy sources for the UK (PIU, (2002)). However, several other sources contribute to the biomass energy potential, including straw, forestry wastes, sewage sludge, landfill gases and municipal solid wastes (MSW). All these sources have some potential for distributed hydrogen production.

Three possible routes for hydrogen from biomass are: electrolytic hydrogen production using biomass electricity, biomass liquid fuel reforming to hydrogen at the forecourt, and reforming of biomass gases from gasification and anaerobic processes.

Biomass combustion systems are in commercial use in niche markets around the world for electricity production, using disparate technologies but generally based around CHP. Biomass gasification technology status, particularly at the large scale (>10 MWe), ranges from research through development to commercial. Anaerobic digestion processes for the treatment of a variety of wet biomass streams are already in commercial use. The biomass gasification or pyrolysis routes are more efficient for hydrogen production than the use of biomass-derived electricity and are discussed further below.

*Hydrogen from biomass gasification.* The biomass feedstock is first dried and sized if necessary, and then gasified to produce a gas (syngas). To produce hydrogen, the cleaned syngas must then undergo several shift reactions. $H_2$ is recovered from the gas stream, and can then be liquefied or compressed for transport. Gasification and gas cleaning equipment is still at the pre-commercial stage. Reforming, shift reaction and recovery equipment is commercially available at large scale and is widely used for industrial hydrogen production, mainly from natural gas. Developments are underway to scale down the equipment and for its use with a variety of syngas inputs.

*Hydrogen from biomass pyrolysis.* Pyrolysis technology is at the research, development and demonstration stage. Like gasification, it is a high temperature reaction taking place in an oxygen poor environment. Biomass pyrolysis takes place in a lower oxygen environment than gasification and produces a mix of solid, liquid and gaseous products. The liquid fuel produced can be transported and stored and allows for de-coupling of the fuel production and energy conversion stages. Liquid fuels from pyrolysis could be reformed to hydrogen at the forecourt, though small scale reforming systems are the advanced development stage and are not yet commercially available. The relative efficiency of gasification and pyrolysis chains would be affected by the hydrogen transport mode and distance associated with its production via gasification. Only hydrogen production from biomass gasification has been considered in the modelling of renewable hydrogen penetration scenarios. Pyrolysis chains are likely to result in lower overall efficiencies, as they involve multiple stages, and would therefore lead to lower hydrogen production levels.

### 3.2.4 Novel technologies for hydrogen production

Technologies currently at the research and demonstration stage for hydrogen production that could be important in the future, but which have not been considered in the modelling, include:

***Photosynthetic processes*** use organisms such as green and blue green algae, or photosynthetic bacteria, to split water or other compounds to form hydrogen.

***Fermentation processes*** use bacteria to ferment carbohydrate-rich organic material, such as crops or food wastes, under dark, anaerobic conditions, to produce hydrogen

***Photochemical processes*** produce hydrogen by using semiconductor material to convert energy from sunlight into electrons to decompose water

***Thermochemical processes*** are also in development, using waste heat from nuclear reactors in an iodine-sulphur process to split water

### 3.2.5 Greenhouse gas emissions

It is possible that biomass chains, like hydrogen chains, could use only biomass-based inputs and thus have greenhouse gas emissions of zero. However, because the biomass chains also include e.g. nitrogen-based fertiliser inputs, the greenhouse gas emissions tend to be greater than for renewable electricity, for example. To illustrate this, it has been estimated that hydrogen from biomass chains could produce between 5 and 17 times the non-renewable energy inputs to the chain, under the assumption that all inputs to biomass production and supply and to hydrogen distribution consist of fossil energy. The GHG emissions from the biomass to hydrogen chain are therefore estimated to be between 5 and 30 kg$CO_2$eq./GJ($H_2$).

### 3.2.6 Costs of renewable hydrogen production

The costs of hydrogen produced from renewables vary widely, and will change significantly with time. The costs in this section are calculated approximately to 2020; beyond this period uncertainty becomes very great and so further calculations have not been conducted.

Figure 4 summarises costs of some different renewable hydrogen fuel options, taken from Howes, (2002); Woods and Bauen, (2003), and including all stages of the chain. A profit margin of 5% has also been included. The figure indicates that the costs of supplying renewable hydrogen from wind or biomass resources are likely to lie above the current pump price of untaxed petrol and diesel, though some costs are very close to this level. It is also expected that, based on mature technologies, the production costs of hydrogen from biomass will be lower than hydrogen from wind electricity. The production costs of hydrogen from biomass may be close to those of hydrogen produced from the steam reforming of natural gas. However, as discussed above, GHG and other emissions are likely to be higher for hydrogen produced from biomass than that produced from wind energy.

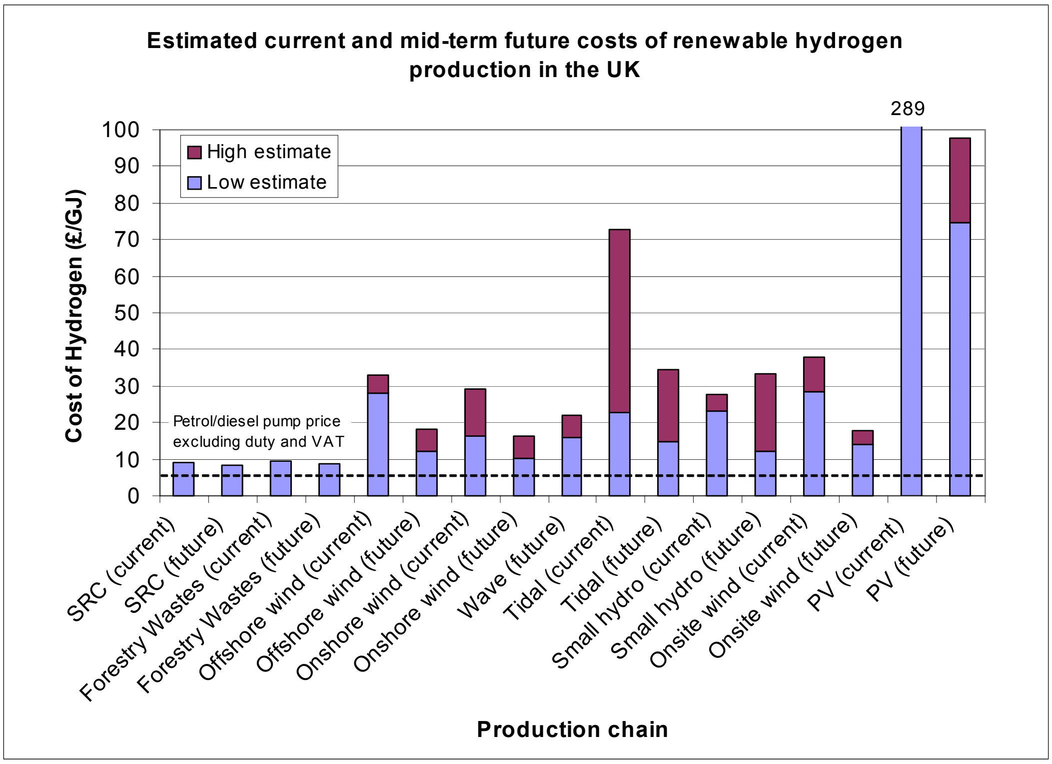

*Figure 4: Comparison of estimated costs of renewable hydrogen for the UK, as delivered to the user*

Sources: Howes, (2002); Woods and Bauen, (2003). Includes distribution costs and profit.

A further detailed breakdown of hydrogen supply costs is given in AEAT, (2003b), which shows a range of between 2.2p/km and 7.1p/km to the consumer for different production routes and pathways in 2020. Renewable pathways have costs at the top end of that scale. However, the costs in the AEAT analysis are almost exclusively from US sources, some of which date back to 1995, whereas the majority of costs shown above are from more recent sources, and must eventually include developments to 2050. This uncertainty must be considered and costs monitored as both the policy and technologies evolve.

*Table 5: Possible weighted average hydrogen (and petrol) costs 2010-2050 (ex-tax)*

| | 2010 | 2020 | 2050 |
|---|---|---|---|
| H2 cost (£/GJ) | 14.5 | 20.6 | 12.6 |
| ICE (p/km) | 2.2 | 3.2 | 1.9 |
| FCV (p/km) | 2.0 | 2.9 | 1.8 |
| Petrol cost (£/GJ) | 5.2 | 5.2 | 5.2 |
| petrol ICE (p/km) | 1.2 | 1.2 | 0.8 |

Note: Untaxed petrol cost per km is given as a reference only, as oil prices to 2050 are at least as speculative as hydrogen costs to that period. The drop in cost is due to improved efficiency.

Table 5 gives an indication of the possible delivered costs of hydrogen from renewable energy in 2010, 2020 and 2050, both in £/GJ and p/km for a motorist using a car with either a fuel cell engine or a hybridised ICE. These costs are derived using a weighted average of the cost of each renewable source and the proportion of hydrogen it supplies. As can be seen, the cost of hydrogen rises slightly over the initial period, and then drops. This is because more hydrogen is produced from technologies such as offshore wind and photovoltaics, which have not yet reached their long-term cost targets in 2020. The model allocates hydrogen production by resource availability and not by price, given the large uncertainties in the latter and the resulting requirement for complex learning functions to be endogenous to the model.

Clearly, both these costs and the petrol costs shown are extremely speculative to 2050, and simply serve as an indication of potential cost to the motorist assuming no form of taxation.

### 3.2.7 Resource assessment and resulting hydrogen production potential

The potential renewable energy resource in the UK is large, though estimates vary considerably. Clearly technology development over the period to 2050 will have a considerable impact on the recoverable (as opposed to theoretical) potential, though the absolute physical limits of resources should become clearer. This analysis also excludes the potential for imports to supplement UK potential.

Table 6 below shows a consolidation of renewable resource estimates taken from several sources. These estimates already take into account land-use, planning constraints, engineering issues and other limiting factors. While one or two sources (e.g. ETSU, (1998)) give consistently analysed estimates for the majority of pathways, subsequent analysis with more recent data suggests that some of the results may be pessimistic. In general for this study, the higher of the available values are assumed, as the analysis extends to 2050, which is further than the majority of other work. The table shows resources that are additional to those available in 2000, as those are already fully used. All of these additional resources are considered to be available for hydrogen production.

Each resource is given in the gross amount that might be accessed, with renewable electricity resource figures given as output from the technology, i.e. electric power, and biomass-based resources shown as the energy content of the materials used, converted directly to Petajoules ($1x10^{15}$ J).

In addition, the penetration has been assumed to be linear. Final resources for 2050 are simply assumed to penetrate in a linear mode from the first point of uptake, which is 2000 for comparatively mature technologies, and 2010 for others. This is a crude but necessary assumption, as the actual use of resources depends on a wide range of complex factors, many of which are highly uncertain.

*Table 6: Raw renewable energy resource available in UK*

| Input resource (PJ) | 2000 | 2010 | 2020 | 2030 | 2040 | 2050 |
|---|---|---|---|---|---|---|
| Onshore wind | 0.0 | 41.0 | 82.1 | 123.1 | 164.2 | 205.2 |
| Offshore wind | 0.0 | 18.7 | 374.9 | 731.2 | 1087.4 | 1443.6 |
| Wave | 0.0 | 0.4 | 47.1 | 93.8 | 140.5 | 187.2 |
| Tidal Stream | 0.0 | 0.4 | 32.7 | 65.0 | 97.3 | 129.6 |
| Small Hydro | 0.0 | 1.3 | 2.6 | 3.9 | 5.2 | 6.5 |
| PV | 0.0 | 0.4 | 117.3 | 234.2 | 351.1 | 468.0 |
| Dry agricultural waste | 0.0 | 19.8 | 39.6 | 59.4 | 79.2 | 99.0 |
| Wood waste | 0.0 | 11.2 | 22.3 | 33.5 | 44.6 | 55.8 |
| Landfill gas | 0.0 | 4.1 | 8.2 | 12.3 | 16.5 | 20.6 |
| MSW | 0.0 | 57.7 | 115.3 | 173.0 | 230.6 | 288.3 |
| Sewage sludge | 0.0 | 5.8 | 11.5 | 17.3 | 23.0 | 28.8 |
| Waste vegetable oil | 0.0 | 3.0 | 6.0 | 9.0 | 11.9 | 14.9 |
| Energy crops | 0.0 | 180.0 | 378.0 | 540.0 | 877.5 | 1080.0 |
| *Total* | 0.0 | 343.6 | 1237.6 | 2095.5 | 3129.0 | 4027.5 |

Note: the energy crop potential in 2050 corresponds to planting 4Mha of land with lignocellulosic crops with an average yield of 15 odt/ha/yr and an energy content of 18 GJ/odt.

### 3.2.8 Importing renewable hydrogen

In the same way that conventional fuel is produced and delivered worldwide, hydrogen could be produced from renewable resources outside the UK. While hydrogen is not as easy to transport as many conventional fuels, the timeframe of this analysis is such that liquid hydrogen tankers and large-scale pipeline systems are conceivable. This would allow hydrogen produced from e.g. biomass in Brazil, hydropower in Iceland, or solar power in North Africa to be brought to the UK. Equally, in some cases the renewable resource (the biomass, or renewably-generated electricity) could be transported and hydrogen produced at an appropriate place in the UK. The economics and logistics of such schemes are speculative at this stage and will depend strongly on both resource cost and transport option.

## 3.3 Hydrogen technologies and status

Hydrogen technologies for industrial and aerospace use are well-established. Those for energy systems are largely still in development.

### 3.3.1 Storage and transport of hydrogen

Hydrogen is the lightest and smallest molecule, making it difficult to store in compact or light systems. Common storage methods include compressed, liquid and solid-state systems. Hydrogen can be transported as a compressed gas in dedicated pipelines or in cylinders, or as liquid hydrogen by tanker or barge. Hydrogen pipelines are in commercial use in many industrialised countries, with lengths of 8-200 km, and may also be a viable option for transporting large volumes of hydrogen for relatively short distances, or when a stable market is established. Transport of both compressed and liquid hydrogen by road is currently used in industry, with liquid hydrogen favoured for long distances, due to a higher energy density and hence lower transport cost per unit of energy. However, compressed gas road transport can be viable for short distances, or where the high minimum capital cost of liquefaction plant is prohibitive.

### 3.3.2 Technologies for using hydrogen in vehicles

***Internal combustion engines***. Hydrogen can be burnt in a standard internal combustion engine (ICE) with some modification. Emissions are very low, though a small amount of $NO_x$ may result from the high temperature combustion process. A reduction in power output may also be apparent if the engine is not optimised for hydrogen. The cost of a hydrogen ICE will be very similar to a conventional engine, though a vehicle would cost more than a standard one due to the high cost of hydrogen storage tanks. Hydrogen ICEs can be tuned to be more efficient than those running on petrol, but over a drive cycle they are still subject to significant losses. Hydrogen vehicles with ICEs and hybrid technology are also under development, with the long-term potential for improvement as yet unclear.

***Fuel cells.*** Hydrogen can be used more efficiently in fuel cells than in ICEs. A fuel cell is a device for directly converting the chemical energy of a fuel into electrical energy – like a battery but with a continuous supply of fuel. Fuel cell efficiencies can be considerably higher than ICEs in practical vehicles, though have less of an advantage in comparison with hybrid technologies. The characteristics of the fuel cell give fuel cell vehicles several potential advantages over ICEs. Polluting emissions from a fuel cell vehicle using hydrogen will be zero, while noise levels will be extremely low, and the fuel cell provides a significant on-board electrical power production capability that could be used for items such as highly efficient air conditioning, or on-board electrical systems.

The fuel cell's primary disadvantage at present is cost, though reliability has also yet to be fully proven in the field. The estimated cost of FCVs varies from several hundred thousand to several million dollars per vehicle. This is because they are essentially hand-built. Real costs are not publicly available. Current *prices* of PEM fuel cells are thought to be in the region US$3,000-12,000 with small-scale units on the market for about US$3,000.

However, detailed engineering modelling has been conducted by several organisations to assess the possible future cost of fuel cells for vehicles (Allison Gas Turbine Division, (1994); Lipman, (1999); Lomax et al., (1998)). These estimate that the cost of fuel cells for vehicles can potentially be brought down considerably by technical development, reduced or cheaper alternative materials use, and mass-manufacture rendering them as affordable as ICE vehicles. This depends on both technical development and mass production, and could happen in the 2010-2020 timeframe, given suitable investment.

For this study it has necessarily been assumed that fuel cell vehicles are cost-competitive with conventional vehicles.

### 3.3.3 Introduction to fuel cells

The main fuel cell under development as a prime mover for transport is the Polymer Electrolyte Membrane (PEM) fuel cell[2], which is expected to have the high power density, reliability and rapid dynamic performance required to replace the ICE.

As on-board power requirements for vehicles rise, the drain on conventional engines becomes greater. Because of this, other fuel cells are under development to operate as auxiliary power units (APUs). The main one amongst these is the solid oxide fuel cell or SOFC.

The PEM operates at around 70°C, and achieves its greatest efficiency and power density when using pure hydrogen. Emissions from a fuel cell operating on hydrogen are only of water. The SOFC operates at around 800°C, so takes time to warm up. However, it is much less sensitive to fuel contaminants than the PEMFC, and can directly combust some hydrocarbons, e.g. natural gas and methanol. Fuel cells for APUs are expected to be sized at around 5kW.

## 3.4 Uptake of hydrogen use in road vehicles

In theory, fuel cells can be used as the prime mover in any road vehicle. However, in the near term their use in heavy goods vehicles is unlikely, as these have high power requirements (meaning large and hence very expensive fuel cells) and their diesel engines and gearboxes are optimised to give much higher efficiency over their typical drive cycle than is possible with other vehicles. By 2030, we assume that fuel cells have been developed to a state where they do offer advantages, and are introduced into HGVs. In the meantime it is also possible to consider the use of hydrogen in heavy-duty ICEs, though on-board storage of very large amounts of hydrogen may take too much valuable space in the near term, until storage technologies can be improved.

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[2] Also known as a Proton Exchange Membrane Fuel Cell, and a Solid Polymer Fuel Cell or SPFC

The major market targeted by the automotive industry for the medium term is in private cars, though the cost and performance requirements of this application remain very challenging. Earlier uptake of fuel cells in vehicles is expected to be good in buses, urban delivery fleets and taxis, however, where the duty cycle and the availability of local refuelling can make them attractive.

The outlook for commercial availability of fuel cells in vehicles is not yet clear, as fully proven pre-production models are not available. However, rapid progress has been made and each manufacturer has between three and five generations of fuel cell vehicle on which to base their future scenarios. Generally, 2020 is regarded as a plausible entry point for fuel cell vehicles into the commercial market, though buses could come earlier.

Even though fuel cell vehicles may be available at this stage, development of refuelling infrastructure will need to be done in tandem to ensure that customers are not put off buying vehicles due to limited fuel availability. However, a large number of manufacturers, suppliers and different resources are being developed and so currently vehicle availability is much more of a limiting factor than is fuel.

For the majority of the modelling, we consider the very first fuel cell cars enter the market in 2020, but that availability is constrained until 2022, as manufacturers build capacity. Buses and LDVs enter in the same time period, while HGVs are only available from 2030. Penetration is assumed to follow a standard ‘s’ curve, as a full econometric model would take significant effort to develop, and the outputs would still be very uncertain due to the wide range of assumptions feeding into the model.

## 3.5 Scenarios and pathways for the UK

Hydrogen could play an increasingly important role as a low carbon and renewable transport fuel. The development of a hydrogen infrastructure, and a renewable hydrogen infrastructure in particular, would need to accompany the introduction of hydrogen vehicles, especially hydrogen fuel cell vehicles. The transition to hydrogen vehicles is likely to be slow and infrastructure will develop accordingly.

### 3.5.1 Scenarios modelled

Scenarios have been modelled to investigate the potential implications of a large-scale introduction of hydrogen-fuelled vehicles into the transport fleet in the UK, over the period 2000-2050. The hydrogen is produced from renewable energy, and the scenarios are intended to investigate the renewable resource required to supply the renewable hydrogen, and the potential for the UK to supply it using indigenous resources. The approximate $CO_2$ emissions implications of the scenarios are also investigated, to enable a future analysis of the ways in which the UK might meet its aspirations of a 60% cut in $CO_2$ emissions from 1990 levels by 2050. This further analysis is not conducted here.

Each alternative fuel scenario has been built around a base case. The base case itself has two variations, a ‘Global Sustainability’ (GS) option, in which vehicle distance driven increases gradually from 2000 but then peaks and drops slightly to 2050; and a ‘World Markets’ (WM) option, in which vehicle distance driven increases throughout the period. These scenarios are intended to represent plausible extremes, allowing the implications of the introduction of renewable hydrogen to be tested.

Two primary hydrogen scenarios have been modelled. In the first, fuel cell vehicles (FCVs) are assumed to have become sufficiently attractive that consumers wish to buy them in all vehicle categories, though heavy goods vehicle uptake occurs later than other vehicle classes, as the advantages of fuel cells are less clear-cut in the near term. All fuel cell vehicles are fuelled by hydrogen from renewable resources; all other vehicles by conventional fuels.

In the second scenario, hydrogen is introduced into internal combustion engine (ICE) vehicles only. This is based on the assumption that FCVs do not meet the cost and performance targets required for their future uptake, but that hydrogen is introduced for environmental policy reasons.

### 3.5.2 Assumptions

Within the two base case scenarios, a high uptake of some form of 'high efficiency' vehicles (HEVs) is assumed from 2004, as shown in Figure 5. The number of vehicle kilometres (vkm) is used as a proxy for the number of vehicles, as it enables energy use and $CO_2$ emissions to be calculated and a comparison to be made against the best expected conventional technology. These factors combine to produce a highly positive environmental base case under the GS scenario, though a less positive one under WM. Under GS, factors such as mode switching, telecommuting etc. are already considered (IAG, (2002))

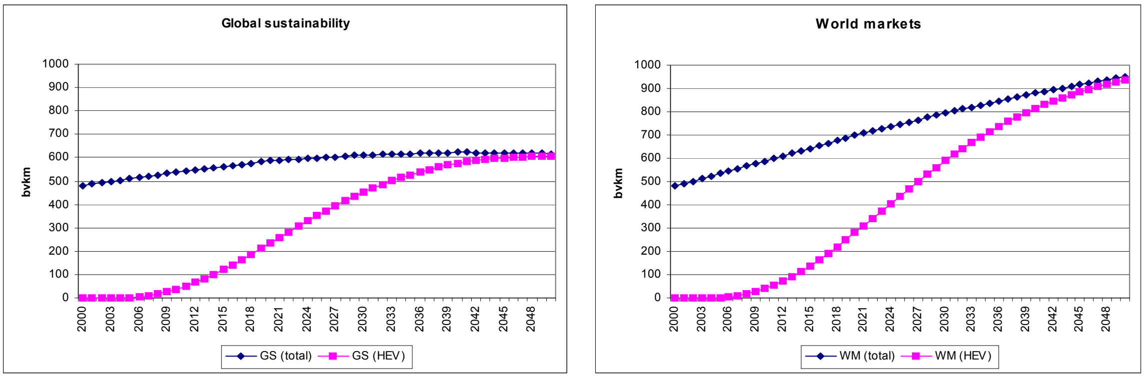

*Figure 5: Total vehicle km travelled under the base case penetration of high efficiency vehicles (HEVs) in the World Markets and Global Sustainability scenarios*

Figure 6 indicates the penetrations of HEVs and FCVs into the market. The fall of HEVs from 2020 onwards is due to their substitution by FCVs. FCVs are assumed to have a very rapid penetration, enabling them to achieve close to 100% of the vehicle stock by 2050.

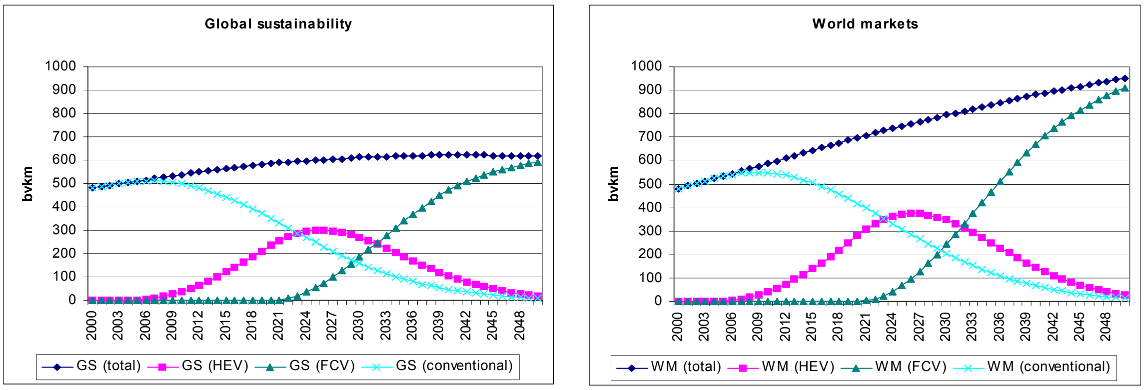

*Figure 6: Penetration of HEVs and subsequently FCVs under the GS and WM scenarios*

In the same way, $H_2$ ICE penetration is represented in Figure 7. This figure simply shows the increase in $H_2$ ICEs and decrease in conventionally-fuelled vehicles. While $H_2$ ICEs also provide nearly 100% of the vehicle stock in 2050, about ten more years are required than for the FCVs due to the less compelling consumer value proposition.

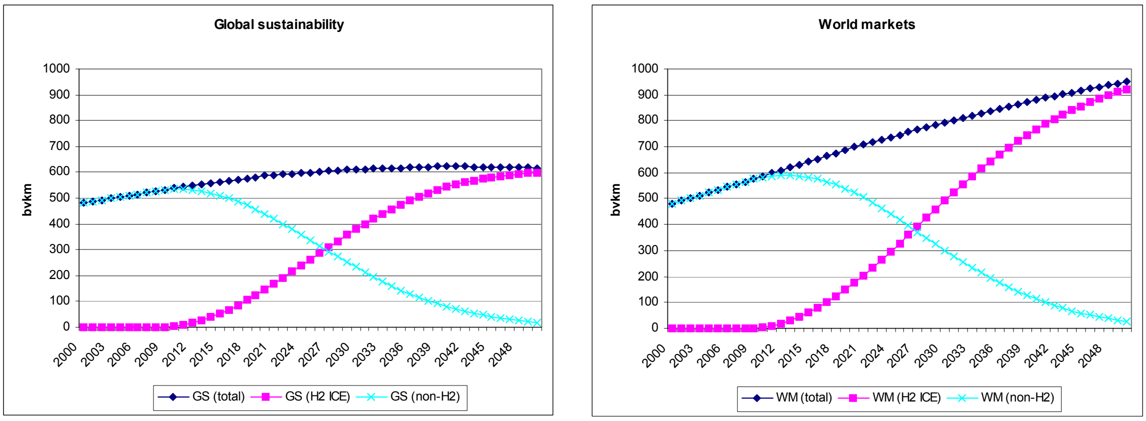

*Figure 7: Penetration of $H_2$ ICEs and replacement of conventionally-fuelled vehicles under the GS and WM scenarios*

All vehicles are assumed to be introduced into all vehicle classes at some stage. Vehicle classes modelled are cars, light goods vehicles (LGVs), heavy goods vehicles (HGVs) and public service vehicles (PSVs). The base case vehicle in the model uses the energy shown in Table 7, while Table 8 indicates the introduction date of new vehicle technologies and their efficiency gains over the conventional stock.

*Table 7: Average energy use by vehicle class in 2004 (for the base case)*

| Vehicle type | Energy use (MJ/km) in 2004 |
|---|---|
| Car | 2.79 |
| PSV | 8.80 |
| LGV | 3.30 |
| HGV | 9.74 |

Source: Eyre et al., (2002)

*Table 8: Input assumptions by vehicle class on technology introduction date and drivetrain efficiency gain over conventional vehicles compared with the 2004 base case*

| Vehicle class | vehicle type | Introduction date | Efficiency improvement over conventional vehicle |
|---|---|---|---|
| HEV | Car | 2004 | 45% |
| | PSV | 2004 | 25% |
| | LGV | 2004 | 45% |
| | HGV | 2004 | 15% |
| FCV | Car | 2020 | 50% |
| | PSV | 2020 | 40% |
| | LGV | 2020 | 50% |
| | HGV | 2030 | 20% |
| H2 ICE | Car | 2008 | 35% |
| | PSV | 2008 | 20% |
| | LGV | 2008 | 35% |
| | HGV | 2008 | 10% |

Primary source: Owen and Gordon, (2003). However, these efficiencies represent compound fleet-average figures to 2050, including all vehicle classes, and assuming full uptake as soon as they become available. In reality not all vehicles will attain the maximum efficiency gain projected, and so this represents an aggressive base case.

For each vehicle type, uptake is driven purely by an s-curve. The complexity of a full stock turnover model was not warranted given the nature of the research, which is to analyse the implications of scenarios and *not* to predict uptake.

### 3.5.3 Hydrogen Resources

In analysing the amount of hydrogen that could be produced from the raw resources discussed in Table 6, different resources are treated in different ways. For all resources directly producing electricity, a simplified production chain is considered, in which electrolysis, compression, storage and transportation losses are estimated. For the biomass and waste resources the conversion chain includes the relevant sections of gasification or digestion, clean-up and reforming, compression, storage and transport. Table 9 indicates the efficiency figures used for all of these conversion steps, with all production routes using at least two of these figures – on-site electrolysis, for example, uses a combined efficiency of 70% for electrolysis and 90% for compression and storage, or 63% overall. This is broadly appropriate for current technology but likely to be pessimistic for the long term. However, these are compound simplifying assumptions, as each case will depend on the pressure, transport distance, and technology type used, along with many other factors. Nevertheless, they are broadly representative of other analyses (e.g. CONCAWE et al., (2003); General Motors et al., (2002); Thomas et al., (1998)) and fall within the uncertainties of the general model.

Only gaseous hydrogen is considered in this report. Liquid hydrogen pathways could also be modelled, and as a gross assumption the total energy requirement would be about 25% greater due to losses in the liquefaction process, leading to greater resource requirements. $CO_2$ emissions would follow energy use in the same way as in the existing chains above.

*Table 9: Average efficiency of conversion of renewable resource to hydrogen*

| Conversion route | efficiency |
|---|---|
| Electrolysis | 70% |
| Compression and storage | 90% |
| Transportation | 95% |
| Syngas to hydrogen | 85% |
| Gasification | 60% |
| Digestion | 50% |

Note that these are compound figures, used for all modelling to 2050 and are therefore not applicable to any detailed individual pathway analysis.

*Table 10: Hydrogen production potential (PJ) from renewable resources in the UK to 2050, by primary source*

| H2 fuel resource (PJ) | 2000 | 2010 | 2020 | 2030 | 2040 | 2050 |
|---|---|---|---|---|---|---|
| Onshore wind | 0.0 | 23.3 | 46.5 | 69.8 | 93.1 | 116.3 |
| Offshore wind | 0.0 | 10.6 | 212.6 | 414.6 | 616.5 | 818.5 |
| Wave | 0.0 | 0.2 | 26.7 | 53.2 | 79.7 | 106.1 |
| Tidal Stream | 0.0 | 0.2 | 18.5 | 36.8 | 55.2 | 73.5 |
| Small Hydro | 0.0 | 0.7 | 1.5 | 2.2 | 2.9 | 3.7 |
| PV | 0.0 | 0.2 | 66.5 | 132.8 | 199.1 | 265.4 |
| Dry agricultural waste | 0.0 | 8.4 | 16.8 | 25.2 | 33.7 | 42.1 |
| Wood waste | 0.0 | 4.7 | 9.5 | 14.2 | 19.0 | 23.7 |
| Landfill gas | 0.0 | 3.5 | 7.0 | 10.5 | 14.0 | 17.5 |
| MSW | 0.0 | 24.5 | 49.0 | 73.5 | 98.0 | 122.5 |
| Sewage sludge | 0.0 | 2.4 | 4.9 | 7.3 | 9.8 | 12.2 |
| Waste vegetable oil | 0.0 | 3.2 | 6.3 | 6.3 | 6.3 | 6.3 |
| Energy crops | 0.0 | 76.5 | 160.7 | 229.5 | 372.9 | 459.0 |
| *Total* | 0.0 | 158.5 | 626.5 | 1076.0 | 1600.2 | 2066.9 |

Table 10 shows that the potential amount of hydrogen fuel that could be produced, transported and finally used on board vehicles using these renewable resources is approximately half of the basic resources themselves.

As an indication, the offshore wind resource of 819PJ in 2050 would take up about 8,000 km$^2$ – or 90km x 90km if in a single block, or about 0.05% of the UK seabed (Border Wind Ltd, (1998); Garrad Hassan and Partners, (2001)). The PV is considered to be all building-integrated on south – and west-facing walls and roofs, and therefore takes no additional land.

## 3.6 Modelling

The modelling conducted is based on a set of technology penetration s-curves. At this point they are set to enable a rapid penetration of alternative vehicles. FCVs, for example, are introduced commercially in 2020 but reach almost 100% penetration by 2050, which is clearly a highly aggressive uptake.

### 3.6.1 Results

The results of the modelling show that if FCVs are introduced into the parc following the assumptions above from the GS scenario, the potential supply of renewable hydrogen is considerably in excess of the fuel requirement, leaving a large amount of resource for other uses. This is shown in Figure 8. Figure 9 gives the same information under the WM scenario, where the excess resource is considerably smaller.

It must be remembered that the white portion of each bar in the figure shows the remaining resource as hydrogen (or the additional resource required, if below the axis), and so is approximately half of the actual unused renewable raw resource. This raw resource would be about 2,000PJ under GS assumptions, and 1,000PJ under WM.

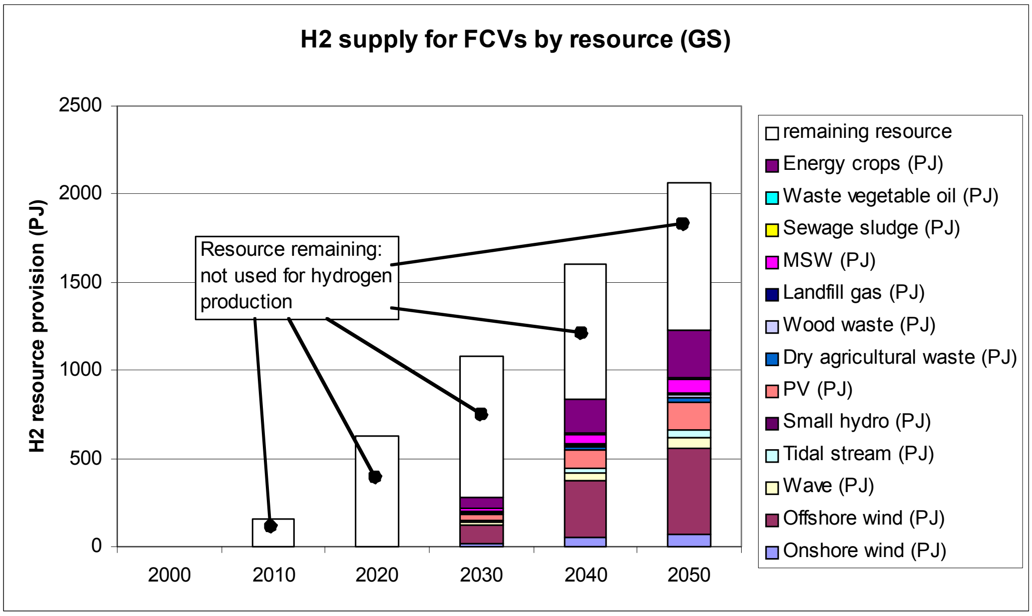

*Figure 8: Hydrogen fuel delivered to FCVs to 2050, split by resource used (GS scenario)*

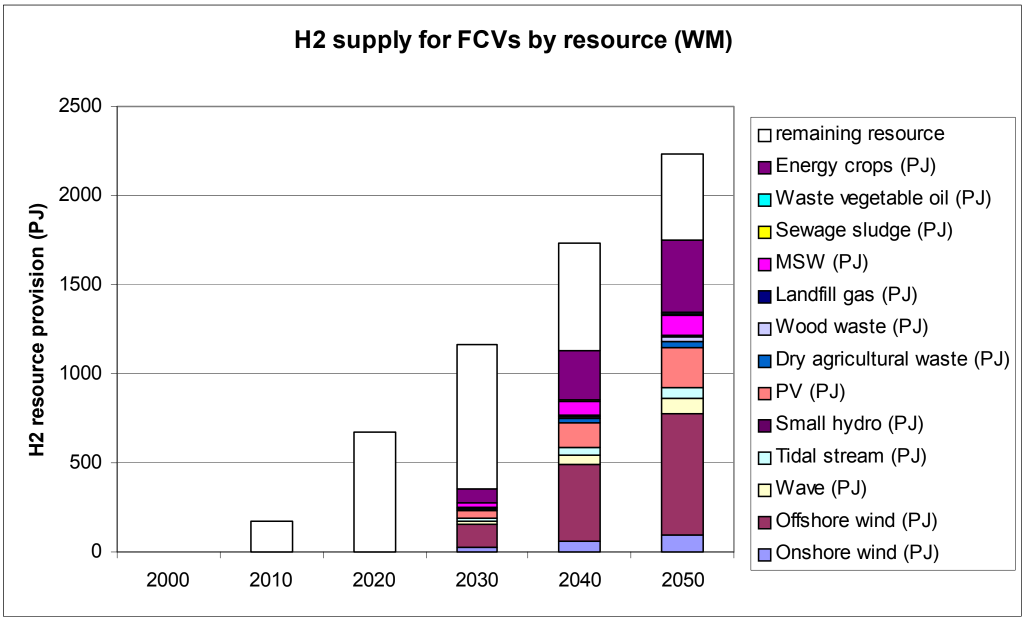

*Figure 9: Hydrogen fuel delivered to FCVs to 2050, split by resource used (WM scenario)*

If hydrogen ICEs are used instead of FCVs, the picture is different. First, the introduction date is much earlier, so resources are required earlier. Secondly, the less efficient ICE requires more fuel, and hence more resource.

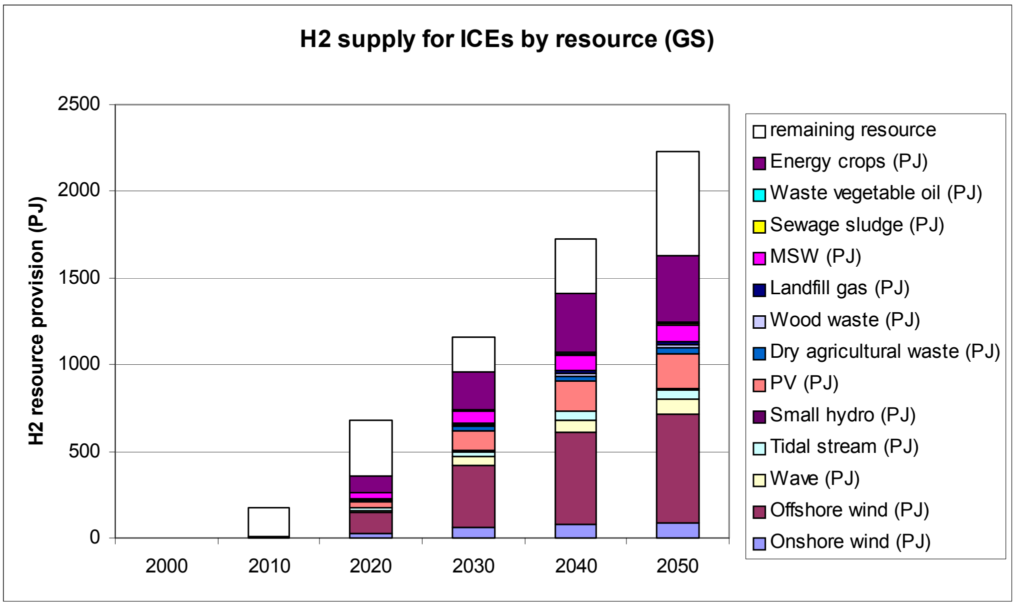

*Figure 10: Hydrogen fuel delivered to ICEs to 2050, split by resource used (GS scenario)*

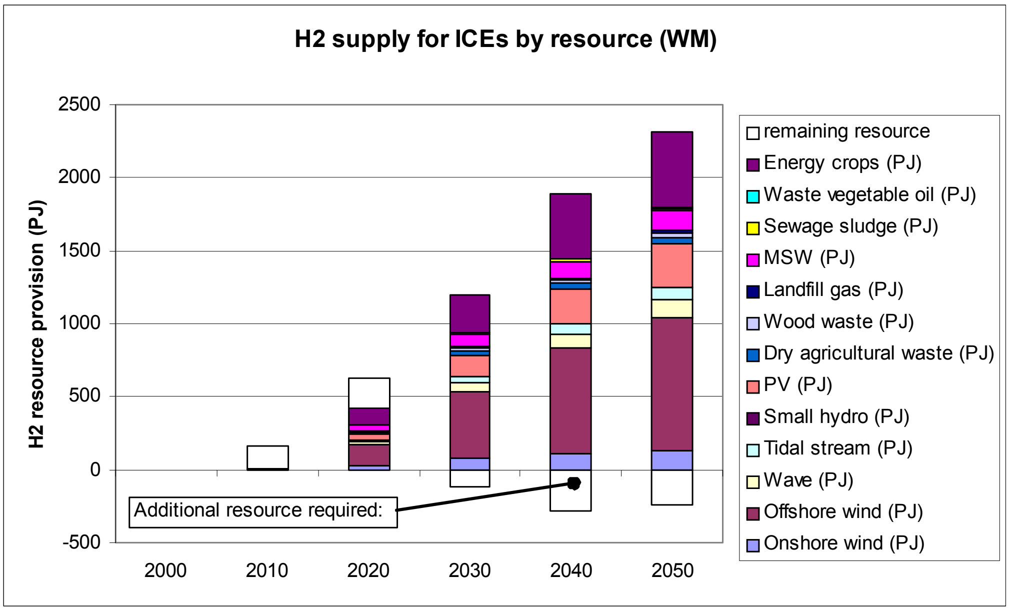

*Figure 11: Hydrogen fuel delivered to ICEs to 2050, split by resource used (WM scenario)*

Figure 10 and Figure 11 show the hydrogen fuel requirements for ICE vehicles under the GS and WM scenarios. While under GS the requirements can be met, the WM scenario shows that resources over and above those assumed to be in place at the time would be required. In these cases hydrogen could be imported, or produced from non-renewable resources such as fossil and nuclear energy. The GS scenario shows an excess of renewable capacity of about 1,200PJ in 2050 (600PJ of renewable hydrogen), while WM shows a deficit of 200PJ of raw resource in 2050, though the deficit in 2040 is larger, at 400PJ. This is due to a more rapid penetration of ICE vehicles and increase in distance travelled than occurs in the exploitation of renewable energy.

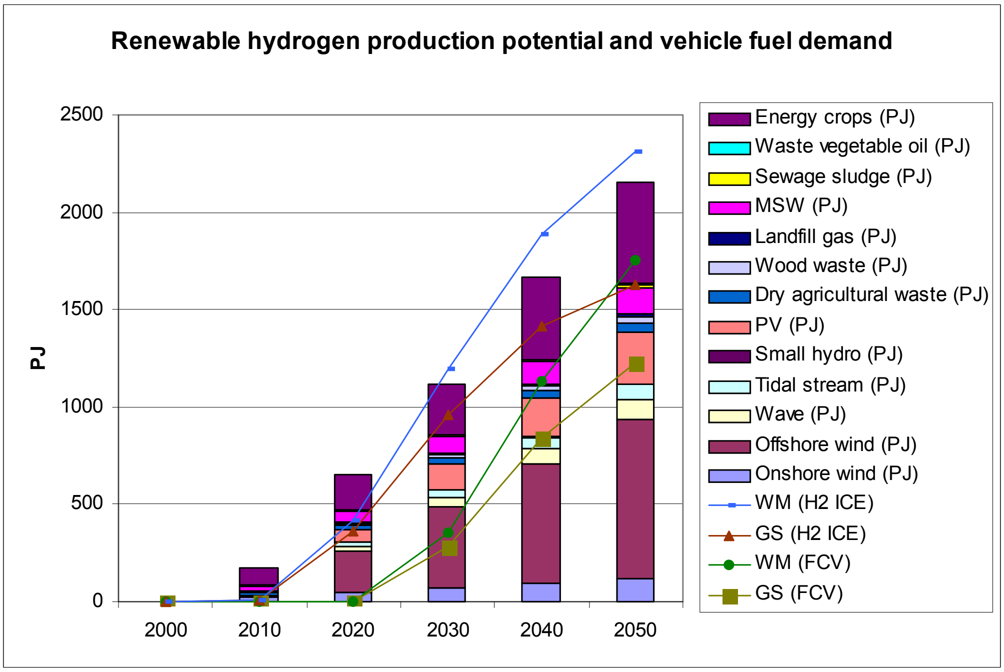

*Figure 12: Fuel requirements of hydrogen vehicle scenarios compared with renewable hydrogen production potential*

Figure 12 shows more clearly the energy requirements of the different scenarios, plotted in conjunction with the renewable hydrogen production potential estimated for the UK. A significant proportion of the energy potential is used for fuel under these scenarios, though under GS using FCVs some 1,000PJ remains in 2050. Since this is hydrogen resource, converted at an efficiency of approximately 50% over the fuel chain, the raw renewable energy resource is around double that amount, at 2,000PJ.

### 3.6.2 Basic implications for alternative energy uses

The energy used to provide renewable transport fuel can not be used to meet other demands, such as stationary heat or power generation. This analysis does not attempt to analyse the merits of matching different resources and different demands. However, Table 11 shows results of the PIU Energy Review (PIU, (2002)) giving possible figures for energy demand in the UK in 2050, under a global sustainability and world markets scenario. Road transport demand has been removed to show the additional requirement if road transport demand is met from renewable fuels.

*Table 11: Possible energy use in the UK in 2050 under different scenarios (without road transport)*

| | Scenario | |
|---|---|---|
| *Sector* | WM | GS |
| Domestic | 2074 | 1534 |
| Service | 1184 | 767 |
| Non-road transport | 2740 | 994 |
| Industry | 1296 | 868 |
| **Total** | **7294** | **4162** |

Source: PIU, (2002)

The table shows final end use and not primary demand. Primary demand will be higher by a factor dependent on the conversion technologies used. The remaining renewable energy resource could not be applied equally to meet all demands. Aviation, for example, which comprises a significant proportion of non-road transport use, is not likely to be supplied by any renewable fuel other than bio-kerosene, which has a limited range of sources available. Other demands, such as electricity, can be supplied directly.

The additional renewable energy available under the different scenarios above varies between zero and 2,000PJ. Purely as an indication, 2,000PJ could meet most of the domestic sector demand for heat and power under WM, and exceed it under GS. This assumes combined heat and power production at approximately 80% overall efficiency. Industrial energy use could be supplied, with additional resource remaining.

The aspiration to provide 20% of UK electricity from renewable sources in 2020 (DTI et al., (2003)), would require electricity inputs of 280PJ under GS and 380PJ under WM. In the context of the transport scenarios, no hydrogen is required in 2020 for fuel cells, but the amount of renewable electricity required to meet the 2020 aspiration could nominally provide about 140PJ (GS) or 190PJ (WM) of hydrogen, about half of the requirements of the equivalent scenarios, in 2030. The $H_2$ ICE cases require 360PJ and 415PJ of hydrogen in 2020, respectively, and so would require a much greater penetration of renewable electricity than the current 2020 targets.

Under the lowest energy demand scenarios for both road transport fuel and other energy use (GS), the remaining renewable resource after fuelling 100% of road transport could meet almost half of remaining total energy requirements in 2050 (assuming a 50% overall conversion efficiency). Under the worst case of WM, no additional resource would be available and the whole of the 7,000PJ demand would have to be met in other ways (perhaps including the import of renewable energy).

### 3.6.3 $CO_2$ emissions

Figure 13 shows approximate $CO_2$ emissions trends under the different scenarios. As can be seen, the introduction of HEVs alone is not enough to reduce emissions significantly, and although they flatten or reduce slightly to 2035, they begin to rise again towards 2050. $CO_2$ emissions fall dramatically with the introduction of renewable hydrogen under all scenarios, with the greater efficiency of the FCVs countered by the earlier introduction of the ICE vehicles to give a similar result under each scenario. As would be expected, the final trend is towards zero.

Importantly, however, the $H_2$ ICE results must be considered in the context of the energy used to produce the hydrogen. In 2030 and 2040, the raw renewable resource remaining after the production of renewable hydrogen under the GS scenario is considerably less than that remaining under the FCV scenario. This means that any concurrent stationary power or heat production from renewable energy would be limited, and $CO_2$ emissions from sectors other than transport could be more difficult to control without imports. Under the WM scenario, not only would the raw resources be insufficient for hydrogen fuel production from 2030 onwards, but some level of imports – or hydrogen from other sources generally – would be required.

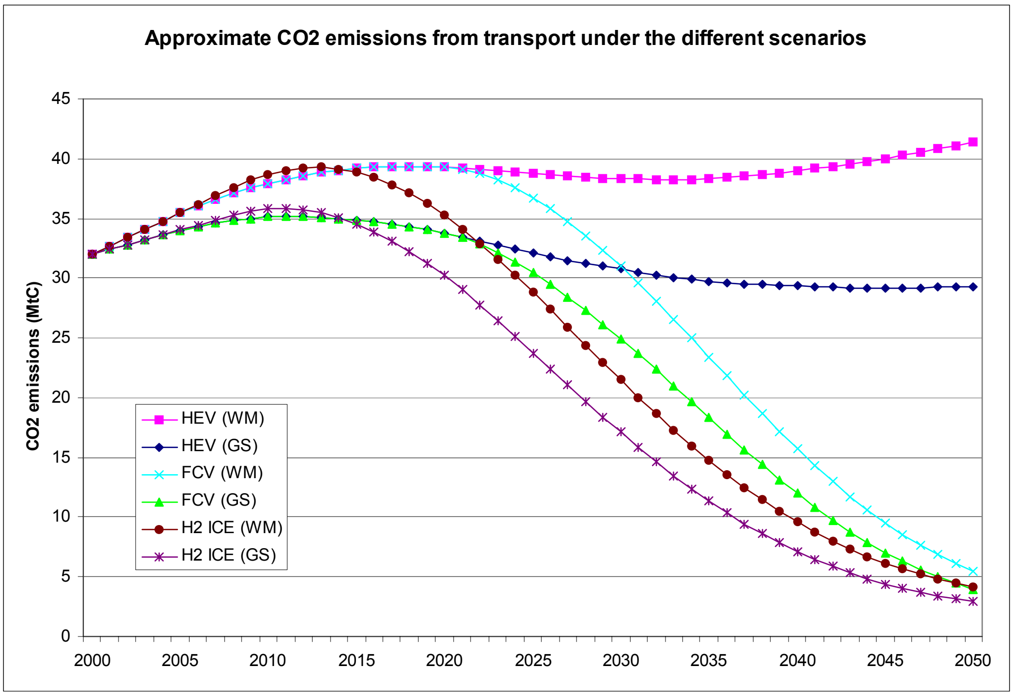

*Figure 13: Approximate $CO_2$ emissions trends under the different scenarios modelled to 2050*

Figure 13 shows only $CO_2$ estimated from energy use, and the curves are not the result of a detailed full fuel cycle analysis. Other greenhouse gases (e.g. methane) are not included, and the emissions from renewable hydrogen are assumed to be 95% less than those from conventional fuel. This is because some biomass fuel cycles, in particular, may have greenhouse gas impacts that are not zero due to factors such as fuel transport and processing.

### 3.6.4 Comments

Given the bold assumptions made for the modelling, these results cannot be more than indicative. However, they do show that, under certain circumstances, the UK could fuel its transport fleet using hydrogen produced from renewable resources. Under optimistic assumptions, sufficient renewable resource would remain to also provide a significant proportion of other energy requirements (heat and electricity). Under more pessimistic scenarios not only might there be no resource remaining for other uses, but also insufficient amounts for hydrogen fuel production.

$CO_2$ emissions drop markedly under all renewable hydrogen scenarios, but only after about 2015-2020, once the fuel has had some opportunity to penetrate the market. Similar $CO_2$ reduction curves can be achieved by both ICE vehicles introduced in 2008 with fairly rapid penetration, and FCVs introduced in 2020 with very rapid penetration, though ICEs will require significantly more resources to provide the hydrogen fuel.

## 3.7 Location of hydrogen generation

The location of generation of the hydrogen is likely to change over the period considered, as technologies develop and different renewable resources are exploited. However, a mix of solutions is likely at all times. In the near term, resources are likely to be of a small to medium-scale, and so some hydrogen will be generated close to the point of use, while a proportion will be transported for a greater distance.

However, a combination of factors suggests that until very large scale production plants and possibly hydrogen pipelines are available, the average distance for transport will not be great – perhaps 50-100 miles. The main considerations are the naturally distributed nature of renewable resources over the UK, and the cost of long distance hydrogen transportation. In some cases it may make sense for hydrogen to be generated at homes or workplaces, should a suitable resource be available. Even in the long term, the large scale centralised production plants are only likely to be based on wind electrolysis as the only concentrated renewable energy source, and so production from other resources will either be transported to points of local demand or put into a hydrogen gas grid.

The comparative economics of hydrogen depend significantly on transport distance, and so an expensive resource close to a demand site may be able to compete with a cheaper resource further away. Producing a simple marginal cost curve for resources is therefore not possible. However, in a given local area the resources will be exploited in order of economic viability, and so wind resources will typically be used before solar, for example. Under the assumptions of the model, all UK resources are exploited before imported hydrogen is considered. In a normal market this is unlikely, as imported hydrogen from very cheap renewable resources may be possible in the longer term.

These resources could include large-scale photovoltaic arrays in e.g. North Africa, followed by liquefaction and subsequent marine transport of the hydrogen, or perhaps even a hydrogen pipeline. Other sources may be large-scale biomass in e.g. South America, or wind, hydro or geothermal in Iceland. Some consideration of all of these options has been made, though none are currently viable or well-costed.

An alternative to transport of hydrogen is to transport an alternative energy carrier (methanol, ethanol and methylcyclohexane have all been considered at some point) and generate the hydrogen locally using a reformer. In some cases this may be cost-effective but will depend on the specific circumstances.

### 3.8 Sequestration

In the few cases where renewables are not capable of meeting the requirements under the model, imported hydrogen has been considered as the means of filling the gaps. However, an important alternative not considered in great detail in this analysis is fossil hydrogen with carbon sequestration. Hydrogen is likely to be produced from fossil fuels in many instances in any case, as it is currently cheaper than most renewable routes. Removing the carbon from the exhaust stream and storing it – probably underground – is an option that is under consideration to meet long term $CO_2$ reduction targets. This adds cost to the production process (about 20% has been calculated for the cheapest case (Foster-Wheeler, (1996); Foster-Wheeler, (1998))) and reduces the efficiency. In addition, not all of the $CO_2$ can be removed in some cases. However, the reductions are of the order of 80-90% and hence significant.

### 3.9 UK Knowledge base – strengths and weaknesses

The UK is not generally recognised as a leader in hydrogen energy, though some of the companies based in the UK have strong hydrogen energy activities in other areas of the world. In addition, pockets of world-class knowledge exist in the academic and industrial R&D communities. The following is an indicative summary of some of these areas of expertise.

*The UK has strengths in:*

- Large-scale energy and fuel provision in general:
    - Companies such as BP and Shell (including some expertise from Shell Hydrogen) are actively working on hydrogen energy concepts and funding demonstrations worldwide.
- Industrial Gases, including hydrogen:
    - BOC and Air Products are both very active in this area, participating in demonstrations and building businesses around hydrogen energy.
- Materials and other industrial processes:
    - Ineos Chlor and Johnson Matthey/Synetix have interests in fuel provision – electrolysis and fuel processing. Some much smaller companies also have relevant technology, e.g. Hydrogen Solar with a novel hydrogen production technology, and Progressive Energy, developing novel methods for $CO_2$-free hydrogen production from fuels such as coal.
- Renewable energy integration:
    - Although other countries have arguably greater strength in this area, companies such as Amec have a worldwide presence in large-scale engineering, including renewables, and a strong passive interest in hydrogen. Small companies such as Element Energy are developing specific skills here.
- Finance:
    - The UK has a large and world-renowned finance sector, with considerable interest in renewable energy and a smaller interest in hydrogen. One of only three venture capital funds focused on hydrogen energy and fuel cells is headquartered in London – Conduit Ventures. Core Technology Ventures, a second, is currently fund-raising for a similar fund, again to be based in London. However, companies financed to date have been outside the UK, due to the stronger support mechanisms and policy framework in other countries.
- Academia:
    - UK work is largely fragmented, and further analysis could be done in this area to assess real relative strengths. As a sample, however, Glamorgan has good work on biomass-based direct hydrogen production such as fermentation; Birmingham has a strong group working on hydrogen storage; Imperial College has strengths in hydrogen energy economics and policy in particular; and many other universities have specific analysis ongoing, e.g. in electrochemistry.
- Fuel cells:
    - The UK has several companies with fuel cell expertise, though the strongest with potential for use in vehicles is Intelligent Energy, and Johnson Matthey supplies many world leading companies with fuel cell components. While the UK is not home to major vehicle development centres, skills in vehicle engineering, motor racing and rapid prototyping

    (Ricardo, ProDrive, Lotus, etc.) could potentially be used here to significant effect. The proposed Centre of Excellence in this area could catalyse further work, though a framework for demonstrations and policy support is also important for overseas manufacturers to develop strong local partnerships and demonstrations.

*Possible UK weaknesses are in the following areas:*

- Alternative fuels, to some extent:
    - Some UK programmes have done well, and the current increasing uptake of alternative fuels appears to bode well for the future. However, other countries have much greater levels of penetration and experience with some fuels.
- Fuel cell and hydrogen vehicle development and demonstration:
    - Although London is a partner in the EU-funded CUTE project with three fuel cell buses to come in 2004, other countries have had demonstration projects for a considerable period.
- Breadth of work:
    - Although world-class work is ongoing in several areas of hydrogen energy in the UK, some key areas are not included, and a wider spread of work in all sectors could encourage the development of a coherent industry.

*Possible ways forward include:*

- The development of the proposed fuel cell centre of excellence for vehicles could act as a catalyst for bringing together much of the research work. However, support both upstream and downstream of this effort are required to support the fundamental research and also the demonstration of technologies developed in this way.
- Further analysis and integration with any work ongoing in other energy areas will be required to understand the potential for both synergies and trade-offs. For example, will demand for renewable fuels in transport help to drive the demand for renewables generally, or will it simply displace them from uses elsewhere? Equally, can integrated energy systems be developed, where perhaps both transport and stationary fuels are generated or used?
- Strategic development of alternative fuel demonstration projects in both hydrogen and biomass. The UK is seen as interesting but not essential by many car manufacturers, but has potential to be attractive to alternative fuel and powertrain suppliers, due to its high fuel duty and densely populated island nature. The latter means that infrastructure development might be more easily financed than in some other countries.
- Participation in international efforts, such as the International Partnership for a Hydrogen Economy (IPHE) and the Hydrogen Technology Platform and Advisory Council generated by the EU’s High Level Group on Hydrogen and Fuel Cells will be very important. Although they may require a reasonably high level of commitment, they can be used to ensure common goals on standards, and help define the UK position. Equally, participation in the IEA Hydrogen

Annexes could be re-evaluated, as it is possible the UK could play a significant role in more areas than it currently is.

- A UK hydrogen energy association of some form would assist in co-ordinating efforts from an external perspective. Whether or not initially funded by government in the same way as Fuel Cells UK, the association should be significantly focused on serving and assisting industry in the area of hydrogen energy.

*International gaps in knowledge are less easy to find:*

- Hydrogen storage is a key area for improved performance of hydrogen vehicles, and the UK conducts excellent work in this area that should be encouraged. The prize is very big, but the international efforts are so large as to make the likelihood of unique breakthroughs small.
- The UK has strengths in innovative vehicle design and rapid prototyping that could be used for more radical developments in alternative fuel vehicles. Redesigning the vehicle around a new architecture – the fuel cell system – much as GM has done with the HyWire, could result in significant improvements in range and performance.

### 3.10 International comparisons

Germany, Japan, Canada and the USA are the leaders in the area of hydrogen and fuel cell vehicles, though some vehicle development is ongoing in both France and Italy. The four countries have large and well-targeted efforts including significant demonstration funding from either national or regional governments.

Demonstration projects are viewed as essential in these countries to enable (a) an increased understanding of infrastructure requirements and potential, (b) public exposure to the technologies, which will strongly influence future technology development and policy, and (c) an assessment of performance of the technologies under real-world conditions.

Each of these countries has a significant effort spread right across from fundamental research to demonstration, enabling most or all of the stages in the value chain to be assessed and developed.

### 3.11 Current UK support programmes

*R&D programmes*

- The majority of work funded in the area of hydrogen energy is under the remit of the EPSRC, though some joint work with other Research Councils is ongoing, for example under the Tyndall Centre.
- Some specific work has been commissioned for or funded by other bodies, such as the DTI, DfT and Carbon Trust.
- No specific DTI or other programme exists at present, which is potentially a serious gap as technologies may be inhibited from development.

*Grant programmes*

- Grants specifically for hydrogen are very limited. Although some funding has been available under the Green Fuels Challenge this is a removal of duty rather than a source of funding.

## 3.12 Steps to move to a renewable hydrogen-based fuel system

Ultimately, the allocation of finite renewable energy resources amongst competing uses will be most efficiently achieved through a market mechanism. From a greenhouse gas perspective, renewable energy may be better used in displacing conventional stationary heat and power plants. However, the overall framework should be focused upon the energy, environment and transport goals of highest importance for the UK, which are likely to include greenhouse gas reduction, air quality improvement and affordable mobility and energy. Given that markets for renewable electricity already exist, any desired production and uptake of renewable transport fuel would require policy incentives to alter the price balance between different uses of renewable energy. For these to operate effectively, the policy framework which creates the demand for each type of renewable energy use must be stable and long term. Depending upon the overall balance of the policy goals, a number of different vehicle energy technologies could be preferable.

If renewable hydrogen as a transport fuel were seen as a favoured route to satisfy a long term policy goal(s) then several steps would be needed to move towards its use. Hydrogen vehicles would need to be encouraged, with suitable fiscal or other incentives for their deployment as well, potentially, as their development by UK organisations. At the same time hydrogen fuel provision would have to be encouraged in a similar manner to other alternative fuels. In the near term it appears unlikely that renewable hydrogen will be available for vehicle use, given the alternative demands for renewable energy, and so a case may be made for other hydrogen sources, such as natural gas. However, policy measures to encourage renewable or low-carbon production of hydrogen should be put in place for the longer term to ensure that fossil sources are not used if renewable resources are available.

It will be important to put measures in place as soon as the direction of policy becomes clear, in order to ensure that pathways are not closed off in the short term. Concentrating only on near-term measures, such as increased fuel efficiency, could push back the time when more significant changes could be made.

## 3.13 Future possibilities for cost reduction or increased benefits of hydrogen technologies

- Many hydrogen technologies, particularly those using renewable energy, are currently expensive. However, these are typical of any new technology requiring large-scale materials sourcing, further product engineering design, and mass-manufacture. Even fuel cell systems, cited as having very high costs, could move towards cost parity with conventional prime mover systems. With current technology and performance, even mass-produced fuel cells will not reach the lowest costs of conventional technologies. However, both cost and performance are being continually improved in line with the improvement in scientific understanding of fuel cell physics and electrochemistry.

- Costs of hydrogen delivered outside a large industrial site are also high at present, though in bulk, hydrogen from some fossil fuels has a very low cost. Costs will come down generally as alternative resources and technologies are explored, and competition between suppliers enters the equation. Hydrogen cost depends on feedstock cost, but the many different possible sources suggest that long-term hydrogen prices will be bounded much more than oil and gas prices, due to the difficulty of supply side collusion. Costs from alternative resources currently appear to set the maximum cost of delivered hydrogen, and this can only drop as they drop, so while the timeframe depends on speed of technology uptake, the cost curves could be predicted if required.

# 4 Biofuels

**Future energy resource requirement**

- Two uptake scenarios have been modelled in combination with the Global Sustainability and World Markets scenarios described in chapter 3. The slow uptake scenario assumes that biofuels penetrate to only half of the indicative targets for 2005 and 2010 set by the EU Biofuels Directive, whilst the rapid uptake scenario achieves double the targets. Both scenarios then allow biofuels to totally displace conventional fuels by 2050.
- High efficiency vehicles are assumed to penetrate the vehicle parc from 2004, as under the hydrogen scenarios.

**Prospective UK supply**

- The main biofuels are synthetic diesels, which can be burned in compression ignition (diesel) engines, and bioethanol which can be burned in spark ignition (petrol) engines. Blends of these with petrol and diesel are commonly used, and in the case of ethanol an ether, ETBE, can be blended as an oxygenate.
- Biodiesel is currently in use in the UK and is expected to grow steeply in the coming year. This is chiefly based upon esterification of waste vegetable oil and rapeseed. R&D is focused on the gasification of lignocellulosic feedstocks such as wood and straw which can be then converted via a Fischer-Tropsch process to a mixture of diesel, kerosene and naphtha.
- Bioethanol is in use in many countries, but not currently in the UK. Present-day commercial production is based upon hydrolysis and fermentation of starch and sugar crops, which in the UK are mainly wheat grain and sugar beet. Hydrolysis technology is currently at the demonstration stage, which would in the future allow the use of more widely available resources such as wood and straw.
- In the modelling, both current and future ethanol and diesel fuels are assessed, produced from a total of four crop types and six residues or wastes. The maximum area available for energy crops is assumed to be 4 million hectares (Mha), after allowing for food production. For reference, the area under set-aside in 2000 was 0.57 Mha and cereal crops, 3Mha. Other studies have assumed available areas in the range 1-5.5 Mha, though it is acknowledged that this area is very hard to assess.
- The modelling results show that for slow biofuel uptake under both Global Sustainability and World Markets scenarios, the UK could meet its own biofuel needs from indigenous sources to 2020. 1.3 and 4 Mha of energy crops respectively would need to be planted by 2020. Under rapid biofuel uptake a small amount of imports would be required from around 2020.
- Under all scenarios, imports are required beyond 2020, as the availability of more efficient conversion processes cannot compensate for the growth in demand and the limited UK resource. The import requirement in 2050 is around two thirds of total fuel demand, with the World Markets scenarios requiring a third more imports in volume terms than those under Global Sustainability.

- In practice the land use for rapid biofuel uptakes would be very hard to achieve in the 2020 timeframe. The setting of realistic biofuel targets and the availability of more efficient lignocellulosic biomass-based technologies could significantly reduce potential land requirements.
- Although land is reserved under the model for food production, no allocation is made to alternative biomass energy uses such as stationary heat and power. As an indication, in 2020, sufficient biomass resources would be left under the slow uptake scenario to produce approximately 50TWhe (out of a total UK forecast electricity demand of 400TWhe) and 30TWhe under rapid uptake.

**Biofuel issues**

- Production costs of biofuels vary according to resource and conversion technology, but midrange projections suggest that advanced technologies could achieve costs that are around three times current petrol and diesel costs. This ignores the value of co-products which are derived from some biomass conversion processes.
- Biofuel chains have $CO_2$ emissions as a result of fertilisers and transport inputs, despite their combustion CO2 being offset by that absorbed in the growing cycle. The variation between chains is wide, but tends to be lower from the more advanced technologies.
- Biofuels are already traded internationally to a small extent, mainly originating in the US and Brazil.
- UK companies are showing increasing interest in biofuel production technologies, though traditionally these areas have been dominated by US, Canada, Germany, France and Sweden. The UK has strengths in plant science and other areas which support aspects of the necessary conversion technology development.

### 4.1 Biomass energy

Biomass energy can be derived from various sources: dedicated plantations; residues from primary biomass production; and by-products and wastes from a variety of processes. Some examples of the wide range of biomass resources are provided in Table 12.

In industrialised countries, most biomass energy use today is based on conventional crops such as sugarcane, corn, sugar beet and rapeseed for the production of ethanol and biodiesel, and on residues from the forestry and wood processing industry for the production of heat and electricity. Agricultural residues, such as straw, are used in much smaller quantities. Dedicated energy crops, such as short rotation coppice, for heat and electricity are rare.

*Table 12: Examples of biomass resources*

| Biomass resource categories | Examples |
|---|---|
| Dedicated plantations | Short rotation forestry and crops such as willow. Perennial annual crops such as miscanthus. Arable crops such as rapeseed. |
| Residues from primary biomass production | Wood from forestry thinning and felling residues. Straw from a variety of cereal crops. Other residues from food and industrial crops such. |
| By-products and wastes from a variety of processes | Sawmill waste, manure, sewage sludge, organic fractions of municipal solid waste, used vegetable cooking oil, etc. |

Biomass potentially has a very wide range of uses, so producing fuel must be considered in the context of other alternatives. In addition, co-products from the different processes will vary, and may in themselves be valuable. Greenhouse gas analysis is especially complex, as a result of the biological interactions of carbon and nitrogen compounds in the soil, amongst other factors.

## 4.2 Introduction to biofuels

Many different fuels can be derived from biomass: biodiesel, bioethanol, biogas, Fischer-Tropsch diesel, dimethyl ether (DME), methanol, synthetic gasoline, hydrogen and electricity. A market for renewable transport fuels exists today based on ethanol from the fermentation of sugar and starch crops and biodiesel from oil crops. The market for these fuels has developed mainly as a result of air quality and energy security issues, and to support the agricultural sector. Hence, ethanol and biodiesel, mainly blended with petrol and diesel, respectively, are commonly used in several countries (e.g. the US, Brazil, France and Germany). It is estimated that 25 Billion litres (Bl) of bioethanol for fuel and about 3 Bl of biodiesel were consumed globally in 2002 (Woods and Bauen, (2003)). In particular, the production and consumption of bioethanol as a fuel oxygenate is growing rapidly. UK biodiesel production is currently about 35 Ml per year and is expected to rise to about 280 Ml per year in the next year, mainly based on waste vegetable oils. There is currently no bioethanol fuel production in the UK. Interest is growing from industry and policy makers in advanced technologies for the production of synthetic diesel and ethanol, and in renewable hydrogen from biomass. These could offer greater production efficiencies, lower costs, and a broader biomass resource base. However, these technologies are currently at the pilot or demonstration stage.

An EU Directive is aimed at facilitating the introduction of biofuels for transport (European Commission, (2003)). The indicative aim is to supply 2% (by energy) of road transport fuels with biofuels by 2005 and 5.75% by 2010. Biodiesel from oil crops and bioethanol from sugar beet are likely to be the dominant biofuels given their commercial maturity relative to other biofuel options.

## 4.3 Biofuel summaries

An indication of the many different biofuels, related production routes and biomass feedstocks are illustrated in Figure 14. The most important and relevant ones are discussed in detail subsequently. Table 14 provides a summary of biofuel costs and

Table 15 a summary of $CO_2$ emissions based on emissions from all stages of the biomass production chain.

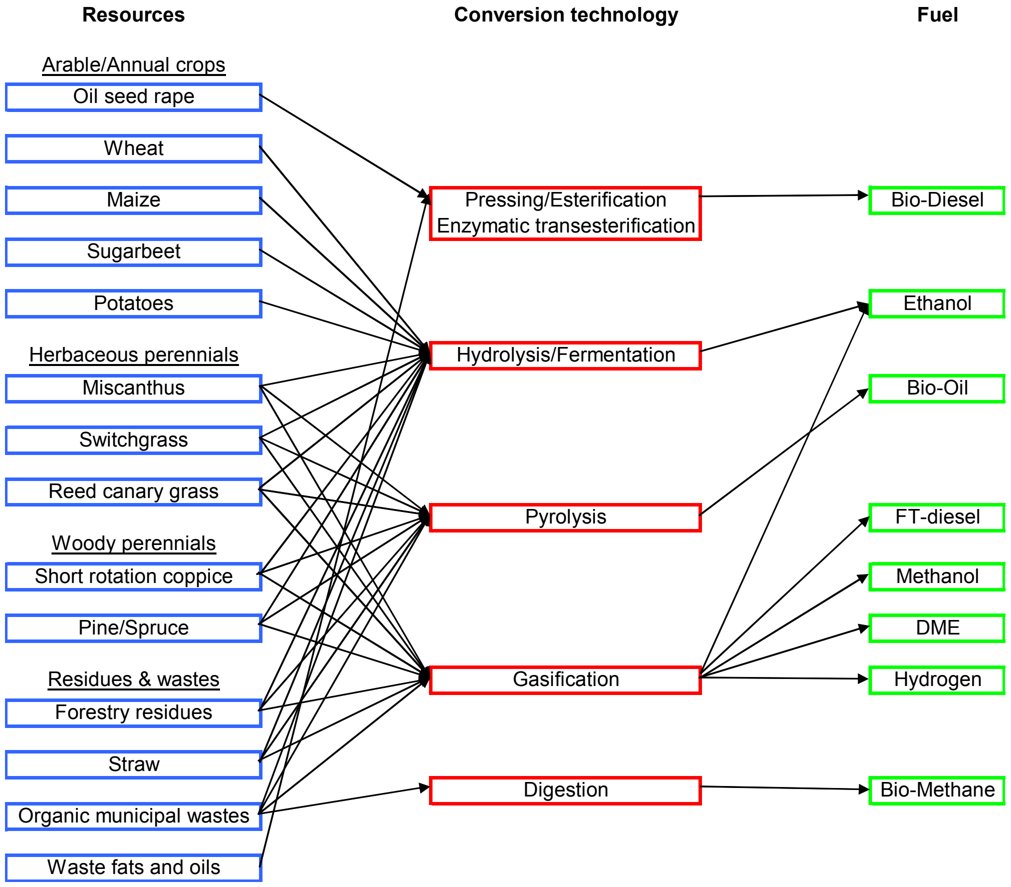

*Figure 14: Biomass-based transport fuel chains*

## 4.4 Biodiesel

### 4.4.1 Production process

Biodiesel[3] can be produced via two principal routes:

1. The extraction of oil from seeds or oil-rich nuts followed by its esterification.
2. The purification and esterification of recovered waste vegetable oils and animal fats. This is more complex than for pure vegetable oils such as rapeseed oil, as the greater concentration of free fatty acids and impurities, such as water, need to be treated or removed.

The blending of vegetable oils with diesel at the refinery is also an option.

### 4.4.2 Feedstock

Biodiesel can be produced from all oil producing crops. In the UK, rapeseed and sunflower are the principal potential sources of biodiesel. Rapeseed represents more than 80% of current global biodiesel production, sunflower 13%, soya bean 1% and

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[3] Biodiesel is also commonly known as Vegetable Methyl Ester (VME) or Fatty Acid Methyl Ester (FAME).

palm oil 1%. Recovered cooking oils and animal fats are another source of biodiesel production.

### 4.4.3 Co-products

The production of biodiesel (rape methyl ester – RME) from rapeseed leads to three major co-products: rape straw, rape meal and glycerine. The straw has a potential value as an energy feedstock to provide heat to the conversion process and / or for the production of electricity or other biofuels (e.g. ethanol). Rape meal has value as a cattle feed and can substitute for imported soya meal. Glycerine, used in the soap making and cosmetics industry, is produced at a rate of about 100kg per 1000kg of esters.

### 4.4.4 Status

All stages of the biodiesel chain can use proven commercial technologies and a number of European countries have an established biodiesel industry, e.g. Germany, Austria and France (based on rapeseed and recovered vegetable oils). Marginal improvements are expected in rapeseed yields and in reducing the energy requirement for oil extraction and esterification.

### 4.4.5 Fuel quality and specifications

The esterified vegetable oils produce a fuel with physical properties similar to those of mineral diesel, with some key differences. Biodiesel has a lower energy content than mineral diesel and around a 10% loss in power can be expected in vehicles powered with 100% biodiesel compared to mineral diesel. It has better lubricant properties than modern ultra low sulphur diesel. It is corrosive to rubber, so that components in the fuel delivery systems need to be replaced with resistant alternatives.

### 4.4.6 Costs

Costs vary widely depending on location, climate and other factors, though a larger market and the availability of substitutes would help to stabilise prices over the longer term.

RME supply costs excluding subsidies and co-product values are estimated to be between £20 and £33/GJ RME (£0.60 and £1.00 per litre). Because of the maturity of the chain there is likely to be little scope for cost reductions. The cost of rapeseed production ranges between £14 and £26/GJ RME. The costs exclude revenues from co-products and any agricultural subsidies. Conversion costs are estimated to be about £6/GJ RME. Current revenues from co-products are estimated to range between £1.5 and £6.5/GJ RME. The costs of biodiesel including revenues from co-products and subsidies are estimated at £0.24 per litre (Woods and Bauen, (2003)).

Biodiesel production from recovered vegetable oil (WVOME), costing around £0.15 per litre, is estimated at £7.6/GJ WVOME (£0.26 per litre).

The blending of vegetable oils with diesel at the refinery could lead to lower costs of biodiesel blends as a result of economies of scale.

## 4.5 Bioethanol

### 4.5.1 Production process

Ethanol can be produced via different biological routes depending on the feedstock. Fermentation is used to produce ethanol from sugar crops. A sequence of hydrolysis fermentation steps is used to produce ethanol from starch crops and lignocellulosic feedstocks.

### 4.5.2 Feedstock

Possible feedstocks for ethanol production in the UK are sugar beet, wheat grain, straw, wood and energy grasses such as miscanthus. Other possible sources are corn (mainly used in the US), sugarcane (mainly used in Brazil) and sweet sorghum.

### 4.5.3 Fuel quality and specifications

Ethanol has been in common use in transport for about 30 years around the world as both neat ethanol and as a blending agent / oxygenate in petrol.

A 10% (v/v) ethanol blend in gasoline contains about 97% of the energy of pure gasoline, but this is compensated by increases in combustion efficiency of ethanol blends leading to similar volumetric efficiency. If ethanol blends are increased to >20% (v/v), a higher compression ratio is needed to produce similar power to that of a same size petrol engine.

Alternatively, ethanol could be converted to the ether ETBE (Ethyl Tertiary Butyl Ether). ETBE can be used as a direct replacement for MTBE (Methyl Tertiary Butyl Ether). MTBE blends of up to 15% are permissible under EU and UK regulations but MTBE is only used in smaller percentages in the UK.

### 4.5.4 Co-products

Ethanol production from sugar beet and wheat grain can also potentially lead to a number of valuable co-products such as animal feed, electricity and heat, secondary plant compounds and oils for the cosmetics and health industries. In the case of ethanol from lignocellulosic feedstocks, possible co-products include heat and electricity.

### 4.5.5 Status

The efficiency of fermentation and distillation of sugars obtained from crops such as sugar beet is nearing its limit, though recent developments in membrane distillation may produce some energy and emissions savings.

Recent R&D has concentrated on starch and cellulose hydrolysis to produce simple sugars followed by their fermentation using existing technologies. Ethanol produced from starch is a commercial process today. Developments have focused on ways to reduce energy requirements and increase yields aimed at improving the energy ratio. However, ethanol production from lignocellulosic biomass is still at the demonstration stage.

### 4.5.6 Costs

**Ethanol from sugar beet and wheat grain.** Ethanol production costs from sugar beet and from wheat grain are estimated to be similar at about £15 per GJ EtOH, equivalent to 32p/l, excluding co-product credits (Woods and Bauen, (2003)). The cost the sugar beet and wheat grain feedstocks is estimated to be about £9 per GJ EtOH, conversion process costs are estimated at about £5 per GJ EtOH, and transport costs at about £0.6 per GJ EtOH. However, in some cases transport costs as high as £3.41 per GJ EtOH have been quoted, including margins. The influence of co-products on the price of ethanol could be significant, with the potential value of the co-products estimated to range between £2.5 and £4.5 per GJ EtOH.

**Ethanol from wheat straw and wood from short rotation coppice.** Lignocellulose hydrolysis processes are at the demonstration stage and costs of future commercial plant are based on projections. Ethanol production costs from wheat straw could lie between £9 and £15/GJ EtOH, equivalent to 19 to 32p/l (Woods and Bauen, (2003)). Ethanol production costs from SRC wood could lie between £8 and £19/GJ EtOH, equivalent to 18 to 43p/l. UK-specific feedstock costs are estimated to lie between £25 and £35 per tonne (dry) for delivered straw (£3.7 and £5.2/GJ EtOH), but during periods of high demand these may be much higher (e.g. up to £55/t), and between £20 and £40 per tonne (dry) for delivered SRC wood chips (£2.4 and £5.0/GJ EtOH). Conversion costs are estimated to lie between £5 and £9/GJ ETOH.

## 4.6 Biomethane

Natural gas vehicles can be run on methane produced from biomass sources, such as organic MSW, sewage sludge and farm slurries. These wastes can be anaerobically digested, to produce biogas, containing 55-70% methane, together with $CO_2$ and other gases. Similarly, anaerobic digestion within landfills produces gas, of similar composition. Methane can then be separated from the biogas, cleaned up (desulphurisation and drying), and compressed or liquefied for use in vehicles. There are several projects worldwide producing and using biomethane for vehicles directly, such as for buses in Sweden, and via the natural gas grid, for example supermarket delivery trucks in Switzerland.

It is possible to fuel all vehicle types with methane. However, currently, the main driver for natural gas use in vehicles in the UK is reduced air pollutant emissions, especially when compared with diesel. As a result, there is most interest in natural gas for heavy vehicles such as PSVs and HGVs, which operate in urban areas. These vehicles can also easily accommodate gas storage cylinders.

Table 13 shows the potential for biomethane as a transport fuel in the UK. Assuming that all vehicles were methane fuelled, a maximum of 13% could be fuelled with biomethane. If methane use were prioritised for heavier diesel vehicles (see above), biomethane could provide up to 53% of the fuel requirement.

*Table 13: Possible contribution of biomethane to UK fuel requirements in 2000.*

| Resource | Estimated resource potential | Biomethane potential PJ/yr | % of total fuel requirement | % of heavy vehicle fuel requirement |
|---|---|---|---|---|
| Biodegradable MSW | 25 Mt/yr | 120 | 7% | 30% |
| Sewage sludge | 1.45 Mt/yr | 7 | ~0% | 2% |
| Farm slurries | 2.4 $TWh_e$/yr | 25 | 4% | 15% |
| Landfill gas | 6 $TWh_e$/yr | 62 | 1% | 6% |
| Total | - | 214 | 13% | 53% |

It should be noted that biodegradable MSW and sewage sludge can be used for hydrogen and liquid biofuel production, and therefore their use for biomethane would reduce the potential resource for other fuels. Biogas from all of these sources can also be used in heat and power generation. It is therefore believed that only a fraction of the resources in Table 13 would be available for biomethane production as a transport fuel, farm slurries and landfill gas in particular.

The resources for sewage sludge, farm slurries and landfill gas are not expected to increase significantly to 2050. However, MSW production is currently increasing at 3% per annum, and is thought likely to continue to increase at least until 2020. Therefore in 2050, the possible contribution of biomethane to the (greatly increased) fuel requirement remains at around 13%.

Biomethane is not considered further in the modelling because of its relatively limited potential and niche applicability.

## 4.7 Fischer-Tropsch synthetic diesel[4]

### 4.7.1 Production process

Lignocellulosic feedstocks (e.g. wood or straw) are gasified and then converted to a mixture of kerosene, diesel and naphtha in a Fischer-Tropsch (FT) process. The diesel fraction could be used to substitute fossil diesel as a transport fuel, kerosene could also be used as a fuel in aviation or for other energy use, and naphtha could be used as a chemical feedstock. Lighter gaseous hydrocarbons are also produced by FT reactors, which can be used to generate heat and electricity.

### 4.7.2 Fuel quality and specifications

FT-biodiesel is chemically similar to mineral diesel and can be used as a direct mineral diesel substitute.

### 4.7.3 Feedstock

A potentially wide range of biomass feedstocks can be used, including agricultural, forestry and biodegradable municipal solid wastes, and wood and grass energy crops.

### 4.7.4 Co-products

In addition to synthetic diesel, the FT process produces a mix of naphtha and kerosene. Electricity and heat may be co-produced with the FT-liquids and used to provide energy required for the conversion process.

### 4.7.5 Status

Biomass gasification technology is at the demonstration stage, while FT process technology is mature. However, the integration of biomass gasification with the FT process is only at a demonstration stage. In Europe, a single pilot plant in Germany produces FT-biodiesel.

### 4.7.6 Costs

FT-biodiesel production from short rotation coppice wood in relatively large scale facilities (400 MWth biomass input) could be between £9 and £15/GJ FT-biodiesel (32 to 54p/l), excluding electricity credits (Woods and Bauen, (2003)). Surplus electricity sales could result in an income of between £0.77 and £2.3 per GJ FT-biodiesel. Feedstock costs (delivered) are estimated to be between £3.3 and £7.9/GJ FT-biodiesel.

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[4] Fischer-Tropsch synthetic diesel is also commonly known as Biomass-to-Liquids (BtL)

Table 14 indicates costs of biofuels produced in the UK, while Table 15 summarises estimated greenhouse gas emissions from their production.

*Table 14*: *Costs of UK biofuel production (ex-tax)*

| **Fuel** | **Feedstock** | **Total supply cost (excluding co-products value[1] and subsidies)** | | |
|---|---|---|---|---|
| | | **£/GJ** | **£/l** | **£/km** |
| Biodiesel[2] | Rapeseed | 20-33 | 0.60-1.00 | 0.04 – 0.07 |
| Biodiesel[2] | Waste veg. oil | 14-26 | 0.42-0.78 | 0.03 – 0.05 |
| Bioethanol[2] | Sugar beet | 15 | 0.32 | 0.04 |
| Bioethanol[2] | Wheat grain | 15 | 0.32 | 0.04 |
| Bioethanol[3] | Wheat straw | 9-15 | 0.19-0.32 | 0.02 – 0.04 |
| Bioethanol[3] | SRC | 8-19 | 0.18-0.43 | 0.02 – 0.05 |
| FT-diesel[3] | SRC | 9-15 | 0.32-0.54 | 0.02 – 0.03 |
| Petrol / Diesel | Oil | 5.20[4] | 0.19 | 0.01 – 0.013 |

[1] Co-product values have been excluded as it is difficult to determine the exact nature of co-products and their influence on the cost of biofuel over the time period considered in the study, and in relation to the potential growth in biofuel supply.

[2] Based on available commercial technology

[3] Based on projected future commercial technology

[4] Based on circa $30 per barrel oil price.

*Table 15: Estimated greenhouse gas emissions from UK biofuel production*

| **Fuel** | **Feedstock** | **GHG emissions[1] (kg $CO_2$ equivalent/GJ fuel produced)** |
|---|---|---|
| Biodiesel | Rapeseed | 17-45 |
| Biodiesel | Waste veg. oil | 1.9-16.1 |
| Bioethanol | Sugar beet | 30-90[2] |
| Bioethanol | Wheat grain | 26-77[3] |
| Bioethanol | Wheat straw | 8-72 |
| Bioethanol | SRC | 4-90 |
| FT-diesel | SRC | 2.4-29 |

[1] Emissions account for fossil fuel inputs to biomass feedstock production and transport

[2] Low value assumes use of sugar beet pulp to fuel conversion

[2] Low value assumes use of straw to fuel conversion

## 4.8 Hydrogen

As discussed in chapter 2, hydrogen can also be produced from biomass resources, by a range of routes. This is an important area of crossover in the development of a long-term strategy for low-carbon fuels in the UK.

## 4.9 Other biofuels and processes

A number of other fuels can be produced from biomass, of which biogas, methanol, DME and electricity are the most relevant. While these may be used in niche markets of a certain significance, they are unlikely to capture a substantial share of the transport fuel market in the future. However, the potential for biogas production from a range of wet organic wastes is large and it could also provide a substantial source of hydrogen via a reforming process.

DME can be used as a clean and efficient fuel in diesel engines. It has the advantage that all syngas can be converted to DME in a dedicated plant, as opposed to a Fischer-Tropsch diesel process that results in fractions of synthetic diesel, kerosene and naphhta. However, DME requires dedicated infrastructure and on-board storage, as opposed to synthetic diesel that can be integrated in the fossil diesel infrastructure.

In the future, hydrogen could be produced directly from wet organic wastes via fermentation, a technology currently at the research stage. Also, synthetic gasoline could be produced through pyrolysis, and research is being carried out in this area. This report has considered ethanol production via solid biomass hydrolysis and fermentation routes, but ethanol could also be produced via the fermentation of syngas obtained from the gasification of solid biomass, a process currently at the research / pilot stage. Promising alternative processes for the production of biodiesel are also being investigated, such as the enzymatic transesterification using lipase.

## 4.10 Scenarios and pathways for the UK

### 4.10.1 Background

Scenarios have been modelled to investigate the potential implications of a large-scale introduction of biofuels in the UK, over the period 2000-2050. The scenarios are intended to investigate the potential biofuel production from a variety of indigenous biomass resources and potential import requirements. The approximate $CO_2$ emissions implications of the scenarios are also investigated, to enable analysis of the ways in which the UK might meet its aspirations of a 60% cut in $CO_2$ emissions from 1990 levels by 2050.

Similarly to the renewable hydrogen scenarios, the biofuel scenarios have been built around a base case. The base case relates to vehicle distance driven and has two variations, a ‘Global Sustainability’ (GS) option, in which vehicle distance driven increases gradually from 2000 but then peaks and drops slightly to 2050; and a ‘World Markets’ (WM) option, in which vehicle distance driven increases throughout the period. These scenarios are intended to represent plausible extremes, allowing the implications of the introduction of biofuels to be tested.

Two biofuels scenarios have been modelled for each of the ‘Global Sustainability’ (GS) and ‘World Markets’ (WM) scenarios. Both scenarios assume a complete transition to biofuels by 2050, but the first assumes a slow uptake of biofuels between now and 2020 and the second assumes a rapid uptake between now and 2020. The slow uptake scenario assumes an introduction of biofuels at a level of about half the indicative targets set out for the EU in the biofuels directive European Commission, (2003)). The rapid uptake scenario assumes biofuels introduction levels about double those set out in the directive (The scenario assumptions are shown in Table 16).

### 4.10.2 Assumptions

Assumptions with regard to total vehicle kilometre travelled, vehicle efficiency and energy consumption are the same as those described in section 3.5 on renewable hydrogen penetration scenarios. In the case of the biofuels scenarios only the penetration of ICE HEVs is considered, as opposed to the modelling of hydrogen-fuelled ICE and FCV vehicles penetration in the case of the hydrogen scenarios. This is illustrated in Figure 15.

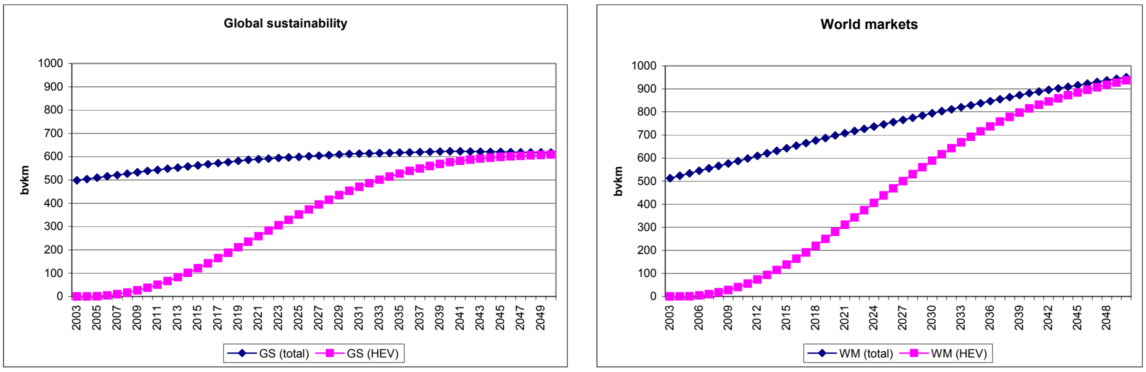

*Figure 15: Total vehicle km travelled, showing penetration of HEVs under the Global Sustainability and World Markets scenarios*

### 4.10.3 Biofuels penetration

Assumptions have been made on the rate of penetration of biofuels and on the different biofuels' shares, including the different processes they may be derived from. The assumptions with regard to different biofuel shares and related processes are based on considerations of technology availability and possible future costs. An underlying consideration that has been adopted is that biofuels will be provided by a variety of resources and processes. Furthermore, it is assumed that biomass will be used to produce equal shares of fuels aimed at replacing petrol and diesel. Ethanol from fermentation and hydrolysis processes is assumed to replace petrol. Two sources of diesel substitute, vegetable oil-based biodiesel and synthetic diesel from a lignocellulosic biomass-based Fischer-Tropsch process, are assumed to replace diesel. Table 16 provides details of the assumptions regarding biofuel penetration and respective breakdown.

*Table 16: Biofuels penetration assumptions*

| **Biofuels shares** | **2010** | **2020** | **2050** |
|---|---|---|---|
| *Slow penetration* | | | |
| Total | 3% | 5% | 100% |
| Breakdown | | | |
| Biodiesel | 1.5% | 2.5% | 0.0% |
| Ethanol (fermentation) | 1.5% | 1.5% | 0.0% |
| Ethanol (hydrolysis) | 0.0% | 1.0% | 50.0% |
| Fischer-Tropsch biodiesel | 0.0% | 0.0% | 50.0% |
| *Rapid penetration* | | | |
| Total | 10% | 20% | 100% |
| Breakdown | | | |
| Biodiesel | 5% | 6% | 0% |
| Ethanol (fermentation) | 5% | 7% | 0% |
| Ethanol (hydrolysis) | 0% | 3% | 50% |
| Fischer-Tropsch biodiesel | 0% | 4% | 50% |

### 4.10.4 Renewable resources - UK sourced

Renewable resource assessments are taken directly from other analyses. The range of renewable resources is modelled out to their maximum in 2050, and linear interpolation is generally used to fit the intermediate points. This is a crude but necessary assumption, as the actual use of resources depends on a wide range of complex factors, many of which are highly uncertain. The potential biomass resource from a range of residues and wastes is the same as that considered for the renewable hydrogen scenarios, as shown in

Table 17. In the case of energy crops, it is assumed that different crops will be used to satisfy the demand for biofuels. An estimate of the agricultural area that can be dedicated to energy crops has been set at 4Mha (ETSU, (1998); Eyre et al., (2002)). This assumes that currently planted arable crops could be diverted to biofuel production and that the area dedicated to these crops could increase slightly. For example, land dedicated to sugar beet in 2002 was about 170,000 ha, but cultivation of sugar beet could be extended by 2 to 3 times the current area. It also assumes that additional agricultural land, both arable and non-arable, could be dedicated to lignocellulosic energy crops. For example, the UK has about 5.5 Mha of land planted with grasses five years old and over, part of which could be dedicated to energy crops.

It is assumed that rapeseed, sugar beet and wheat production for biofuels production will peak in 2020 and decline thereafter to zero in 2050. Rapeseed, sugar beet and wheat production for biofuels will be replaced by lignocellulosic energy crops, based on their potential for achieving lower biofuel costs. Table 18 shows the maximum land area dedicated to energy crops.

*Table 17: Exploitable residue and waste biomass resources in the UK to 2050*

| Input resource (PJ) | 2000 | 2010 | 2020 | 2030 | 2040 | 2050 |
|---|---|---|---|---|---|---|
| Dry agricultural waste | 0.0 | 19.8 | 39.6 | 59.4 | 79.2 | 99.0 |
| Wood waste | 0.0 | 11.2 | 22.3 | 33.5 | 44.6 | 55.8 |
| Landfill gas | 0.0 | 4.1 | 8.2 | 12.3 | 16.5 | 20.6 |
| MSW | 0.0 | 57.7 | 115.3 | 173.0 | 230.6 | 288.3 |
| Sewage sludge | 0.0 | 5.8 | 11.5 | 17.3 | 23.0 | 28.8 |
| Waste vegetable oil | 0.0 | 7.5 | 14.9 | 14.9 | 14.9 | 14.9 |
| *Total* | 0.0 | 106.0 | 211.9 | 310.4 | 408.9 | 507.4 |

*Table 18: Maximum land area dedicated to energy crops*

| Energy crop | Land (Mha) | |
|---|---|---|
| | *2020* | *2050* |
| Rape seed | 1.0 | 0 |
| Wheat | 1.7 | 0 |
| Sugar beet | 0.3 | 0 |
| Lignocellulose crops | 1.0 | 4.0 |

**Energy crops.** The potential from dedicated energy crops in the UK is dependent on three main factors: i) yields, ii) costs (including subsidies), and iii) land availability. The UK's total agricultural land area is about 18.5 Mha, of which about 5.9 Mha is arable land and 3 Mha are under cereal crops. The agricultural set-aside land area was 0.57 Mha in 2000, equivalent to approximately 10% of arable land area and it is possible that land taken out of food production will increase in the future. Various studies have put the potential land surpluses between 1 Mha and 5.5 Mha (e.g. ETSU, (1994)). However, future land availability will depend on a number of factors which are extremely difficult to predict e.g. subsidies and CAP, environmental policies, and the viability of UK food exports, cereals in particular. Surplus, or even reclaimed land could be used for energy crops land in the future.

## 4.11 Potential for biomass and biofuels imports

There is some international trade in bioethanol and biodiesel. Examples include ethanol export from Brazil to Sweden and Switzerland, and UK imports of biodiesel from continental Europe.

A UK study on biofuel imports considered sources, processes and costs of importing biodiesel and bioethanol in 2002 and 2020 (AEAT, (2003a)). Data and studies on biofuels trade are scarce, representing a limiting factor with regard to the reliability of associated cost figures. For 2002, the lowest cost routes to bioethanol were found to be imports produced from corn in the US and from sugar cane in Brazil, and from oil seed in the US for biodiesel (Table 19). By 2020, costs for bioethanol from Eastern Europe had fallen below those from the US, and the availability of Fischer-Tropsch processes for biodiesel production resulted in lower cost biodiesel from wood and straw in Eastern Europe. Enzymatic hydrolysis of wood and straw in Eastern Europe also becomes a relatively low cost (£8.66/GJ) source of bioethanol in 2020. In all cases, import of intermediate products is more expensive than import of the fuel.

*Table 19: Estimated lowest costs of biomass imports in 2010 and 2020 ( AEAT, (2003a)). Resource costs are before taxation.*

| Fuel | Feedstock and process | Source | Resource costs £/GJ (p/l) | |
|---|---|---|---|---|
| | | | 2002 | 2020 |
| Bioethanol | Corn | US | 8.82 (18.8) | 7.88 (16.8) |
| Bioethanol | Sugar cane | Brazil | 7.39 (15.7) | 6.65 (14.2) |
| Bioethanol | Corn | Eastern Europe | - | 7.07 (15.0) |
| Biodiesel | Oil seed | US | 10.81 (35.5) | 10.72 (35.2) |
| Biodiesel | Wood/straw FT | Eastern Europe | - | 5.40 (19.4) |

### 4.11.1 Modelling

The modelling is based on a set of technology penetration s-curves. At this point they are used to enable a rapid penetration of alternative vehicles. However, these curves have not yet been validated against real possible replacement rates of stock, for example.

Allocation of biomass resources to the different biofuel production processes is proportional to resource availability.

Table 20 summarises productivity levels for different biofuels and related energy crops used in the modelling. Note: t bio-MSW refers to the raw biodegradable fraction of MSW with an estimated moisture content of about 65%

Table 21 summarises productivity levels for different biofuels per unit feedstock input.

*Table 20: Productivity assumptions for biofuels*

| Biofuel chain | Productivity | |
|---|---|---|
| Biodiesel from waste vegetable oil | 37.3 | GJ / t WVO |
| Biodiesel from rapeseed | 10.7 | GJ / t rapeseed |
| EtOH from sugarbeet | 2 | GJ / t beet |
| EtOH from wheat grain | 8.3 | GJ / t wheat grain |
| EtOH from wheat straw | 6.9 | GJ / t straw |
| EtOH from lignocellulosic crops | 6.3 | GJ / odt |
| FT-biodiesel from lignocellulosic crops | 4.4 | GJ / odt |
| FT-biodiesel from biodegradable MSW | 2.5 | GJ / t bio-MSW |

Note: t bio-MSW refers to the raw biodegradable fraction of MSW with an estimated moisture content of about 65%

*Table 21: Productivity assumptions for biofuels from different feedstocks*

| Biofuel chain | Productivity (GJ/ha) |
|---|---|
| Biodiesel from rapeseed | 38.5 |
| EtOH from sugarbeet | 123 |
| EtOH from wheat grain | 58 |
| EtOH from wheat straw | 31 |
| EtOH from wheat grain and straw | 89 |
| EtOH from lignocellulosic crops | 94.5 |
| FT-biodiesel from lignocellulosic crops | 66 |

Note: Total petrol consumption in the UK for road transport in 2002 was 19.7Mt (936PJ), and diesel consumption 17.7Mt (808PJ). Approximate land requirements for replacement of these fuels can be calculated from the figures above if necessary.

### 4.11.2 Results

The results of the modelling of biofuels shares and sources to satisfy the biofuels penetration assumptions in section 4.10.3 are illustrated in Figure 16 to Figure 19. The results of the modelling show that the assumed slow and rapid biofuel penetration can be achieved without biofuel imports in the year 2020, but would require a significant uptake of energy crops, roughly 1.3Mha and 4Mha for the Global Sustainability and World Markets scenarios, respectively. Table 22 shows the land requirements modelled for the different biofuels penetration scenarios.

The scenarios also indicate that substituting large amounts of road transport fuels with biofuels will need to rely on significant imports. A total substitution of petrol and diesel by biofuels in 2050 may need to rely on the import of between 67% and 76% of the biofuel, with indigenous resources possibly supplying up to about 500PJ.

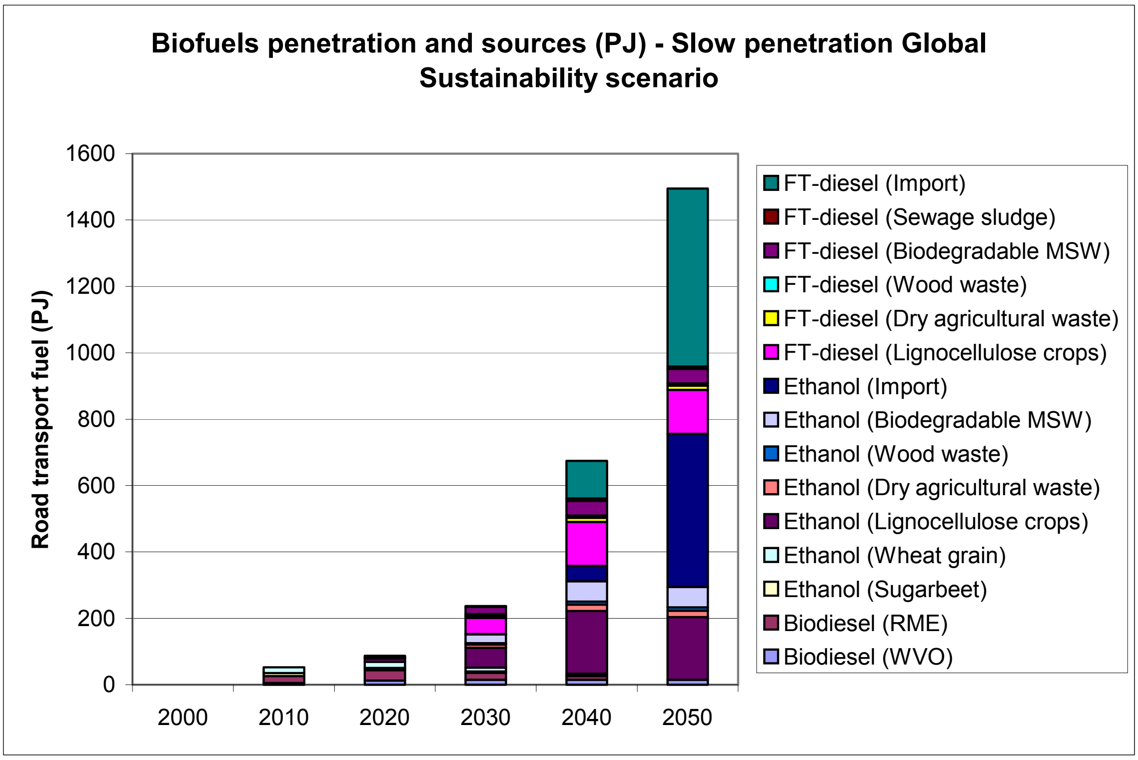

*Figure 16: Biofuels shares and sources – Slow uptake Global Sustainability scenario*

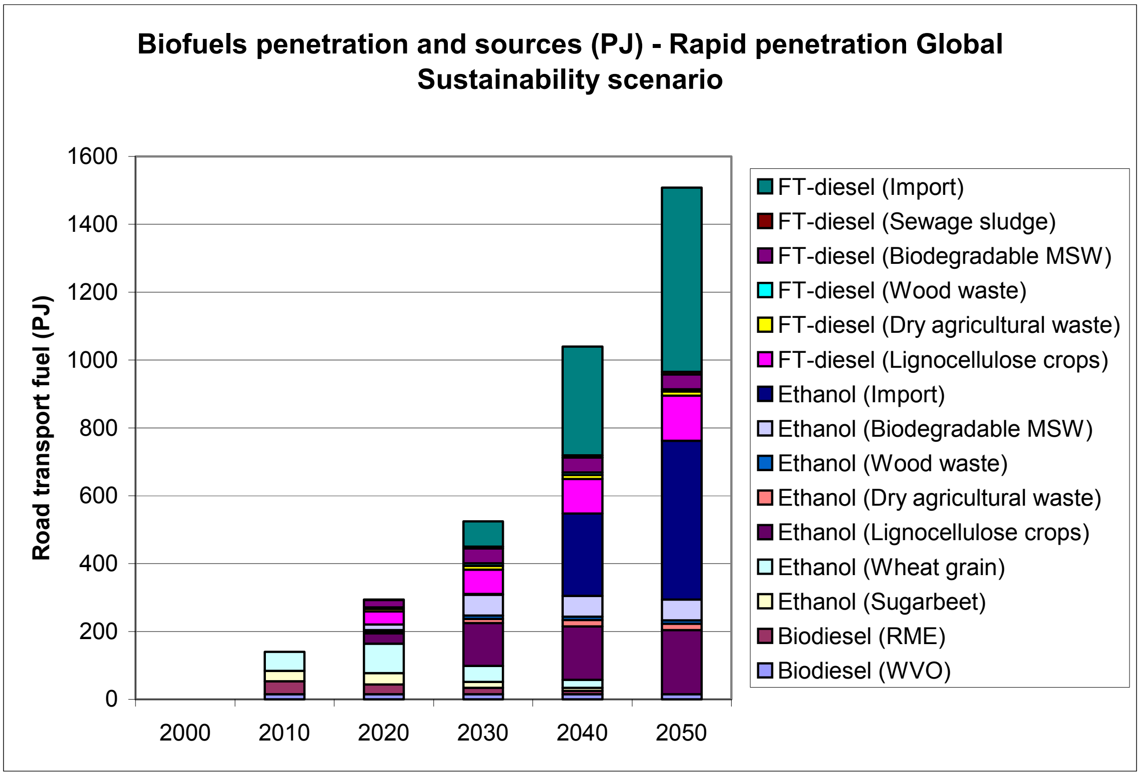

*Figure 17: Biofuels shares and sources – Rapid uptake Global Sustainability scenario*

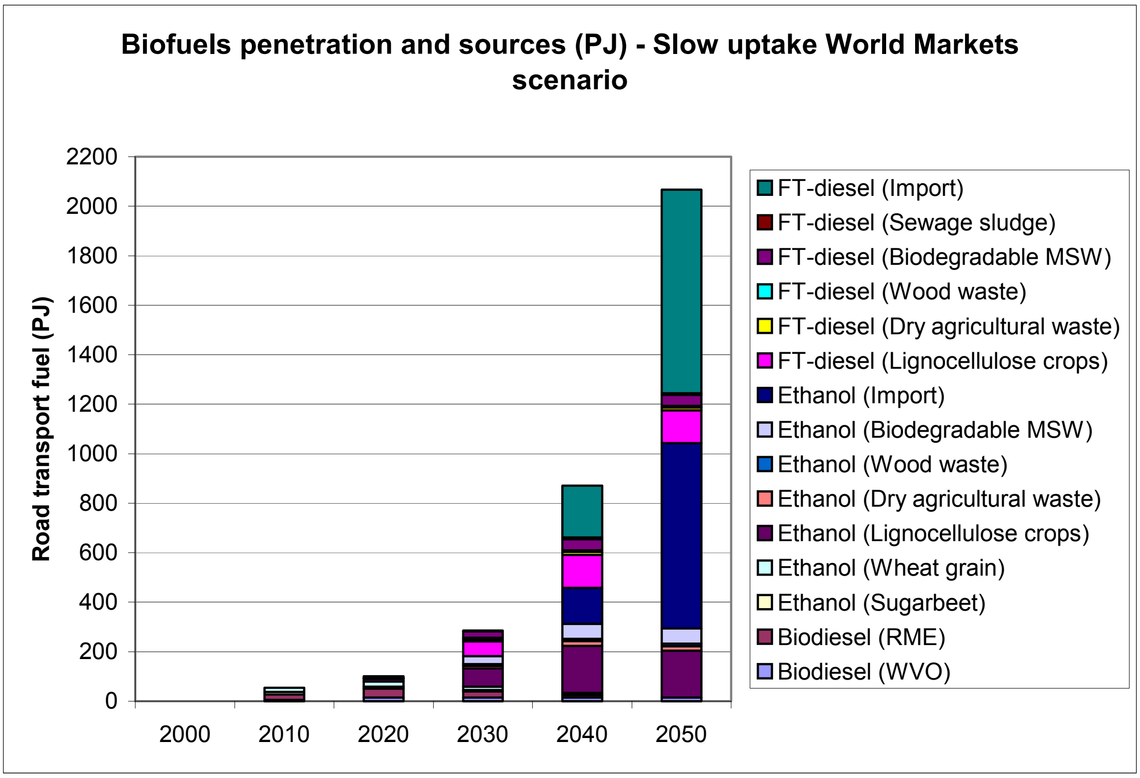

*Figure 18: Biofuels shares and sources – Slow uptake World Markets scenario*

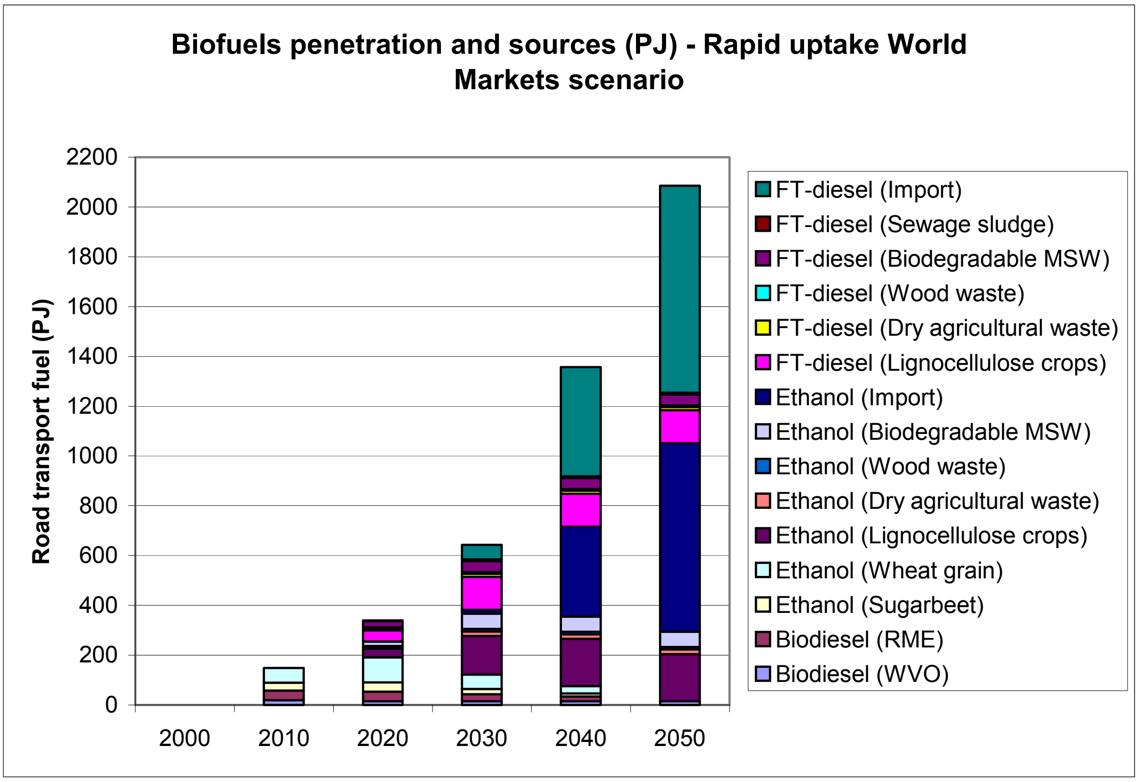

*Figure 19: Biofuels shares and sources – Rapid uptake World Markets scenario*

*Table 22: Land area requirements of biofuel penetration scenarios*

| Biomass resource requirement (land) | | | | | | |
|---|---|---|---|---|---|---|
| **Global Sustainability** | 2000 | 2010 | 2020 | 2030 | 2040 | 2050 |
| *Slow uptake* | | | | | | |
| Rapeseed | 0 | 534,453 | 816,112 | 544,074 | 272,037 | 0 |
| Sugar beet | 0 | 72,738 | 57,170 | 38,986 | 20,801 | 0 |
| Wheat grain | 0 | 291,395 | 313,839 | 209,226 | 104,613 | 0 |
| Lignocellulose crops (EtOH) | 0 | 0 | 107,890 | 738,593 | 1,369,297 | 2,000,000 |
| Lignocellulose crops (FT-diesel) | 0 | 0 | 0 | 666,667 | 1,333,333 | 2,000,000 |
| TOTAL | 0 | 898,586 | 1,295,011 | 2,197,546 | 3,100,082 | 4,000,000 |
| *Rapid uptake* | | | | | | |
| Rapeseed | 0 | 999,481 | 749,611 | 499,740 | 249,870 | 0 |
| Sugar beet | 0 | 242,459 | 266,254 | 137,023 | 78,910 | 0 |
| Wheat grain | 0 | 971,317 | 1,511,075 | 1,007,383 | 503,692 | 0 |
| Lignocellulose crops (EtOH) | 0 | 0 | 323,670 | 882,447 | 1,441,223 | 2,000,000 |
| Lignocellulose crops (FT-diesel) | 0 | 0 | 597,342 | 1,064,895 | 1,532,447 | 2,000,000 |
| TOTAL | 0 | 2,213,257 | 3,447,952 | 3,591,488 | 3,806,143 | 4,000,000 |
| **World markets** | | | | | | |
| *Slow uptake* | | | | | | |
| Rapeseed | 0 | 565,279 | 999,481 | 666,321 | 333,160 | 0 |
| Sugar beet | 0 | 76,933 | 63,021 | 42,014 | 21,007 | 0 |
| Wheat grain | 0 | 308,202 | 357,662 | 238,441 | 119,221 | 0 |
| Lignocellulose crops (EtOH) | 0 | 0 | 122,955 | 748,637 | 1,374,318 | 2,000,000 |
| Lignocellulose crops (FT-diesel) | 0 | 0 | 0 | 666,667 | 1,333,333 | 2,000,000 |
| TOTAL | 0 | 950,414 | 1,543,119 | 2,362,079 | 3,181,040 | 4,000,000 |
| *Rapid uptake* | | | | | | |
| Rapeseed | 0 | 999,481 | 999,481 | 666,321 | 333,160 | 0 |
| Sugar beet | 0 | 256,444 | 303,433 | 167,391 | 102,873 | 0 |
| Wheat grain | 0 | 1,027,340 | 1,722,075 | 1,148,050 | 574,025 | 0 |
| Lignocellulose crops (EtOH) | 0 | 0 | 368,866 | 912,578 | 1,456,289 | 2,000,000 |
| Lignocellulose crops (FT-diesel) | 0 | 0 | 680,753 | 1,120,502 | 1,560,251 | 2,000,000 |
| TOTAL | 0 | 2,283,265 | 4,074,608 | 4,014,841 | 4,026,598 | 4,000,000 |

### 4.11.3 $CO_2$ emissions

Figure 20 shows approximate $CO_2$ emissions trends under the different scenarios for the time period 2000 to 2050. As can be seen, the introduction of highly efficient HEVs alone is not enough to reduce emissions significantly, and they begin to rise again towards 2050. Biofuels could lead to substantial $CO_2$ emissions reductions in the period to 2020 based on the exploitation of indigenous resources. Emissions reductions could be up to about 6MtC, based on the low estimates of emissions from biofuel chains. A rapid or large introduction of biofuels would need to rely heavily on biofuels imports, and emissions will depend on the emissions balances of the imported fuels. The introduction of biofuels could lead to dramatic decreases in $CO_2$ emissions. The figure is based on low estimates of emissions from biofuel chains for the UK and assumes that fuel chain emissions of imported biofuels are equal to the average emissions from the UK biofuel chains (see Table 15).

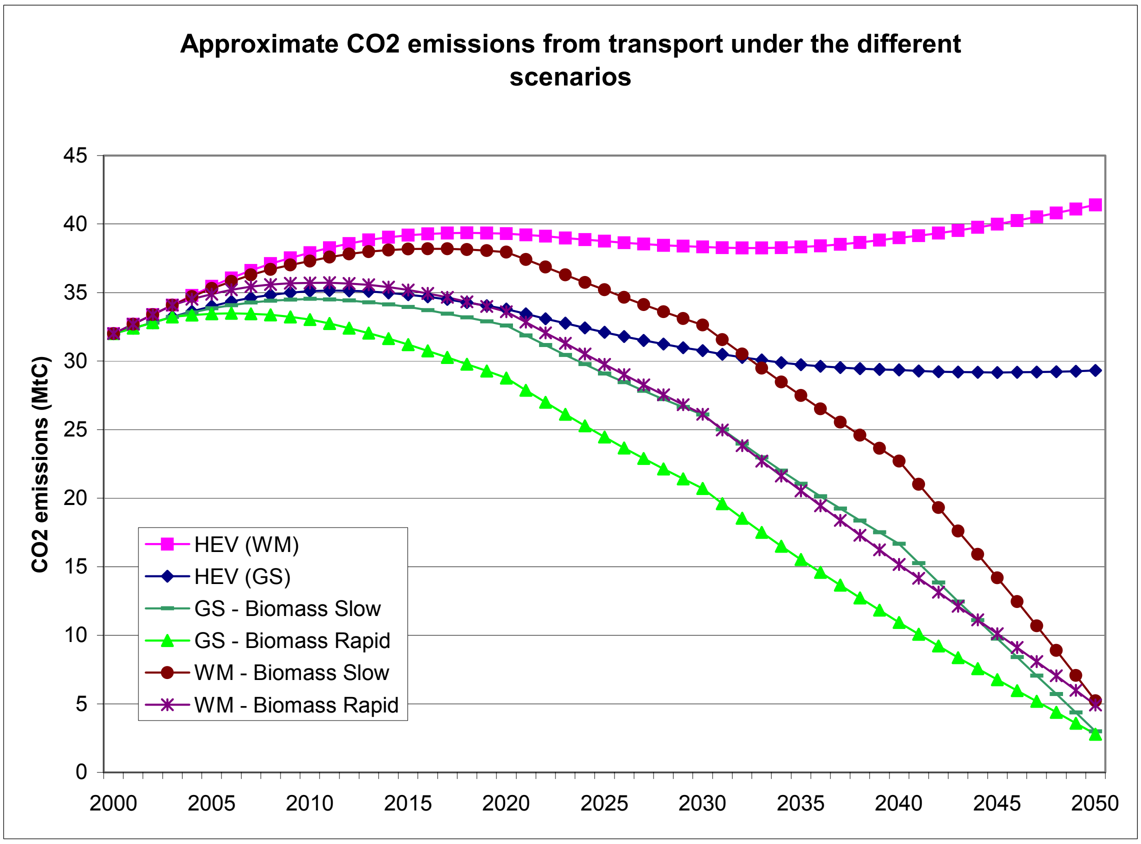

*Figure 20: Approximate $CO_2$ emissions trends under the different scenarios modelled to 2050*

## 4.12 Discussion and conclusions

The scenarios above are strongly dependent on a number of assumptions in relation to shares and types of biofuels introduced, resource allocation to the production of different biofuels, and fuel chain efficiencies and $CO_2$ emissions.

The scenarios indicate that biofuels could contribute a substantial share of road transport fuels by 2020 based on potential UK biomass resources, but the practical implications of exploiting the resources need to be carefully considered.

In the slow biofuels uptake scenarios, 1.3 to 1.5Mha of land would be dedicated to energy crops by 2020. These would mostly be arable crops, with only a relatively small contribution from lignocellulosic crops of little more than 100,000 ha. This is a scenario that could realistically be achieved in the time period considered. The rapid biofuels uptake scenario would require the large part of all suitable arable crops to be diverted to biofuel production and the additional plantation of close to 1Mha of lignocellulosic crops by 2020. This scenario would clearly not be feasible and satisfying the imposed biofuel demand would have to rely to a large extent on imports. The introduction of more efficient lignocellulosic biomass based technologies has an important impact in easing land requirements.

In the slow biofuels uptake scenario, a theoretical 140TWh (equivalent to about 50TWhe) of non-crop biomass resources could be available for other energy uses in 2020, mainly as a result of the low introduction of lignocellulosic ethanol and synthetic diesel routes. Also, there is likely to be very little exploitation of lignocellulosic crops for biofuel production, which could instead be exploited for electricity and heat. UK electricity demand is estimated to be about 400TWhe in 2020 (EP68).

In the rapid biofuels uptake scenario, unless there was a significant reliance on imported biofuels, there would be significantly less biomass resources available for uses other than for biofuels production. Very large areas of land would need to be dedicated to oil, sugar and starch and lignocellulosic crops, leaving little or no potential for energy crops for electricity and heat. Of the non-crop biomass resources, a theoretical 90TWh (equivalent to about 30TWhe) could be available for electricity and heat in 2020.

To increase the biomass penetration beyond the shares indicated in the scenarios for 2020 will require significant biofuel imports. In the Global Sustainability scenario, biofuels from non-crop resources could contribute up to about 10%. The exploitation of 4Mha of land for energy crops could lead to a total biofuels contribution of up to 33% of transport fuel demand.

Biofuels could lead to substantial reductions in $CO_2$ emissions in the period to 2020, but uncertainties remain over the level of emissions due to possible use of fossil fuel in certain biofuel production processes. However, energy inputs to biofuels production could in principle be renewable e.g. use of sugar pulp to supply process energy for bioethanol production from sugar beet, leading to very low $CO_2$ emissions from the fuel chain.

Very large reductions in $CO_2$ emissions could be achieved from a large penetration of biofuels beyond 2020. In particular, lignocellulosic biomass-based fuel chains hold promise for very low emissions because of the use of lignin produced on site to supply energy to the process. However, because of the need for significant biofuels imports, reductions in $CO_2$ emissions will strongly depend on the emissions balances of biofuels imports.

## 4.13 Issues with biofuel introduction

Today's biofuels are expensive relative to petrol and diesel, whose pre-tax pump price is estimated to range between £2.8 and 5.4 per GJ (9 to 20p/l) for oil prices ranging between \$10 and \$30 per barrel. The introduction of biofuels will then require a range of support mechanisms.

The development of a long term viable renewable diesel substitute depends strongly on the development of Fischer-Tropsch systems applicable to biomass feedstocks. The technical and economic viability of such systems is uncertain. Fischer-Tropsch systems applicable to biomass are currently at the pilot stage.

Significant quantities of ethanol as a petrol substitute can be produced from a range of widely cultivated sugar and starch crops. However, access to a broader resource base and lower costs for ethanol production are likely to depend on the development of hydrolysis processes for the conversion of lignocellulosic biomass. Hydrolysis systems are currently at the demonstration stage.

Public acceptability of energy crops, in particular lignicellulosic energy crops, may be an issue. Little experience exists of the acceptability of energy crops because of their limited diffusion to date. Rapeseed plantations have in some cases been reason for public concern. However, the variety of energy crops on which biofuel production could be based and the adoption of good practice in implementing and managing crops at the local level may limit public concern issues in the short term. A transition to a less diverse feedstock, short rotation coppice for example, in the long term may need to address issues of public acceptability more carefully.

The profitability of energy crops to the farmer will be key to their uptake. Uncertainties remain on this issue in relation to yields and establishment / management costs associated with energy crops, the price farmers will be able to sell the crops for and the evolution of prices, practices (e.g. organic farming) and support for food crops. A better understanding of determining factors in the uptake of energy crops for biofuel production is required. This requires a better understanding of the value chain associated with the production of biofuels and its comparison with biomass to electricity and heat chains.

### 4.14 UK situation

UK production of biodiesel from rapeseed and waste vegetable oils is increasing rapidly, but the UK and has no bioethanol fuel production or commercial activities in relation to other biomass-derived transport fuels. However, there has been a recent increase in interest in producing ethanol from sugar beet and from agricultural and forestry residues and woody crops. The UK research and development base in the biofuels area is very limited, with some research in fermentation for ethanol and hydrogen production, and in hydrogen production from biomass gasification. Leading countries in the area of biofuels are the US, Canada, Germany, France and Sweden.

*The UK has some strengths in:*

- Research on feedstocks
    - Universities and institutes with strong research in plant science and breeding, energy crop field trials and other R&D on energy crops
- Conversion technology research
    - University research on fermentation at Glamorgan University and Imperial College London, and on hydrogen production from biomass gasification at Warwick University. Research and development on hydrolysis and fermentation at British Sugar.
- Fuel supply intermediaries
    - Companies such as Greenergy, Rix Biodiesel, Petroplus and Broadland fuels are involved in biodiesel supply.

*Possible UK weaknesses are in the following areas:*

- Limited R&D in conversion technology e.g. biofuels production from biomass gasification and hydrolysis
- Limited demonstration and commercial activities in all areas of the supply chain, due to limited support and demand for biofuels.

*International gaps in knowledge:*

- Demonstration of very low carbon biofuel production from oil, sugar and starch crops, in particular rapeseed, sugar beet and wheat.
- Proof of commercial process for ethanol production from lignocellulosic feedstocks
- Demonstration of commercial scale process for synthetic diesel production
- RD&D in hydrogen production from biomass

- Conversion technology applicability to different feedstocks

*Possible ways forward include:*

- Stimulate production of traditional biofuels (biodiesel from oil crops and waste vegetable oils and ethanol from sugar and starch crops) to specific environmental standards.
- Promote R&D in advanced technologies for the production of ethanol, synthetic diesel and hydrogen from biomass.
- Promote R&D in plant and crop science in relation to energy crops for biofuels production.
- Demonstrate advanced conversion technologies using a variety of biomass feedstocks in the UK, e.g. agricultural and forestry residues, biodegradable municipal solid waste, and lignocellulosic energy crops.
- Stimulate market for biofuels in strategic manner taking into consideration environmental benefits of different biofuel chains, potential for cost reductions, and potential contribution to transport fuel demand.
- Participate actively in international biofuels efforts e.g. IEA Bioenergy Task.
- Promote a UK bioenergy network linking UK RD&D and commercial activities in biomass applications for transport fuels, electricity and heat.

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# 5 Mixed scenario and overall implications

**Future energy resource requirement**

- The mixed scenarios assess the complementary introduction of biofuels and hydrogen over the period to 2050, in combination with the slow and rapid biofuels uptake, Global Sustainability and World Markets scenarios. Biofuels are assumed to be introduced from 2004 and then, from 2020, the production and use of renewable hydrogen is assumed to take priority and remaining biomass resources are used to produce biofuels for non-fuel cell vehicles. Hydrogen dominates strongly by 2050 though biofuels are still present throughout the period in all cases.
- Once again, the scenarios are not forecasts, but they do serve to illustrate an evolution towards ultra low carbon transport which is in line with potential fuel and technology availability.

**Prospective UK supply**

- In all scenarios, UK resources would be sufficient to fuel all transport fuel needs to 2050. However, under World Markets scenarios, renewable vehicle fuel production would require almost all of the available renewable energy resources in the UK.

**Overall summary**

- If very low $CO_2$ emissions from transport are a key goal by 2050, then renewable hydrogen and fuel cells are the combination that could be served from UK resources even under high demand growth scenarios. However, the necessary technology is unlikely to be available before 2020, delaying the $CO_2$ reduction.
- Hydrogen internal combustion engine vehicles could be introduced about a decade earlier than fuel cell vehicles, though their lower efficiency means that all renewable energy resource would be used up under high growth scenarios.
- Biofuel penetration could increase steadily from its present low base to deliver ultra low $CO_2$ from the whole vehicle fleet by 2050. However, this would entail significant imports under all growth scenarios and also relies upon the use of large areas of land that are not currently productive, which may not prove feasible.
- In view of these findings, a mixed introduction of biofuels in the short term and then renewable hydrogen could prove to be the most effective means to reduce $CO_2$ from road transport and conserve UK renewable energy resources.
- This study does not deal with practical implementation issues or the allocation of finite renewable resources amongst competing potential uses. The economics of the different options described will be critical in determining which are most attractive and merit more detailed assessment.

## 5.1 The mixed scenario

The mixed scenario illustrates the possible complementary introduction of biofuels and hydrogen (as shown in Figure 21 to Figure 24). Biofuels are assumed to be introduced in the period 2004 to 2020 based on the same penetration rates as in the biofuels scenarios discussed in Chapter 4. Then, from 2020 the production of renewable hydrogen for FCVs, including biomass-derived hydrogen, is assumed to take priority and the remaining biomass resources are used to produce biofuels for non-FCV vehicles.

The scenario illustrates that biofuels produced in the UK could provide a source of renewable fuels prior to the introduction of FCVs and complement renewable hydrogen production after 2020. Under the Global Sustainability scenario UK renewable resources could be sufficient to satisfy all transport fuel needs by 2050. Under the World Markets scenario, renewable transport fuel production would require almost all available renewable energy resources in the UK.

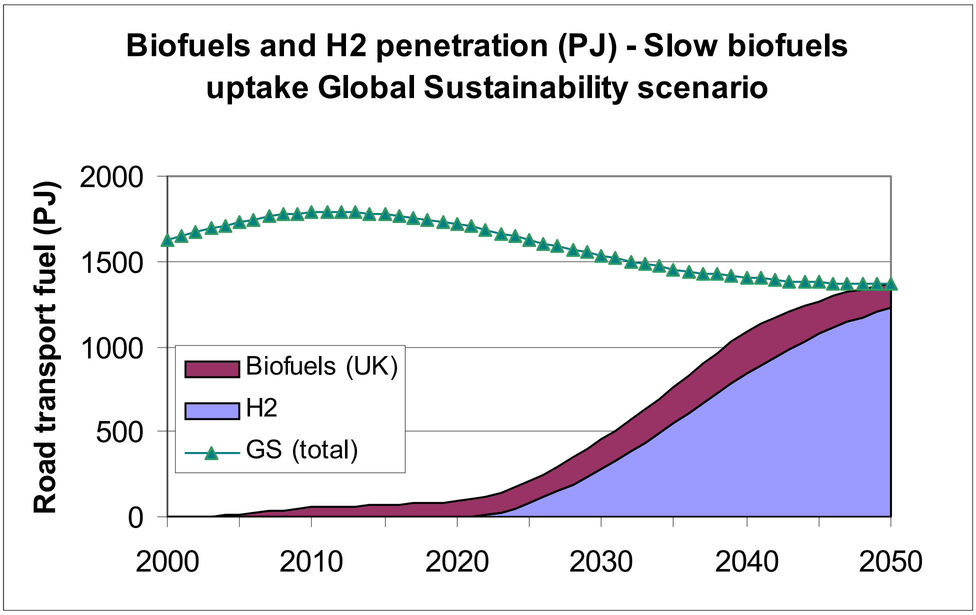

*Figure 21: Mixed hydrogen and biofuels scenario (GS) with slow biofuels uptake*

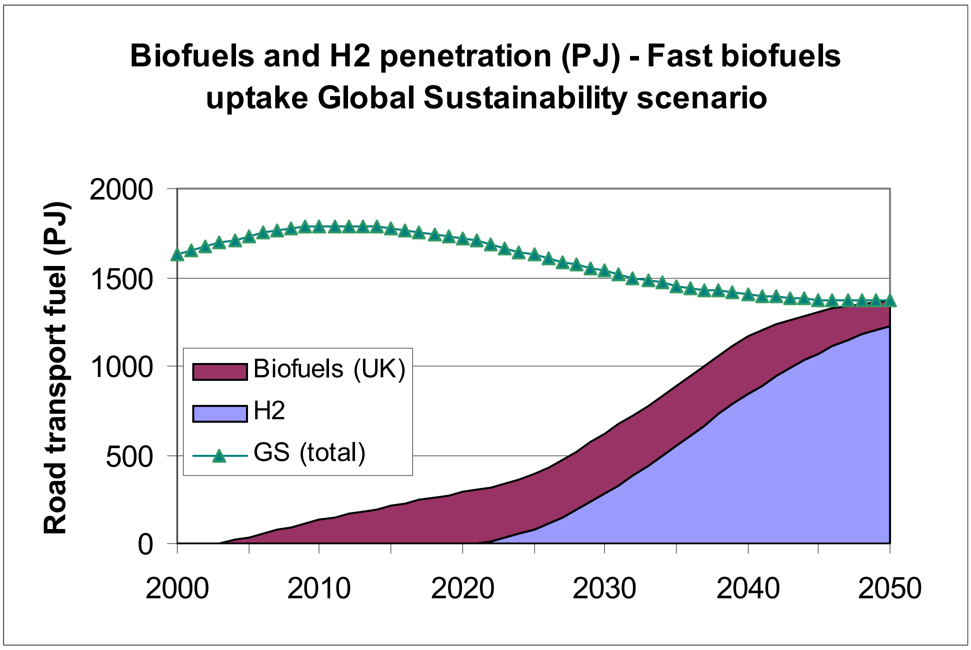

*Figure 22: Mixed hydrogen and biofuels scenario (GS) with rapid biofuels uptake*

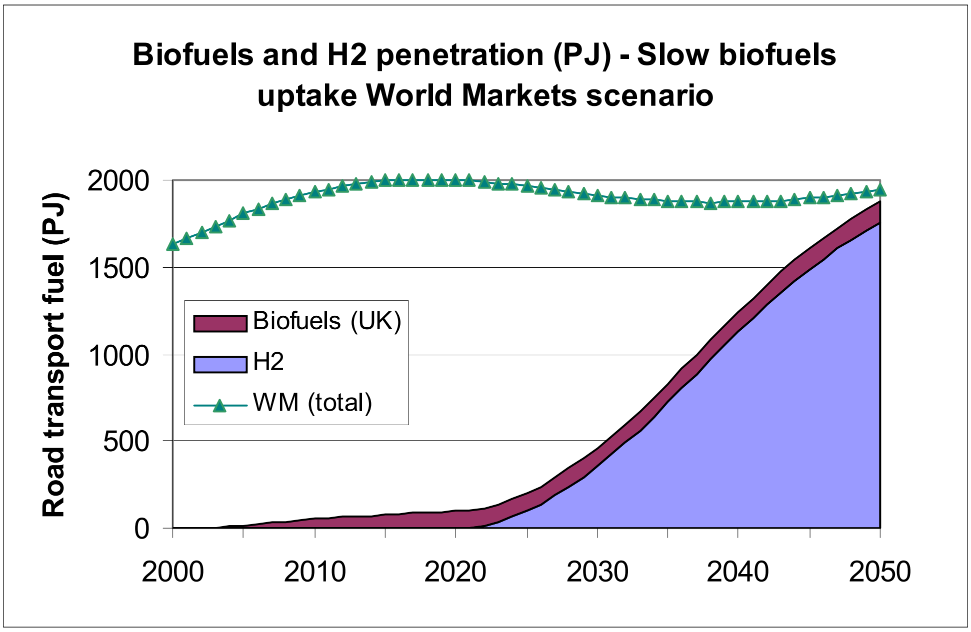

*Figure 23: Mixed hydrogen and biofuels scenario (WM) with slow biofuels uptake*

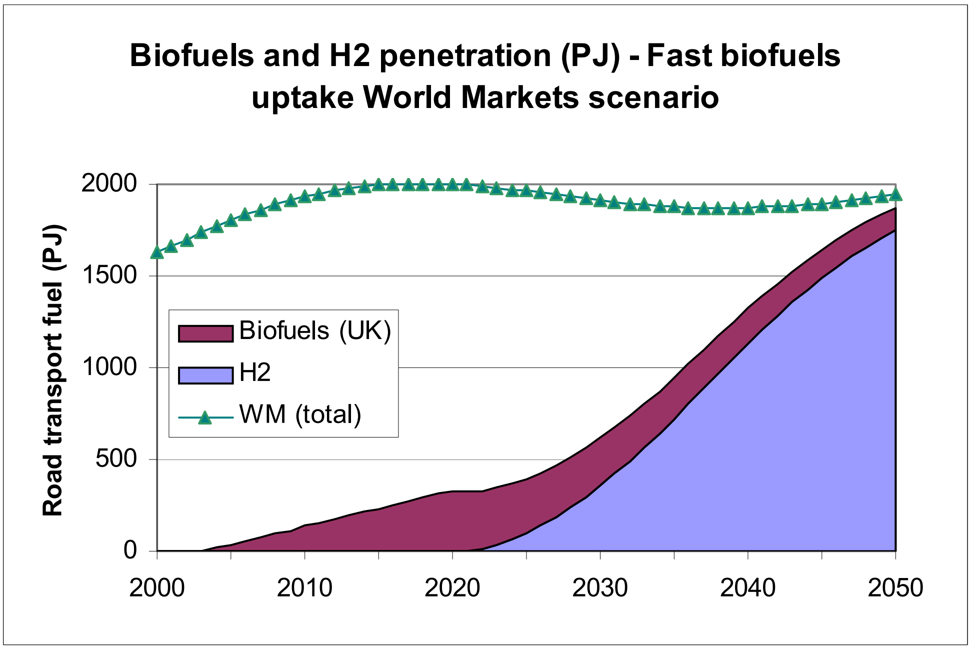

*Figure 24: Mixed hydrogen and biofuels scenario (WM) with rapid biofuels uptake*

## 5.2 Comments on all scenarios

The hydrogen, biofuels and mixed scenarios illustrate:

- the importance of biofuels in providing a source of renewable transport fuels in the short term (to 2020) with potentially significant benefits in terms of $CO_2$ emissions, and in supplying hydrogen and complementing hydrogen as a transport fuel in the long term (beyond 2020) ;
- the importance of hydrogen in providing a larger possible renewable transport fuel source and potentially greater $CO_2$ reductions (in the long term, starting in 2020).

The scenarios do not consider issues relating to the practical implementation of renewable transport fuel production, such as non-technical constraints on the exploitation of renewable resources, competition for biomass resources and for renewable electricity end-uses, energy crop establishment rates, and biofuel and hydrogen production facility build rates. However, the scenarios show that there is a large technical potential for the complementary production of biofuels and hydrogen, and that this potential is likely to remain substantial after consideration of possible constraints.

## 5.3 Common issues

### 5.3.1 Introduction

Common threads emerge for all of the options under consideration. While some policy mechanisms and technology support may be very specific to a certain short-term fuel choice, others will provide more general support and a potentially valuable lead-in to later initiatives. In the very short term it will be important to take some of the opportunities offered by the limited regrets moves (see Chapter 6), though more specific support for certain areas may be essential if they are to continue to develop to a point at which they are valuable. For example, the combination of introducing a new fuel at the same time as a new technology will meet with much stronger resistance than either alone, and so the introduction of FCVs using renewable hydrogen could be delayed. As an indication of the implications of this, Figure 25 shows the potential difference in carbon emissions if FCVs using renewable hydrogen were introduced ten years later than is assumed for this model (i.e. in 2030, or 2040 for HGVs), keeping all other assumptions the same. Under the GS scenario, for example, the dotted lines show that the delayed introduction of FCVs suggested above could result in carbon emissions that are approximately 10MtC greater in 2035 than for the earlier FCV introduction. This earlier benefit could allow significant UK $CO_2$ reductions to accrue, or allow valuable flexibility in dealing with other sectors.

Biofuels in conventional engines could potentially be introduced with less resistance, and so are less likely to suffer a similar delay. A rapid introduction of biofuels can have significant impacts on short and medium term $CO_2$ emissions. However, these will depend on the $CO_2$ emissions that can be achieved by the different biofuel chains (see Table 16). Any policy measures that are taken should be considered in the light of alternative uses of energy resources, $CO_2$ abatement costs of alternative measures and broader environmental considerations. The mixed scenario described in section 5.1 shows the potential for biofuels to be introduced early on and to complement hydrogen in the long term as FCVs penetrate the market. This allows the early uptake of renewable fuel, with the more varied resources available for hydrogen production allowing the rate of penetration to be sustained.

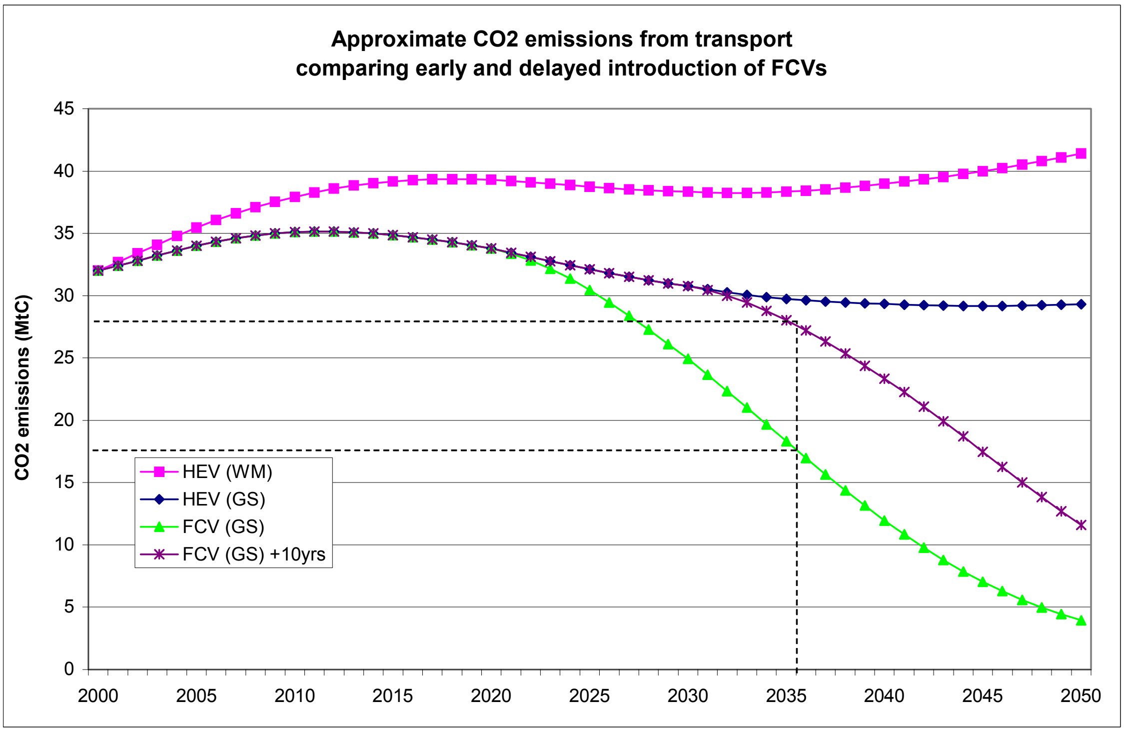

*Figure 25: A $CO_2$ comparison of a ten year difference in introduction of FCVs using renewable hydrogen*

### 5.3.2 Demand reduction and behavioural shifts

As can clearly be seen in the difference between the Global Sustainability and World Markets scenarios, a significant reduction in $CO_2$ emissions could be brought about by reducing the number of vehicle kilometres travelled. This reduction can subdivided into: (i) reducing the number of vehicles travelling, and/or (ii) reducing the average length of journeys. Clearly, the latter can be achieved by reducing the number of long journeys, by eliminating short journeys, or by modal switching so that journeys are undertaken using other types of transport.

In all cases, reducing the total vkm travelled will not only lead to a reduction in $CO_2$ emissions, but also enable substitution of conventional fuel with alternatives such as hydrogen or liquid biofuels to be achieved more quickly and with greater impact, due to the smaller volume of fuel to be replaced.

### 5.3.3 Technology development

Many technologies for producing, transporting and using both hydrogen and liquid biofuels require further development before they can be introduced into wide-scale use. Some of these technologies, especially those used for gasification, are common to the production of both hydrogen and biofuels. Research and development in these areas, coupled with demonstration and validation of the more advanced technologies, will enable reliability to be improved and costs to be reduced.

### 5.3.4 Targeted demonstration projects

Demonstration projects using alternative fuels, coupled with some form of education and public outreach, are extremely important. Consumer awareness and acceptance of new technologies are linked closely to familiarity, while new vehicle purchases or fuel switching based on environmental awareness require a knowledge of the alternatives and their effects.

Demonstration projects with a suitably high public profile for the specific technology under test are very important in achieving these goals, while also allowing manufacturers to understand the performance of their technology in real-world conditions in different areas. Developing a set of strategic demonstration projects using suitable fuels, technologies and vehicles will be an essential step in introducing low-carbon fuels.

### 5.3.5 Fiscal and policy incentives for low carbon fuels

Unless the product is a perfect substitute for an existing product and available at the same or lower cost, fuel switching must be assisted by fiscal and policy incentives, potentially both for purchaser and supplier. Existing incentives, such as lower fuel duties on road fuel gases, have had some effect on encouraging their uptake. However, these incentives must be clear and easily available, and be in place for a long enough period of time to give purchasers security. If it is felt that the incentive will be removed in the near term, neither suppliers nor purchasers will be able to take the risk of investing. Rumours over the continuation of the road fuel gases incentives, for example, have caused some to delay their investments.

Ideally, more than one form of incentive will be provided, for example a fuel duty incentive guaranteed over the near term, set within a positive policy framework over the longer term. These incentives should be designed so as not to clash with other areas, for example broader environmental or energy policies, and should ideally allow developers to meet other international policy targets at the same time. In addition, technologies which carry a significant degree of risk will require capital subsidies.

### 5.3.6 Common and clear fuel duty based on $CO_2$ emissions

Given that the potential for reducing $CO_2$ emissions is a clear focus, the development of incentives that are clearly based on this target, such as a graduated fuel duty, is important. The rationale for current fuel duties is opaque to many people, and basing a fuel duty on the carbon content of a fuel, or the $CO_2$ or greenhouse gas emissions produced over the fuel chain, may be a way of making this more transparent. While it might introduce complexity in terms of requiring standardisation and monitoring of fuel chains, it would benefit from study.

A more sophisticated duty or incentive, based not only on $CO_2$ but also other emissions, might be too complex to implement. Instead, different emissions or other objectives, such as noise reduction, could be targeted using other mechanisms such as vehicle excise duty.

## 5.4 Summary

The mixed approach to long term renewable fuel provision is arguably the most achievable of the scenarios studied, though it is not moderated by several important ‘real world’ considerations. Nonetheless, it serves to illustrate that the potential $CO_2$ reductions of an early introduction are large and that hydrogen may play a very large part in long term renewable fuel provision. This mixed approach also makes it all the more important to consider the best allocation of finite biomass resources and renewable electricity between competing renewable energy applications. Policy initiatives to create renewable energy price signals now could have a strong bearing upon transport fuel transitions in 20 or more years’ time.

# 6 Summary and conclusions

This report summarises an analysis of the potential for the UK to provide renewable fuel for road transport in the period to 2050, and some of the broader implications of doing so. The modelling assumes an aggressive long-term penetration of renewable fuels, produced from UK resources as far as possible. The $CO_2$ emissions implications, renewable resource requirements, development of renewable transport fuel production technologies, and implications for the wider energy system are analysed in brief.

Two principal scenarios are used for modelling. Global Sustainability assumes that vehicle kilometres (vkm) rise gradually and then begin to fall by 2050. World Markets has a continuously rising number of vkm throughout. The base case over which advanced technology and renewable fuel introduction are laid is of an aggressive penetration of high efficiency vehicles.

## 6.1 High level conclusions

The results of the modelling of biofuels scenarios show that the assumed slow and rapid biofuel penetration can be achieved without biofuel imports in the year 2020, but would require a significant uptake of energy crops, roughly 1.3Mha and 4Mha for the Global Sustainability and World Markets scenarios, respectively. While the slow biofuels uptake scenario could realistically be achieved in 2020 based on domestic resources, the rapid biofuels uptake is likely to have to rely to a large extent on biofuels imports. Between 90 and 140TWh of biomass resources are estimated to be available for other energy uses after allocation of resources to biofuel production in 2020.

In the Global Sustainability scenario, a total substitution of petrol and diesel by biofuels in 2050 would need to rely on the import of more than 67% of the biofuels, with indigenous resources possibly supplying up to about 500PJ. Biofuels from non-crop resources could contribute up to about 10%, and the exploitation of 4Mha of land for lignocellulosic energy crops could lead to a total biofuels contribution of up to 33% of road transport fuel demand. The transition to hydrogen fuel could allow biomass resources to be used in complement with other renewable resources to supply a greater share of transport fuel. The contribution of liquid biofuels and biomass-derived hydrogen could reduce $CO_2$ emissions from road transport fuels to very low levels.

The results of the modelling of the hydrogen scenarios show that, in the case of the Global Sustainability scenario, if gaseous renewable hydrogen is used in internal combustion engines, introduced at a rapid rate of penetration from 2008, then renewable resources could be sufficient to supply the whole UK requirement until 2050, with some additional resource remaining to supply heat and power demand. For World Markets, renewable energy is in shortfall from 2020 onwards, when hydrogen achieves about 25% penetration into the fuel mix. This shortfall is small, and probably within the uncertainty of the modelling. Imported renewable hydrogen is a possible means of making up the difference, as is hydrogen production from non-renewable sources. As hydrogen penetration into the fuel mix increases, the shortfall changes as more renewable resources are exploited.

If fuel cell vehicles are used in place of internal combustion engines, but only introduced in 2020, the renewable resource is sufficient to provide for the whole transport fleet at all times. Considerable resource remains under both GS and WM scenarios, sufficient to provide close to 50% of remaining energy demand under an optimistic scenario, but much less under a scenario of high demand growth.

$CO_2$ emissions fall dramatically under both hydrogen ICE and FCV scenarios. Although the base case is also aggressive in choosing a rapid penetration of highly efficient vehicles into the UK fleet, $CO_2$ emissions only drop in the near term. As vkm continue to rise, the emissions rise again after about 2030. However, under the renewable hydrogen scenarios, $CO_2$ emissions begin to drop below the base case between 2015 and 2020, and then continue downwards to approach zero in 2050

The hydrogen scenarios suggest that, if hydrogen is to be produced from UK renewable resources, both offshore wind and photovoltaics will be important technologies for the long term as a large requirement could emerge. In practice, photovoltaics are likely to be widely distributed, often at single building scale, and so may not be well-suited to volume hydrogen production. In the near term a wide range of biomass resources can be used for producing liquid biofuels, but in the longer term biomass resources may be increasingly dedicated to hydrogen production. However, technology development and demonstrations will be required in order to determine the most viable routes.

## 6.2 Summary of options

The analysis conducted here is speculative, based on the assumption that many technologies currently under development will reach maturity and become cost-effective. In addition the analysis is not based on neither economic nor financial modelling – the level of costs and revenues will be critical to ensuring that there is a value proposition for consumers and supply side actors. It also ignores the supply side benefits for 'UK plc' of different pathways. Finally, the human behavioural dimension is not addressed and this is undoubtedly vital to the success of such major shifts.

Against this background of uncertainty it is very difficult to recommend a single course of action which is likely to maximise long term $CO_2$ reduction from transport. In fact, the high level of uncertainty suggests that an analytical framework is needed which assists in the selection of actions by grouping their sensitivity to uncertainty. A suggested framework is shown below in Table 23, together with the generic categories of action. Specific actions within each category are then discussed, followed by recommendations in the section that follows.

*Table 23: Option framework for low carbon vehicle transition*

| 'Limited regrets moves' | 'Options' | 'Big bets' |
|---|---|---|
| • Reduce vehicle energy use<br>• Encourage use of available fuels and vehicles<br>• Further study<br>• Research & development<br>• Raise awareness | • Support key fuels and vehicles which require modest further development<br>• Demonstrate emerging fuel production and vehicle technologies | • Strong support for a single technology or pathway |

### 6.2.1 Limited regrets moves

**Reduce vehicle energy use**. This has several components, as discussed in chapter 2.

The introduction of more efficient conventionally-fuelled vehicles is a very important step to preparing for a transition to a very low carbon transport future. Without the reduction in fuel consumption from this range of measures then any later introduction of new fuels will place higher demands on fuel volumes and resources.

The HEV technologies that are being commercially introduced are part of this step and their introduction is being supported by measures such as purchase subsidies (in the case of hybrid vehicles) due to their cost disadvantage. More general efficiency improvements across the fleet are encouraged by voluntary agreements with vehicle manufacturers, graduated vehicle excise duty and congestion charge exemption. As these incentives become tighter and/or other technical options are exhausted then vehicle companies may increasingly turn to HEV technologies, potentially reducing their cost and thereby the need for subsidies.

Reduction in total vehicle kilometres is another logical component of reducing energy transport use. However, it implies potentially major shifts in behaviour, land-use patterns and personal values. Nonetheless, policy is already focused on the marginal journeys where alternatives may exist.

**Encourage use of available hydrogen vehicles and biofuels**. UK pioneers exist in both hydrogen (limited numbers of hydrogen ICE vehicles will be marketed shortly) and fuels (biodiesel is already available in blends). Support measures such as purchase subsidies and fuel duty incentives are in place to assist this introduction.

Increased experience with such vehicles would bring several benefits. Hydrogen ICE vehicles would provide ‘real-world’ experience of working with hydrogen as a fuel and would encourage a limited fuel infrastructure to develop, in addition to providing valuable opportunities for public awareness-raising. However, they do not represent the most efficient way to use hydrogen and this is unlikely to be renewably-sourced in the near term.

Biodiesel and bioethanol can be commercially produced. Current commercial options from oil crops and fermentation of sugar and starch crops offer $CO_2$ reductions with limited disruption to the supply chain and to vehicles. Though, more advanced pathways promise higher volumes and lower costs.

**Further study**. Many of the remaining issues which create uncertainty are not well understood. Better information can be achieved through studying some of these in greater depth, either to assess their implications or to understand their resolutions.

As stated earlier, a great deal of uncertainty exists about the technical and commercial viability of many of the key technologies discussed in this report. Technology-watch is a limited regrets move which provides a better understanding of the state of the art and the potential outlook whilst limiting exposure to the risks of failure. However, it provides no participation in shaping this outlook. Current examples of technology watch by UK institutions include: fuel cell vehicles; large scale hydrogen from biomass; FT-diesel.

**Research and development**, however, offers an opportunity to participate in the direction of development and ultimately to profit from it. R&D sits at the start of a spectrum which continues into option development and beyond. If relatively low cost projects are chosen where no solution has already emerged and a good case can be made for UK involvement then this can be seen as a limited regrets move. Examples include activities in hydrogen storage; biomass fermentation; energy crops.

A range of non-technical issues are vitally important to the potential transition, particularly the economics and UK competitive advantage potential within biofuels.

Linked to this is the potential conflict between stationary heat and power uses for biomass and biofuels. A better understanding of these issues would help government to predict the fiscal requirements to overcome natural market forces. Relatively limited modelling of biomass energy resources and economics at the national level has taken place to date.

**Raise awareness**. Stakeholders at all stages of the supply chain from primary energy producer to consumer could benefit from a greater awareness of the long term vehicle energy choices facing the UK. This could potentially encourage innovation, assist in gaining policy support, create demand from early adopters and limit problems associated with public perception.

### 6.2.2 Options

Options are moves which imply a bigger commitment than limited regrets moves, but not ones that put everything at stake or which cannot be reversed without significant loss. Their chief benefit is that if the transition appears to follow the favoured path then one is very well positioned to take advantage of this.

**Support key fuels and vehicles which require modest further development**. This option covers those pathways which are not yet commercialised but which might play a key role in the future. UK experience in their development and deployment could accelerate their uptake and increase competitive advantage for UK organisations in any section of the supply chain. Examples include system integration of renewable electricity and hydrogen production; fuel and vehicle infrastructure for flexible fuel or 100% biofuels; biogas utilisation as a vehicle fuel.

**Demonstrate emerging fuel production and vehicle technologies**. Several of the potentially key technologies are at a stage of development where their success is quite uncertain, but those who demonstrate them will gain important experience. This experience could provide competitive advantage for UK organisations, or provide valuable lessons in options that are closed. Examples include fuel cell vehicles; lignocellulosic hydrolysis; large scale biomass gasification.

### 6.2.3 Big bets

Such moves, implying high risk-reward ratios, are taken by those who believe that they have sufficient knowledge of the future. In this context big bets could involve a major investment programme in a single technology or pathway, predicated upon the emergence of very low carbon transport fuels. There are a few UK companies that are exclusively fuel cell vehicle, hydrogen or biofuel focused, though only the smallest of these do not have some other form of income to reduce their risk. Some regard the upbeat moves towards FCV introduction by some vehicle majors as big bets, but in practice their scale in proportion to other activities would put them in the class of significant options.

## 6.3 Recommendations

The very high degree of uncertainty involved in transition to very low carbon vehicles needs to be balanced with the long term nature of the potential transition and the benefits of moving early. What is clear is that it is not possible to predict clearly enough for the UK to place any big bets at this stage. However, the UK should pursue several limited regrets moves, as well as a selected number of options.

Importantly, a better understanding of the resources and economics behind biofuels and the interface with other uses of biomass should be addressed very soon as this will assist in focusing policy efforts.

Unless contradicted by the economics, in the near term the UK should continue to pursue the range of measures that are in place to encourage HEVs and the use of existing biofuels and forthcoming hydrogen vehicles. The early availability of very low $CO_2$ fuels also offers a 'hedge' should hybrid technology fail to become accepted or widespread. The incentives for hydrogen, biodiesel, bioethanol and other biofuels should be based upon clearly understood specific fuel chain $CO_2$ levels. This and the accompanying debate will ensure that all potential routes are explored whilst ensuring that there is a focus on reducing $CO_2$.

A careful technology watch should be maintained upon fuel cell vehicles, large scale hydrogen from biomass and FT-biodiesel. If signs of significant progress are observed then the UK should consider supporting increased levels of R&D activity in these areas. Existing R&D efforts in the field of hydrogen, fuel cells and biofuels should continue to be supported.

Fuel cell vehicles are becoming available for demonstration, though the UK is unlikely to benefit widely on the supply side of this technology so these would mainly provide insights about deployment and public awareness-raising. The EU is strongly considering very large-scale 'lighthouse projects' with transport and stationary hydrogen demonstrations (HLG, (2003)), and links should be maintained to these to ensure maximum learning is derived from the different national activities.

The UK could be a significant producer of renewable fuels based on its large renewable energy resource potential. Near term options should be carefully placed in projects which develop system integration of e.g. wind and hydrogen.

In the near to medium term advanced biofuel technologies based on hydrolysis and gasification should be developed and demonstrated. Ethanol, synthetic diesel and hydrogen could be produced, based on a variety of lignocellulosic feedstocks.

The wider implications of these recommendations must also be considered, as transport policy in this case will also have to interact very closely with environmental, energy and agricultural policy, at the very least. These recommendations and the wider consideration of their impacts will need to be revisited frequently, in line with changes in the level of uncertainty surrounding them.

## References

AEAT (2003a), International resource costs of biodiesel and bioethanol. AEAT/ENV/ED50273/R1, AEA Technology, Harwell, UK.

AEAT (2003b), Platinum and hydrogen for fuel cell vehicles. AEAT/ED48034, AEA Technology, Harwell, UK.

Allison Gas Turbine Division, GMC (1994), Research and development of proton exchange membrane (PEM) fuel cell system for transportation applications: initial conceptual design report. DOE/CH/10435-01, US Department of Energy.

Border Wind Ltd (1998), Offshore wind energy - building a new industry for Britain. Greenpeace, Hexham, Northumberland.

CONCAWE, EUCAR, and JRC (2003), Well-to-wheels analysis of future automotive fuels and powertrains in the European context.

DTI, DfT, and DEFRA (2003), The Energy White Paper: Our energy future - creating a low carbon economy. Department of Trade and Industry, Department for Transport, Department for Environment, Food and Rural Affairs, London, UK.

ETSU (1994), An Assessment of Renewable Energy for the UK. Report R-82, ETSU, Harwell, UK.

ETSU (1998), New and Renewable Energy - Prospects in the UK for the 21st Century: supporting analysis. ETSU, London, UK.

European Commission (2003), Directive 2003/30/EC of the European Parliament and of the Council on the promotion of the use of biofuels or other renewable fuels for transport. 2003/30/EC, European Commission, Brussels, Belgium.

Eyre, N, Fergusson, M, and Mills, R (2002), Fuelling road transport: Implications for energy policy. Energy Saving Trust, Institute for European Environmental Policy, National Society for Clean Air, London, UK.

Foster-Wheeler (1996), Decarbonisation of Fossil Fuels. Report no. PH2/2, IEA Greenhouse Gas R&D Programme.

Foster-Wheeler (1998), Precombustion Decarbonisation. Report No. PH2/19, IEA Greenhouse Gas R&D Programme.

Garrad Hassan and Partners (2001), Scotland's Renewable Resource. Scottish Executive, Edinburgh.

General Motors, BP, ExxonMobil, Shell, TotalFinaElf, and LBST (2002), GM well-to-wheel analysis of energy use and greenhouse gas emissions of advanced fuel/vehicle systems - a European study. L-B-Systemtechnik, Ottobrunn, Germany.

HLG (2003), Hydrogen energy and fuel cells - a vision of our future. European Commission, Brussels, Belgium.

Howes, J (2002), The potential for renewable hydrogen as a transport fuel for the UK, MSc Thesis, Imperial College London, London, UK.

IAG (2002), Long-term reductions in greenhouse gas emissions in the UK. Inter-departmental Analysts Group, London, UK.

Lipman, T (1999), Zero emission vehicle scenario cost analysis using a fuzzy set-based framework, PhD Thesis, University of California, Davis, Davis.

Lloyd, AC (2000), The California fuel cell partnership: an avenue to clean air. Journal of Power Sources, 86(1-2), 57-60.

Lomax, F, James, B, Baum, G, and Thomas, C (1998), Detailed manufacturing cost estimates for polymer electrolyte membrane (PEM) fuel cells for light duty vehicles. DE-AC02-94CE50389, Directed Technologies, Inc.

Marsh, G, Taylor, P, Haydock, H, Anderson, D, and Leach, M (2002), Options for a low carbon future. AEA Technology, Harwell, UK.

Martinez-Frias, J, Pham, A-Q, and Aceves, SM (2003), A natural gas-assisted steam electrolyzer for high-efficiency production of hydrogen. Int. J. Hydrogen Energy, 28(5), 483-490.

Owen, NJ, and Gordon, RL (2003), "Carbon to hydrogen" roadmaps for passenger cars: update of the study for the Department for Transport and the Department of Trade and Industry. Ricardo Consulting Engineers, Shoreham by Sea, UK.

PIU (2002), The Energy Review. Performance and Innovation Unit, Cabinet Office, London, UK.

Thomas, C, James, B, Lomax, F, and Kuhn, I (1998), Integrated analysis of hydrogen passenger vehicle transportation pathways. DE-AC36-83CH10093, National Renewable Energy Laboratory (NREL).

Woods, J, and Bauen, A (2003), Technology status review and carbon abatement potential of renewable transport fuels in the UK. DTI report B/U2/00785/REP - URN 03/982, Department of Trade and Industry, London, UK.

## Annex 1: Tripartite report

The study carried out by Nick Eyre, Malcolm Fergusson and Richard Mills (the ‘tripartite’ study) (Eyre et al., (2002)) also analysed the potential for the UK to produce renewable fuels from biomass-based sources over the period to 2050. The report addressed the question of the trade-off between $CO_2$ benefits arising from the use of renewable fuels in transport versus their use to displace fossil fuels in other sectors, especially in electricity generation. To understand this trade-off, detailed modelling was carried out on the future energy mix, transport use, and other factors. The study concluded that if the basis of comparison were $CO_2$ emissions reductions alone, then renewable electricity was best used to substitute for fossil fuelled power plant and not for the production of transport fuel until considerable surplus could be generated. It also concluded that biomass might provide a valuable source for renewable fuels, either liquids or hydrogen, in the much nearer term.

As part of the analysis the tripartite report concluded that it might be possible for the UK to produce almost all of its road transport fuel requirements, by planting 25% of UK agricultural land (4Mha) with indigenous wood crops. This depends on the use of highly efficient vehicles and on low transport demand growth.

This study concludes that indigenous biomass sources (biomass residues and wastes and energy crops) could supply closer to one-third of transport fuel demand in 2050. Initially, the difference between these conclusions may seem large. However, this analysis is based on average vehicle efficiency that is lower than that assumed in the tripartite study (a long-term reduction of 45% in energy use, while Eyre et al., (2002) use a 65% average reduction across the entire parc). This assumption means that nearly 50% more energy is required in our 2050 scenarios than in those of the tripartite report.

In addition, this analysis assumes a 50:50 split between final production of some form of bioethanol and an F-T biodiesel, while the tripartite study includes hydrogen in the mix, ensuring the overall efficiency of fuel production and use is higher. In the hydrogen scenarios modelled in this report energy crops also make a significant contribution, but they are allocated according to their proportional availability in comparison with e.g. wind power, and so less land is used for biomass-hydrogen than could potentially be made available.

The period to 2050 contains enormous uncertainties and so neither report can be regarded as being either accurate or inaccurate. However, the different outcomes serve to show the different potentials under different assumptions, and may allow a more effective path to be chosen to meet policy objectives. Clearly, maximising vehicle efficiency and minimising vehicle kilometres travelled are key areas for strong policy development, in addition to technology development and fuel changes.