UK CARBON REDUCTION POTENTIAL FROM TECHNOLOGIES IN THE TRANSPORT SECTOR

for

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and

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by

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EXECUTIVE SUMMARY

Reducing CO_2 emissions from UK transport is likely to require a combination of measures, including increased energy efficiency, new technology introduction, and fuel switching. Apart from demand-side management, the most important technologies can be divided into (a) vehicles and (b) fuels.

Key vehicle technologies are:

- battery electric vehicles, for niche markets including urban journeys
- hybrid-electric vehicles, replacing conventional gasoline and diesel vehicles
- fuel cell vehicles, potentially able to replace all conventional vehicles

Different fuels can be used in these different vehicles:

- electricity will be required for battery vehicles, and for some hybrids, known as plug-in hybrids
- biofuels can be introduced either as blends in current fuels, and used in current vehicles and hybrids, or potentially at levels of 100% with some engine modifications
- hydrogen is probably required for fuel cell vehicles, and could be also used in internal combustion engines

Each of these technologies and fuels faces technical, cost and policy challenges before it can compete commercially. However, these do not appear insurmountable. Each also offers benefits other than simply possible reductions in CO_2 emissions from transport. In the near term, hybrid vehicles and biofuels are expected to be the main contributors to reductions in emissions. The environmental impact of biofuels is complex and care should be taken in evaluating and monitoring their real-world effects, especially if either raw materials or finished fuels are imported. In the longer term, but only if technical development is successful, fuel cell vehicles using hydrogen offer the potential for major emissions reductions.

The table below gives indicative figures, and ranges, of costs of carbon reduction from different fuels and routes. It is extremely important to note the uncertainty inherent in all of the cost and price assumptions made here, especially as the timescales increase. Robust policy must be based not only on these numbers, but also on other factors that have not been examined under the analysis conducted for this report.

Fuel chain		**Fuel cost (£/GJ)**	**Cost driven (p/km)**	**Carbon emissions (g/km)**	**Cost of carbon saving (£/tC)**	**Cost of carbon saving (£/tCO$_2$)**
Gasoline	**2010**	3.4-6.1	7.8-9.2	155-171	n/a (baseline)	n/a (baseline)
	2020		7.7-9.0	140-155		
Diesel	**2010**	3.4-5.8	5.7-6.8	147-162		
	2020		5.7-6.7	133-147		
Gasoline hybrid	**2010**	3.4-6.1	8.7-9.4	133-147	1629-5089	444-1388
	2020		8.6-9.2	111-122	1523-3280	415-895
Diesel hybrid	**2010**	3.4-5.8	6.2-6.8	121-134	negative	negative
	2020		6.2-6.7	101-112	negative	negative
Bioethanol	**2010**	7.9-13.8	9.1-10.2	20-114	405-1673	125-456
	2020	7.9-13.8	8.9-9.9	9-114	485-2647	138-722
Biodiesel	**2010**	11.3-16.9	7.5-8.4	8-83	negative - 222	negative-61
	2020	11.0-16.9	7.2-8.1	8-83	negative - 5	negative-66
Hydrogen	**2020**	6.0-22.3	8.2-14.2	8-97	334-4461	91-1217

Although these technologies and fuels are compared on a CO_2 basis, the cost of CO_2 saving as a single comparator for these technologies has strong potential to mislead. It depends strongly on the choice of baseline. It is very sensitive to assumptions about future pricing, which are in turn very uncertain, and must be put into clear context. For example, many CO_2 abatement options depend on others, and so selecting the least-cost CO_2 abatement option at any given point may lead to technology lock-in, increasing the cost of future reductions. Also importantly, air quality, security of energy supply and other benefits, such as positive externalities of innovation, will need to be taken into account, rather than simply focusing on CO_2 cost, when comparing the potential of future technologies. Unfortunately, these issues are outside the remit of this analysis

Electric vehicles

Battery electric vehicles (BEVs) still face significant barriers which are likely to prevent mass production and major market diffusion in the medium term. In the longer term, these barriers could potentially keep BEVs within niche applications such as urban commuting, rather than allow them to enter the mass market.

Although lithium-ion technology is believed to provide a significant improvement margin in terms of cost and performance, specific energy storage and corresponding vehicle range remain relatively limited compared with gasoline or diesel vehicles, and battery charging time is still high for most customer expectations, unless fast charging is used. The latter requires more complex and considerably more costly charging stations and would require very aggressive policies for infrastructure to be put in place.

From the point of view of CO_2 emissions, electric vehicles need to be evaluated on a life-cycle basis, as emissions depend entirely on the source of the electricity. For their introduction to significantly contribute to CO_2 emissions reduction, a coherent strategy would have to be pursued in the electricity generation sector, with an increase of renewable or nuclear based power, or the generalisation of carbon capture and sequestration technology.

Hybrid electric vehicles

Hybrid electric vehicles use an electric motor in conjunction with a conventional internal combustion engine (or fuel cell) to improve drive cycle efficiency and hence reduce fuel use.

This reduces emissions by the same amount. Hybrids generally show much greater benefits in slow or stop-start driving than at high speed. Diesel vehicles in Europe are already quite efficient, and hybrid technology therefore is less competitive than in e.g. the USA. Future diesel hybrids may improve this situation.

Hybrid vehicles, and potentially plug-in hybrid vehicles, may well prove a better alternative than battery electric vehicles for widespread market diffusion, as the challenges they face are less onerous. They can also use biofuels in the same way as conventional vehicles.

For high levels of emissions reduction, hybrids need battery technology to reach greater power density and energy density than is currently the case, at an acceptable cost. Unless a significant breakthrough occurs soon in battery technology, and if fuel cells can overcome their technology issues, hybrid systems may end up being a ‘transition’ technology in Europe. If fuel cells do not become successful then hybrid vehicles using biofuels could make a significant contribution to CO_2 emissions reduction. Plug-in hybrids might play a role within a dedicated fleet as they do overcome some of the barriers faced by battery electric vehicles. Limited policy actions are required for this as hybrids are already part of automakers short term commercial plans.

Fuel cell vehicles

Fuel cell vehicles are in demonstration in several countries worldwide. They still face technical barriers to introduction, including lifetime and durability concerns. However, significant progress has been made over the past decade and modelling suggests that mass-production costs will be fully competitive with conventional vehicles, if the technical challenges can be overcome. These challenges are largely related to fundamental materials properties within the fuel cell stack. Storage of hydrogen is also a key issue, as fuel cell vehicle range is still limited to 350 miles at best. Although improved storage technologies would make the transition to fuel cells significantly simpler, designing fuel cell vehicles with a different architecture from conventional vehicles could also produce a vehicle that is fully competitive with all the main attributes of current internal combustion-engined cars. Success in introducing such vehicles will then depend crucially on a decision by policy-makers and automotive companies whether or not to invest in/support the risky period of early uptake, before the different actors can see full returns on their investments. At this early stage, it is not especially relevant to model possible cost differences in fuel cell vehicles to see if they will be exactly competitive with conventional vehicles – it is much more valuable to demonstrate them and understand the real-world benefits and problems that will need to be overcome.

Fuel cell vehicles offer possibly the best long-term potential given the extremely wide range of possible hydrogen sources, but require support in research, development and demonstration in the short term, and in the initial stages of commercialisation in the longer term. Monitoring and careful policy are required to ensure that low-carbon hydrogen is used, once appropriate.

The early introduction of fuel cell vehicles into the UK will depend heavily on strong policy support, as no indigenous manufacturers exist. A considerable difference in the time the first small fleets arrive will have a concomitant impact on the time of uptake, and in the potential for subsequent knock-on benefits for CO_2 reductions, amongst other things. Delays in this area could result in a 5-10 year lag in the UK in comparison with other regions. Of course, support should only be given if the potential of fuel cell vehicles is considered achievable, but demonstrations will be needed, short-term, for evaluation.

Biofuels

Biofuels are the only renewable transport fuel option that can be commercially deployed today. Apart from improved energy efficiency, they are the only supply-side measure available to decrease the reliance of the transport sector, road transport in particular, on fossil fuels, and reduce the greenhouse gas emissions from the sector.

1st generation biofuels, ethanol and biodiesel, derived from sugar, starch and oil crops are produced and marketed in different parts of the world. Although they are commercial, they are only competitive at an oil price greater than 60US$/bbl (on an energy content basis). The lowest cost option is ethanol produced from sugarcane in Brazil, which is competitive under certain circumstances below 60US$/bbl, followed closely by ethanol from corn in the US. In Europe, ethanol from wheat and biodiesel from oil seed rape are competitive at oil prices starting at 70US$/bbl. There is some scope for reducing the production costs through technological innovation in the processing plants. However, feedstock costs weigh heavily on the production costs in temperate climates.

The greenhouse gas emissions savings associated with 1st generation biofuels vary depending, for example, on process plant configuration, and on allocation of emissions and emissions benefits to co-products. Analyses show that emissions savings can range between 7% and 77% for ethanol from wheat, and between 38% and 57% for biodiesel from oilseed rape. Emissions from feedstock production are a major contributor to the biofuel chain emissions balances. Therefore, managing these emissions is a crucial factor. While important greenhouse gas savings can be achieved from 1st generation biofuels produced in the UK, these will depend largely on the fuel chain configurations. Similar considerations apply to imported biofuels. This emphasises the importance of greenhouse gas assurance for biofuels, to ensure that biofuels are indeed making a material contribution to reducing greenhouse gas emissions.

Technologies are being developed that could broaden the biomass resource base that could be used to produce biofuels, as well as the fuels produced, and could potentially lead to lower greenhouse gas emissions and costs of biofuel chains. Biological processes are being developed that could convert feedstocks such as wood, straw and components of municipal solid waste into ethanol and hydrogen, and thermochemical processes are being developed that could produce a range of synthetic fuels (e.g. synthetic diesel and gasoline, dimethylether, hydrogen) from biomass-derived syngas. Some of these options have reached the demonstration stage. The costs of these technologies are high, and uncertainties remain over the cost reduction potential though technological improvement, learning effects, and economies of scale. A crucial element to the viability of 2nd generation technologies will be the availability of low cost feedstocks. Greenhouse gas emissions from 2nd generation biofuels plants using lignocellulosic feedstocks could be very low, leading to emissions reductions greater than 70%.

The biofuels sector is experiencing a very strong growth worldwide as illustrated by the significant growth in activities and plants in Brazil, the US, Europe and parts of Asia. Research, development and demonstration efforts are also intensifying, in particular on 2nd generation technologies, and a number of first-of-a-kind commercial plants are being constructed or at advanced planning stages. There is a significant technical potential for biofuels production, even in temperate and relatively densely populated regions like Europe. The actual potential will depend on the amount of resources that could be dedicated to biofuels production in practice, and the possibility of using lignocellulosic resources. At current oil prices, biofuels are generally not cost competitive with petroleum-derived fuels, so interest and growth remains largely driven by government policies aimed at providing incentives for the use of biofuels.

The production of transport fuels from biomass faces a number of challenges. These include: the need for cost reductions, in order to be increasingly competitive with petroleum-derived alternatives; the commercialisation of lignocellulosic conversion technologies (2nd generation technologies), in order to increase the resource base and possibly reduce costs; improvements in the greenhouse gas balance of conventional bioethanol and biodiesel routes, in order to maximise the environmental benefits from these routes; ensuring sustainable practices are followed along the entire fuel chain, in order to ensure the sector’s long-term viability; improvement of the integration of biofuel into fuelling infrastructure, in order to facilitate their introduction and reduce their costs. Addressing these challenges is crucial to the development of a sustainable biofuels industry, and government policies should be aimed at addressing them. However, government policies should also consider biomass use for biofuels in the context of (a) meeting energy and environment objectives across different energy market segments and (b) biomass use in other applications.

Hydrogen

Hydrogen offers the option of complete energy diversity, as it can be produced from all primary resources, both renewable and conventional. However, technology development is required, particularly in small-scale production, and the simultaneous development of an infrastructure for vehicles and the supply of those vehicles will be essential to ensure uptake, and to ensure that all actors receive a suitable return on investments in fuels and infrastructures. Costs for hydrogen vary widely depending on the primary resource used and the mode of production.

A cost-effective supply of hydrogen – even with high CO_2 emissions –would help to start the market in the short term, while policies would be required longer-term to ensure that the hydrogen used is low carbon. As with biofuels, some analysis will be required to identify the trade-offs between resources that could be used for multiple purposes: hydrogen, electricity, heat or other fuels.

Particular areas for technology development include small-scale electrolysis techniques, particularly those compatible with renewable energy; biomass routes to hydrogen production and carbon capture and storage. At the same time, however, some emphasis must be put on creating demand for hydrogen, as a lack of market pull will also hinder development of truly commercial technologies.

In general, hydrogen is poorly understood by both the public and by policy makers, and hence what is probably an overly cautious approach is adopted by the latter. While pilot projects for the use of hydrogen in transport have been temporarily excluded from fuel duty in order to encourage early uptake, much stronger signals could be sent if there was a duty exclusion up to a certain volume of hydrogen instead, coupled with continuing enhanced capital allowances for infrastructure, and further demonstration projects.

Hydrogen also faces regulatory and legislative barriers, including standards that have been developed in the context of industrial plants and are not directly transferable to transport issues. An evaluation should be made to ensure that any anomalous regulations and legislation can be addressed, while standards on hydrogen for road fuel use are developed in conjunction with other countries. Also of vital importance is work on public acceptance, of hydrogen vehicles, refuelling infrastructure and production plants.

Summary

Making a significant impact in reducing CO_2 from transport will require policy decisions that may be initially unpopular. It is important to stress that many external benefits will arise. However, policies to encourage hybrid vehicles, support biofuels where a good case for CO_2 reductions has been made, and support new technology demonstrations such as fuel cells are essential. Without these it will be impossible to make early inroads into CO_2 emissions reductions, and also very difficult to judge the real costs, benefits and barriers in a UK context. Of course, demand reduction, integrated public transport and behavioural switching will also be essential, not just new technology development.

The area of alternative fuels is complex and increasingly overlaps with other power and energy options for the UK (e.g. the use of biomass for heat and power, the potential for renewable electricity to be used for hydrogen production, and the incentives given by the RO and RTFO). A dedicated unit, within or external to Government, that specifically tracks and measures these different variables would provide an invaluable input to ensuring that policy-making responds both to technology and cost developments, and to the latest thinking in terms of resource allocation.

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INTRODUCTION

Carbon emissions from the UK transport sector grew by 6% in absolute terms over the period 1993-2003. They are approximately 25% of total UK emissions, and this proportion is growing. If the UK is to achieve a 60% reduction in greenhouse gas (GhG) emissions against 1990 levels by 2050, reducing emissions from the transport sector will be essential. However, both the number of vehicles in the UK and the mileage they drive are forecast to continue to increase, and if this cannot be reversed, significant efficiency improvements and fuel switching will be required.

This report sets out the current status of key emerging technologies in the road transport sector which may contribute towards reducing emissions from that sector, and highlights technology and cost issues that may need to be considered in policy setting. A brief review of existing UK Government policy measures and their potential impact on the uptake of these technologies is also undertaken.

An indication of costs of these technologies is given, both as a cost per unit of energy and of reducing CO_2 emissions relative to certain baselines. These costs are sensitive to a wide range of factors and must be seen as only one part of choosing a promising technology or of supporting it in the future.

IMPORTANT ISSUES AND CAVEATS

The status of all of these technologies is, by definition, uncertain. We have given what are currently considered by a range of experts to be realistic estimates, but technology breakthroughs could easily change them by a considerable margin. In general, this will bring about an improvement, so these estimates may generally be taken as conservative.

Introduction of these technologies may depend to some extent on a virtuous circle of support which provides momentum, and not on pure competition. Favourable conditions at an appropriate time could give one technology a lead which others will then not be able to match. This could apply particularly to the investments required to scale up production of e.g. fuel cells, and to the provision of a fuel infrastructure for hydrogen. Cost and technology projections all assume that investment into the technology continues.

Cost of CO_2 saving as a single comparator for these technologies has strong potential to mislead. It is very sensitive to assumptions about future pricing, which are in turn very uncertain. It must also be put into clear context. For example, substantial reductions in CO_2 emissions may be easily made at negative cost if all drivers switch to smaller vehicles. However, this would have considerable impact on the revenues of the automotive OEMs, and so the overall economic impact *might be* negative. Also, many of these CO_2 abatement options in turn depend on others, and so selecting the least-cost CO_2 abatement option at any given point may lead to technology lock-in, increasing the cost of future reductions. Perhaps intuitively, a low cost per tonne of CO_2 may only be achievable with major investment, so that the cost can be amortised over a very large number of units. Finally, air quality, security of energy supply and other benefits, such as positive externalities of innovation, will need to be taken into account, rather than simply focusing on cost. Some of these issues are specifically highlighted below, while others fall outside the remit of this work.

Assuming that vehicle km are not reduced, the two possible ways of reducing CO_2 emissions from road transport involve changing either technology (to make it more efficient) or fuel (to reduce carbon content or upstream carbon emissions), or potentially both. This report looks at each in turn, considering vehicle technologies first.

Costs in this report are given in 2006£, without any applicable taxes or duties. Conversions from other currencies have been made at appropriate rates. The variation in costs due to exchange rate fluctuation is likely to play a minor part in any uncertainties associated with the future fuels and vehicles market, given the high volatility associated with many existing fuels.

It is extremely important to note the uncertainty inherent in all of the cost and price assumptions made here, especially as the timescales increase. Robust policy must be based not only on these numbers, but also on other factors that have not been examined under this analysis.

VEHICLE TECHNOLOGIES

1.1 Fuel cell vehicles

A fuel cell vehicle is primarily an electric vehicle, with the main motive power provided by a fuel cell. Almost all fuel cell vehicles are hybridised with batteries, to recover braking energy from the wheels, and to optimise the sizing of fuel cell, currently the most expensive system component. The use of fuel cell vehicles is potentially important as it allows a fuel switch away from conventional petroleum products, but also as it may offer quite different characteristics to the end user, and therefore may be more marketable than conventional vehicles using alternative fuels, which often have drawbacks but limited compensatory advantages. The vast majority of fuel cell vehicles run on pure hydrogen stored on board, though some work has been and is being done on the on-board processing of other fuels into hydrogen.

1.1.1 Hydrogen fuel cell vehicles

Hydrogen fuel cell vehicles are defined as those that run on pure hydrogen which is stored on board the vehicle directly – as a compressed gas, liquid or in solid state.

1.1.1.1 Technology background

Fuel cells work by electrochemically combining a fuel (usually hydrogen) with an oxidant (oxygen from the air) to produce electricity, water and heat. A fuel cell itself is effectively silent, as it has no moving parts, but the ‘balance of plant’ includes pumps and air blowers, which create some noise and reduce efficiency and reliability. Fuel cells for transport are almost exclusively of the Polymer Electrolyte Membrane (PEM) type, because it has high power density and a solid electrolyte, removing problems with handling potentially corrosive liquid electrolytes.

All major automotive manufacturers are working with fuel cells, either by developing them in-house (e.g. GM, Toyota, Honda), by using fuel cells provided by specialist developers (e.g. Renault, Ford), or both (e.g. DaimlerChrysler, Honda). Some are considerably more optimistic about the technology than others, with Honda’s claims early in 2006 that it would enter production with its fuel cell car in “3-4 years” seen as the most aggressive. However, DaimlerChrysler has proposed an initial launch in 2012, and Ford says its technology will reach “commercial readiness” in 2015. GM has adopted a range of 2010-2015 for “commercial viability”. At the early launch stage, a few tens of thousands of vehicles would be made available by each manufacturer, at the most. These would require a carefully co-ordinated fuelling infrastructure development and so would probably be launched only in a few key regions, to enable servicing and support to be concentrated in those areas. The number of fuel cell vehicles currently in use worldwide is about 500, mainly in controlled fleet demonstrations (ref Fuel Cell Today).

The technology and particularly the cost status of PEM fuel cells are far from clear. Some limited data are available from manufacturers, with more from research institutions and modelling exercises. However, currently lifetime, durability and cost are not suitable for fuel cells to be commercialised in road vehicles.

Further understanding of the fundamentals of fuel cells is required in order to solve some of the technology issues, such as durability. This could also contribute to reducing cost. However, mass-production techniques will have the most significant impact in cost reduction, and detailed modelling studies suggest that fuel cell drivetrains could potentially be fully cost-competitive with internal combustion engines when produced in standard automotive volumes (i.e. in excess of 500,000 units per annum), using current technology. Detailed assumptions can be found in[1] but essentially assume high order volumes, which will bring down the cost of components. Figure 1 shows a statistical cost spread for mass-manufacture of fuel cell stacks under these assumptions.

Fuel cells face other key issues with regard to performance in different environmental conditions (high/low temperature, altitude, humidity etc.). A particular problem is low-temperature starting, though the most recent systems will start at -20°C and work is ongoing for lower temperatures.

Hydrogen storage issues are identical to those discussed under internal combustion engines, in section 1.2.

1.1.1.2 Status

Estimates of fuel cell costs are subject to considerable uncertainty. For a meaningful comparison with conventional vehicles it is necessary to make assumptions about both manufacturing volume and near-term attitudes to pricing on the part of the automotive companies. For example, it is considered very likely that, for a period of time, the Toyota Prius hybrid vehicle cost considerably more to manufacture than the price at which it was sold. However, it was viewed as an important strategic investment by Toyota and, as increased volume of production was introduced, the cost came down. From anecdotal evidence, it is now thought that the Prius is sold at a small profit. For fuel cell vehicles to be introduced while mass-manufacture is just beginning, a similar appetite for bearing cost will be required for all manufacturers. The cost to the consumer, therefore, is primarily a function of what the market will bear.

Current fuel cell stack costs (the key contributor to system costs) are between £200-400 per kW, compared with an internal combustion engine at £20-50/kW. However, these stacks are made in batch processes and assembled primarily by hand. Engineering estimates of stack costs if current technology was used and they were made in automotive volumes (500,000 per annum) is around £50/kW. These costs are forecast to drop further as materials are optimised and technology changes made.

Uncertainty in cost is shown below in detailed modelling conducted for the US Department of Energy. Figure 1 shows that a fuel cell system (stack plus pumps, heat exchangers etc.) could cost in the region of £50/kW in high volume (the mean cost shown below).

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[1] Carlson, EJ, Kopf, P, Sinha, J, Sriramulu, S, and Yang, Y (2005), Cost Analysis of PEM Fuel Cell Systems for Transportation. *NREL/SR-560-39104*, TIAX LLC, Cambridge, Mass.

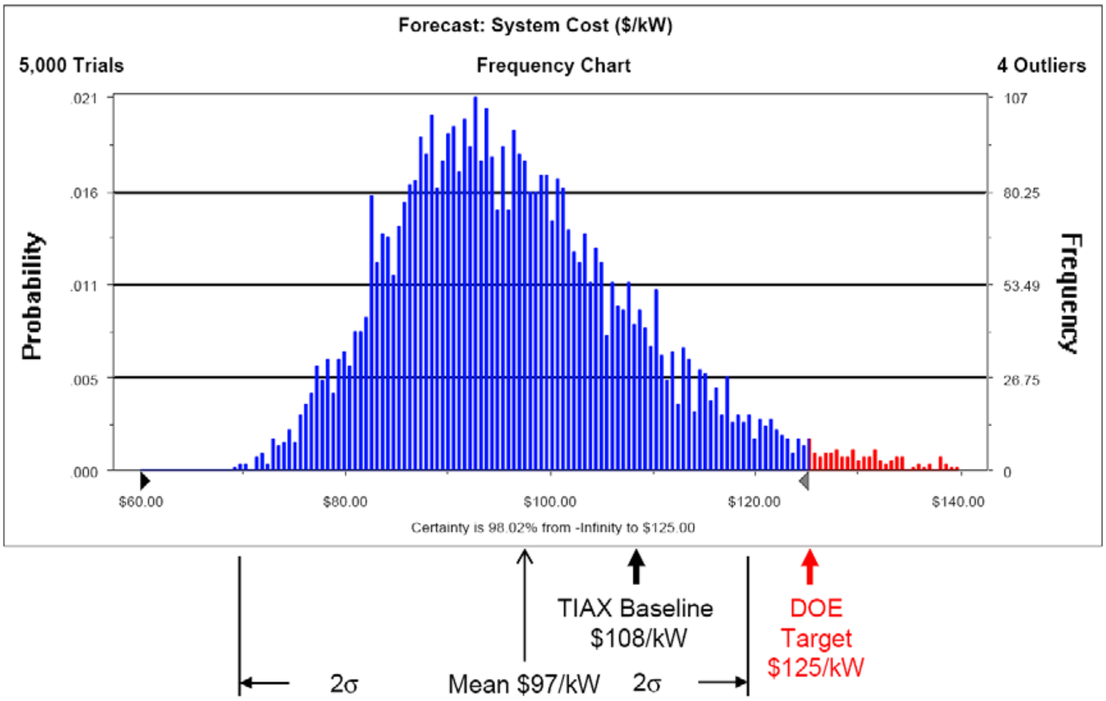

Figure 1: Statistical variation in possible future fuel cell system costs due to uncertainty in inputs

The current lifetime of fuel cell stacks is dependent on their use. However, warranties of around 2,000hrs are typical for the very few early stacks provided for vehicle demonstrations. A lifetime of around 5,000hrs is required for a total vehicle range of 150,000 miles. In laboratory testing, around 9,000hrs has been achieved, but without some of the additional environmental stresses such as pollution to which the vehicle will be subject. The Citaro buses running as part of the CUTE project in London have shown stack lifetimes in excess of 2,000hrs, and continue to operate.

The range of a fuel cell vehicle is dependent on the amount of fuel stored, typically in the form of compressed hydrogen. Current tanks can store enough for a car to travel about 200 miles on a single fuelling, though alternative methods such as Honda’s (described below) may allow up to 350 miles. It is generally considered, though with limited justification, that 350 miles will be the minimum range required for a commercially acceptable vehicle.

Although probably one hundred companies are working in PEM fuel cell stack technology, developing fuel cells for the automotive sector requires very high investment costs and exhibits high levels of uncertainty. Because of this, only a few fuel cell stack producers have targeted this area. These include Ballard, Toyota, Honda, DaimlerChrysler, GM, Nuvera, and United Technologies Corporation (UTC). They rely on component parts from other companies such as DuPont and 3M. Currently, neither the completed stacks nor the individual component parts are perfect for automotive requirements, making development in this area a complex and potentially slow process, even though many of the companies have joint development agreements.

1.1.1.3 Vehicle design

Putting a fuel cell drive system, which is electric and distributed by nature, into a vehicle can be done in ways that are markedly different from conventional drivetrains. The connections to the wheels can be electrical rather than mechanical, making the position of the fuel cell irrelevant. This has been demonstrated in concept cars such as the Hypercar™ and in fuel cell vehicles such as the GM Hy-wire and Toyota Fine-N. The Hypercar demonstrates that if the vehicle is designed around the key constraints of a hydrogen fuel cell system – primarily the hydrogen storage – and if lightweight materials are used, all aspects of the performance can equal or better a conventional vehicle, overcoming some of the issues related to customer acceptance. This would require extensive retooling within the automotive OEMs, but considerable retooling will in any case be required in the event of major production of fuel cells.

While fuel cell vehicles are likely to be based on conventional designs for the period to 2010, the higher volumes required for full commercial introduction may contain many elements of the more advanced models described above. These vehicles could therefore justifiably be assumed to be fully competitive with conventional vehicles by 2020. This assumes (a) that mass-production has been implemented, and (b) that technical issues concerning lifetime and durability have been solved. If fuel cells can be made to work as desired through technology research and development, there is no intrinsic reason why they would be more expensive than conventional engines in mass production. Put another way, if fuel cells work, there is no reason they cannot be mass-produced at a competitive price, given investment in mass production facilities.

1.1.1.4 Vehicle sectors

Fuel cell peak efficiency is similar to internal combustion engine peak efficiency, but is much greater than the ICE at low load. Vehicles are very rarely operated at their peak efficiency, especially in congested areas. The comparison used in this analysis is of average vehicles over standard drive cycles, as single-point efficiency comparisons are extremely misleading. Although efficiency is important, the advantages of a fuel cell are more to do with its potential to use different primary resources, all of which can be turned into hydrogen, zero local emissions, and the expected benefits of having an all-electric vehicle platform[2].

The fuel cell offers greatest efficiency benefits over conventional engines when operated at low percentages of full load, for example in urban driving. This is also where the zero pollution benefit of fuel cell vehicles is greatest. This suggests that urban vehicles such as buses may be good options for technology introduction. However, buses also operate for much longer periods than private cars, for example, and so the lifetime of the fuel cell will have to be considerably greater than the 5,000 hours mentioned above[3]. In addition, the number of cars is considerably greater than that of buses, so the major opportunity for emissions reduction will come in the car sector. For the purposes of this analysis, it is considered likely that fuel cell technology for buses will be primarily at the status of advanced demonstration vehicles during the period around 2010. By 2020, however, fuel cell development should be considerably advanced, and the extended lifetime required for commercial bus use could be attainable. From a policy perspective it is important to consider that introducing buses will give an opportunity for many people to become accustomed to the technology and to the infrastructure required to support private cars, which strongly increases the level of acceptance in most cases[4].

The use of fuel cells in HGVs as primary power is likely to occur later than for other sectors. This is due to the very high mileage and hence lifetime and fuel storage requirements of such vehicles, coupled with the high efficiency of current HGV diesel engines with large numbers of gears. Together, these factors imply lower efficiency gains possible by using fuel cells. However, fuel cells could be used as Auxiliary Power Units (APUs) in cars, buses and HGVs to feed electrical loads. This would obviate the need for conventional engines to run at extremely low efficiency while generating electrical power, but this would also require

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[2] As shown in E4tech (2004), Liquid biofuels and hydrogen from renewable resources in the UK to 2050: a technical analysis. Department for Transport, London, UK, increases in engine efficiency alone are insufficient to help the UK meet CO_2 targets in the long term

[3] Conventional buses also have replacement engines through their lifetime, and the fuel cell buses could do the same. The exact lifetime required is thus not yet clear.

[4] O'Garra, T, Mourato, S and Pearson, P, Analysing awareness and acceptability of hydrogen vehicles: A London case study, *International Journal of Hydrogen Energy, Volume 30, Issue 6, May 2005, Pages 649-659*

suitable fuel to be provided. APUs are not considered further in this analysis, though their development is being pursued by several major companies.

In the timeframe to 2020, some fuel cell buses are expected to operate, with increasing success. However, it is unlikely that large-scale penetration will be achieved, with only a few tens of buses expected in 2010 in the UK, even under optimistic estimates. In the HGV sector, it is unlikely that any penetration will begin before 2020. For this reason, both buses and HGVs are not considered in the quantitative analysis later in this report.

1.1.1.5 Key issues

Fuel Cell

Primary uncertainties regarding the performance of a future fuel cell vehicle are largely related to technology fundamentals. The exact performance and degradation mechanisms of membranes, catalysts and some other components are not fully understood, nor are ways of improving them. However, improvements of one or two orders of magnitude have already been made in these areas over the comparatively short timeframe of a single decade, and as yet no intrinsic reasons have been found that would make the fuel cell non-viable. We therefore assume that all of these issues can be solved over the period to 2020, to allow the performance of a fuel cell to be competitive with conventional vehicles.

Hydrogen Storage

Hydrogen storage is not currently adequate to provide a fuel cell vehicle with comparable range to a conventional vehicle unless considerable modifications are made to the former (e.g. the Hypercar concept). However, the level of barrier this presents is not easy to quantify, as for many journey patterns a range of 200 miles would still only necessitate refuelling every few days. An improvement in storage material would make fuel cell vehicles much more attractive, however.

The cost of hydrogen storage is non-trivial, being considerably higher than the plastic tank required for petrol or diesel. Even if a hydrogen store is found with the right characteristics to provide good vehicle range, the cost will almost certainly be higher than for conventional fuels. This will add something of the order of £500-2000 per vehicle to the costs.

Improved hydrogen storage is therefore still viewed in this report as a key enabler for hydrogen vehicles in general, and research and development should continue to be supported. Conversely, however, it is not viewed as an insurmountable blocker or barrier.

Infrastructure

If the technical issues can be resolved, possibly the greatest barrier to the introduction of fuel cell vehicles is the *simultaneous development of infrastructure and provision of vehicles* at a rate which enables all actors to receive an adequate return on investment and for consumers to be satisfied with their choice in terms of fuelling coverage. While uncertainty exists about whether it is achievable, the attractiveness of a fuel cell vehicle is unlikely to have a major impact on the diffusion of the vehicles into the market. Vehicles are only likely to be released by the manufacturers *once they are attractive* to consumers. More important will be the availability of fuel at a sufficient range of outlets for the consumer to feel comfortable. These must be considered in conjunction with vehicle range, typical driving patterns, and advances in telemetry that can be used to indicate when refuelling might best take place (e.g. when a fuelling station is close by). Hydrogen infrastructure is not itself a barrier, but ensuring that all actors get a return on investment requires the coordination discussed above.

In contrast to the development of petrol and diesel provision, hydrogen and fuel cell vehicles provide a social benefit, potentially at private cost, as they are intended to replace an existing, low-cost, well-functioning system for environmental and security of supply reasons. Customer expectation is considerably higher than it was when ICEs were replacing horsedrawn transport, and so parallels with the early development of petrol and diesel supply are difficult to draw.

A perfect substitute for the current refuelling infrastructure is not likely to be necessary until hydrogen vehicles constitute a major part of the national fleet. A much less dense network could still be used to cover a suitable area, though without providing high levels of competition in the short term. The initial infrastructure could be centralised or decentralised in nature, using locally available energy such as gas or electricity from the grid. In the longer term it is likely that a centralised infrastructure would be (a) more cost-effective and (b) have greater potential for CO_2 emissions reduction.

Real costs of refuelling infrastructure are still difficult to obtain, and very location-dependent. With high utilisation, it appears that companies can generate suitable returns on investment, given a long-term horizon[5]. To get this high utilisation will require appreciable numbers of vehicles in the areas surrounding the refuelling facilities, and hence strong co-ordination between authorities, automotive and energy companies. Clear signals from Government that this is considered a long-term option will be required, and potentially support in the early, but post-demonstration, stages.

Considerable international development is underway as regards codes and standards for refuelling facilities, such as nozzle and storage tank development. The UK is involved to some extent in these, but the lead tends to be in countries with strong automotive industry such as the US, Germany and Japan. Infrastructure projects are being supported by government in many of these areas, and Japan and the USA each have 10-15 hydrogen refuelling facilities.

1.1.1.6 Summary

Fuel cells still offer the potential for a very major shift in transport technology, and combined with low-carbon hydrogen provision, could significantly reduce long-term CO_2 emissions from the sector. However, barriers to entry and uncertainties remain high. Significant progress has been made in all areas of fuel cell technology over the past decade, and it does not appear that any intrinsic barrier has yet been reached. However, performance is still not sufficient to compete directly with existing internal combustion engines, and ways to overcome some of the technology barriers are not yet clear. Cost is considered to be an issue, though with fuel cell production still in very small batches and limited markets to drive competitive pricing, the limited available data may be somewhat misleading. In mass production volumes the difference between fuel cell and conventional vehicles may effectively be negligible.

A well-designed hydrogen fuel cell vehicle *could* potentially compete directly with a conventional vehicle in the near term if lightweight materials and good hydrogen storage packaging were the priorities. Concept designs by Toyota and GM have shown this, as have more individual firms such as Hypercar Inc. Honda’s claim of entering low-volume production around 2009-10 appears to back this up.

The fuel cell must be combined with a source of low-carbon fuel, most likely hydrogen, in order for many of its benefits to be maximised. Overcoming technical issues to ensure competitive fuel cell performance is a critical barrier, but orchestrating a successful *simultaneous roll-out of fuel and vehicle* will also be one of the most significant challenges to their uptake. This will require close co-ordination between auto industry, fuel providers and policy makers.

Several large-scale exercises have been undertaken to try to model the uptake of hydrogen vehicles in the future. Most involve large national or international energy system models. A major difficulty with these models is typically that a limited amount of endogenous change

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[5] E4tech (2005), The economics of a European Hydrogen Automotive Infrastructure. *A report for Linde AG.*

can be embodied, and so the model will pick results for future technologies based on parameters we are able to estimate (or guesstimate) today. For any technology early on the development curve this will typically be grossly inadequate, and so uptake is, in practice, almost impossible to predict.

1.1.2 Fuel cell vehicles with on-board reformer (methanol or gasoline)

Both gasoline and methanol, amongst other fuels, have been suggested as possible fuels for fuel cell vehicles, thereby overcoming problems intrinsic to hydrogen – the development of an infrastructure to provide it, and the limited amount of energy that can be stored on board. However, only a single manufacturer, Renault, is currently continuing work in this area, developing a gasoline reformer system in partnership with fuel cell company Nuvera. Other companies, such as GM, Toyota, and DaimlerChrysler have abandoned their investments in this area. The US Department of Energy stopped funding work on gasoline reformers in 2004 as it became clear that no tangible efficiency (and hence fuel use or CO_2) benefits would be realised in comparison with hybrid internal combustion engine vehicles, and that the systems produced would be overly complex and expensive. It is not generally considered that fuel cell vehicles with on-board reformers will be competitive, and so they will not be considered further in this analysis.

1.2 Hydrogen internal combustion engine vehicles

Hydrogen can be used as any conventional automotive fuel, by exploding it in the cylinders of internal combustion engines. This offers the potential for a simpler introduction of hydrogen than through fuel cell vehicles, though it reduces some of the benefits available, particularly efficiency. Using hydrogen in this way requires some modifications to a petrol engine, but dedicated hydrogen engines could easily be built, and have been in the past. BMW has tested vehicles that can run on both hydrogen and petrol, switching automatically to the latter once the hydrogen tank is exhausted and hence offering fuel flexibility. Ford and Mazda have also conducted considerable work in this area, the latter using a rotary engine. BMW have stated an intention to market 7-series hydrogen vehicles in the near future while Mazda have also begun to offer limited leasing options in Japan for a hydrogen car (the RX-8 Hydrogen RE) that can also run on petrol. In theory, a hydrogen engine can be at least as efficient as a petrol or diesel engine at peak, or even more so. However, over a typical drive cycle a fuel cell is more efficient.

Although in principle an engine could use liquid hydrogen directly, in practice the hydrogen is vaporised before combustion. The only difference between liquid and gaseous hydrogen use apart from that is in the storage and refuelling requirements, which are identical to those for fuel cell vehicles.

Hydrogen internal combustion engine vehicles offer the potential for early introduction of hydrogen vehicles at marginal cost differentials from conventional ones – primarily associated with the cost of hydrogen storage. Manufacturers have mentioned costs of ‘a few thousand pounds’ associated with this, in an upmarket vehicle. This early introduction could assist with the economics of developing hydrogen infrastructure, as vehicles would be available to use the fuelling stations. Hydrogen ICE vehicles have very low (though not zero) regulated emissions – a very small amount of NO_x which can easily be removed using a catalytic converter – and so also assist with improving local air quality.

ICE vehicles using hydrogen would consume more primary resources than the same number of fuel cell vehicles, due to their lower efficiency[6], and so their introduction in large numbers

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[6] E4tech (2004), Liquid biofuels and hydrogen from renewable resources in the UK to 2050: a technical analysis. Department for Transport, London, UK

does not contribute as well to improving security of energy supply, nor to overall CO_2 emissions reduction if the resources are therefore unavailable for other energy uses.

For both ICE and fuel cell vehicles, a key challenge is to store enough hydrogen on board the vehicle to enable it to have a useful range. For ICEs the problem is greater than for fuel cell vehicles, as their efficiency is lower and hence they require more fuel for the same distance travelled.

1.2.1 Liquid hydrogen

Hydrogen can be stored as a liquid at temperatures of -253°C, which gives a high storage density and thus helps to provide a good range for a hydrogen vehicle. However, keeping the hydrogen at such a low temperature for a long period of time is difficult, so losses occur, and the energy required to liquefy the hydrogen is considerable. At this stage, few OEMs are considering liquid hydrogen as their preferred solution. BMW is one of the few, which is linked to its decision to offer internal combustion engine vehicles. As these are less efficient than fuel cells over a typical drive cycle, more hydrogen is required for a similar range and so the highest density hydrogen store is preferred. The BMW 7-series hydrogen vehicles can travel on the order of 100 miles on hydrogen before automatically switching to the petrol tank.

1.2.2 Gaseous hydrogen

The majority of OEMs are using hydrogen stored as a compressed gas, typically at 35MPa, but increasingly at 70MPa. This provides a range of up to about 200 miles for a typical fuel cell vehicle. Honda has a hybrid storage system which uses a metal hydride under pressure. This combines the benefits of a hydride (a solid state store for hydrogen) with pressurisation to increase its capacity. The Honda vehicle can travel about 350 miles on a single refuelling. One possible problem is the length of time or the efficiency taken to refuel, as putting hydrogen into a hydride requires thermal management to prevent the system from becoming too hot.

1.3 Battery electric vehicles

Battery electric vehicles (BEVs) are vehicles which only rely on batteries, or a combination of batteries and supercapacitors, to power the drivetrain. Most of the energy comes from the electricity grid via appropriate charging stations and is stored onboard, but often vehicles are also equipped with braking energy recovery systems.

1.3.1 Technology background

Battery electric vehicles have been developed at one stage or another by most automakers, with a particular focus during the 1980s and 90s. Several went ahead and actually produced commercial models. However, modest range and excessive recharging time has essentially limited electric vehicle sales to the market of dedicated fleets, and all major auto manufacturers have discontinued commercial production. Some still produce electric vehicle prototypes occasionally but the field has been essentially left to specialised firms.

Battery electric vehicle design is very simple compared with gasoline or diesel fuelled vehicles. Connections between the energy delivery system and the wheels are electrical, which offers much more flexibility than mechanical conversion systems. ‘Tank to wheel’ energy conversion efficiency is very high compared with conventional drive trains as electric motors now reach 90% efficiency and battery conversion efficiency lies between 70 and 95% depending on the type and use of the battery. Most battery electric vehicles can also recover part of the braking energy (typically 30 to 40%), using electric motors in generator mode. The vehicle may have a single electric motor or one for each of the wheels.

Early electric vehicle models relied on lead-acid and NiCd batteries, and more recently on NiMH technology, but neither performance nor cost have not proved suitable for commercial success. Newer technologies such as NaNiCl, lithium-ion, lithium-ion-polymer, and lithium-metal-polymer have shown promising capabilities and should lead to greater energy density, though these come at typically higher cost, and sometimes with other issues.

The electric motor driving the wheels can be of DC, synchronous AC, or asynchronous AC types. DC motors are characterised by low cost and high reliability, while synchronous and asynchronous motors benefit from greater efficiency and power density. Synchronous motors with permanent magnet, together with inverter control, are often used for battery vehicles. Motors are a relatively mature technology area, though work in cost reduction is important. The use of hub-mounted motors rather than a central motor with axles is potentially valuable, but the robustness of individual wheel motors must be very high to resist damage under normal driving conditions. Work is ongoing in this area.

When recharging, most battery electric vehicles use direct electrical connection known as conductive coupling. Another approach is inductive coupling which does not require cable connection but is more costly and less efficient.

1.3.2 Status

Electric vehicle development over the past ten years has been dominated by smaller firms, low volume developments within major automakers, and collaborations between major automakers and specialists. Smaller firms have met with varying levels of success though there is a wide range of activity worldwide. Major automakers have been less successful in the past, though some are re-entering the field. Collaborations between major automakers and specialists have also met with varying success, but are commonplace.

Several major automakers tested the market for battery electric vehicles in the 90s, but without commercial success. In Europe, where the total fleet is a little more than 25,000 battery electric vehicles, Peugeot were once the most active in the field with about 12,000 electric vehicles sold, but ended their production in 2002. In the US, GM, Ford and Toyota produced and leased battery electric vehicles for several years essentially in order to comply with the California's Zero-Emission Vehicle Mandate. Again, production of those vehicles ended rapidly. Honda did not have any more success in Japan with its EV plus.

The field was therefore left to specialised smaller firms, who continue to develop the technology. Some target the commercialisation of battery electric vehicles for niche markets (utility vehicles, low-speed small urban private vehicles and neighbourhood vehicles), while others use those prototypes as a platform for the demonstration of their technology (battery providers).

More recently, those firms have released prototypes with substantially improved driving range compared with previous models. The characteristics of the BlueCar, a joint project between the Bolloré Group, EDF (via its participation in Batscap) and Matra Auto Engineering, are shown in Table 1. Although Bolloré Group does not intend to become a vehicle provider, this prototype illustrates a possible commercial electric vehicle in the near future. The Bolloré Group recently decided to invest in a new battery production facility which could potentially deliver 10,000 battery systems a year. Several new prototypes will be built in 2006 and the firm considers £13,800 a potentially achievable short term price target for the 'BlueCar' vehicle. In Canada, Electrovaya produces the Maya 100 (see Table 2), an electric vehicle based on lithium-ion super polymer battery technology with an impressive range of up to 360 km, according to the firm, and a maximum speed of 140 km per hour. This vehicle will also be available in Europe via the Norwegian firm Miljobil Grenland. The battery electric version of the Cleanova II from SVE (Dassault and Heuliez) may be commercialised as soon as 2008 for dedicated fleets. SVE claims a range of 200 km achieved with lithium-ion battery technology. The operating cost of such a vehicle in France is estimated at about £0.70 per 100 km.

Table 1: Characteristics of the 'BlueCar' battery electric vehicle

Average range	200-250 km
Max speed	125 km per hour
Full recharge	6 hours (50% after 2 hours)
Express recharge	a few minutes for 20 km autonomy
Energy storage	lithium-metal-polymer, 27 kWh, < 200 kg
Constant power	30 kW
Peak power	50 kW
Maximum torque	170 Nm
Acceleration	6.3 sec. from 0 to 60 km per hour

Table 2: Characteristics of the 'Maya 100' battery electric vehicle

Average range	> 300 km
Max speed	140 km per hour
Full recharge	6 -8 hours
Energy storage	lithium-ion superpolymer, 40 kWh, < 300 kg
Constant power	25 kW
Peak power	42 kW
Maximum torque	200 Nm

In order to keep track of improvements in battery technology, some of the major automakers entered agreements with specialised firms, who develop electric versions of their conventional models for occasional prototype demonstrations. Volkswagen is working together with US-based Hybrid Technologies on a lithium-ion battery electric vehicle concept. DaimlerChrysler released battery electric prototypes of the Smartcar, in collaboration with zyteck (a 30 kW two seat vehicle with a 110 km range, and a specific consumption of 12 kWh per 100 km). An electric version of the Smartcar had already been commercialised by Hybrid Technologies.

In Japan, larger firms such as Mitsubishi and Fuji Heavy Industries (owner of Subaru) decided to develop the technology needed for compact battery electric cars internally, and to market those in collaboration with TEPCO, the major Japanese electric utility. Mitsubishi has developed three concept battery electric vehicles in the last two years with the Colt EV, the Lancer Evolution, and finally the Concept-EZ. The Concept-EZ delivers 80 kW, a maximum speed of 150 km per hour, and has a range of 120 km. The firm is planning to commercialise an electric minicar by 2008 which will use its In-wheel Electric Hybrid System (an electric motor for each of the four wheels), will achieve a 250 km range after a four hours recharge, and will be available at £9,900. TEPCO will provide the charging technology and the rechargeable batteries. Fuji Heavy Industries is developing the minicar R1e based on manganese lithium-ion battery technology, with a limited 120 km range (expected to be increased to 200 km) but with an impressive 90% recharge in 5 minutes using single-phase 220V AC outlets of the same kind as those used in Japan for large home air conditioners. The battery lifetime equates to about 150,000 km. Commercialisation is planned for 2010.

1.3.3 Vehicle design

BEVs are based on the same design as conventional vehicles, with an electric motor replacing the ICE and batteries replacing the fuel tank. The high weight and sometimes large volume of batteries may lead to problems with space availability, and can reduce the performance of the vehicle, which is typically heavier than standard. Most of the specialist vehicles are smaller and use lighter weight materials.

1.3.4 Vehicle sectors

Obvious niche markets for battery electric vehicles are dedicated fleets such as utility vehicles which require less flexibility of use than private cars, or low-speed small urban private vehicles and neighbourhood vehicles used for short trips only. This is a potentially promising area for BEVs, but they will still require some form of support before prices come down to fully competitive levels.

The potential future use of battery electric vehicles for the much larger passenger car fleet is strongly dependent on breakthroughs in the field of battery technology and on the willingness of public authorities and possibly power utilities to actively promote the development of public recharging (and most probably fast recharging) infrastructure to complement home based private charging outlets.

Heavy duty vehicles, both buses and HGVs, are unlikely to use batteries alone due to their high mileage and power requirements, but may use hybrid systems in the long run.

1.3.5 Implications

If we consider about 29.3m passenger cars on the road in the UK in 2004, average new registrations of passenger cars of 2.5m per annum, and a 5% share of BEVs between 2007 and 2020, this leads to about 1.75m battery electric vehicles on the road by 2020 in the UK (2.6% of the total passenger car fleet). These would require about 3.2 TWh of electricity, i.e. about 0.8% of the DTI total electricity demand forecast of 399TWh, assuming that each vehicle is driven 15,000 km per year on average and that average specific energy consumption is 12 kWh/100 km.

Using the average grid CO_2 intensity to 2020 of the scenarios examined by the Science & Technology Committee of the House of Commons[7], and using 12 kWh/100 km as an average energy use for BEVs, 1.75m BEVs would generate between 633,000 and 785,000 tons of CO_2 per year, i.e. about 2% of current yearly CO_2 emissions from road transport.

1.3.6 Key issues

Energy storage technology

The development of advanced battery technology is the most fundamental issue for battery electric vehicles. Wider market diffusion essentially requires greater range (energy storage) and faster charging. Table 3 shows the goals required for commercialisation by the United States Advanced Battery Consortium, a partnership between the U.S. Department of Energy (DOE) and DaimlerChrysler, Ford, and General Motors, while Table 4 indicates that most advanced batteries are close to, for example, the minimum requirements. Whether their cost can be cut down to commercially acceptable levels (i.e. less than £80/kWh in runs of 25,000 units) remains to be demonstrated, but numerous collaboration initiatives and R&D investments in the private sector suggest some level of optimism. Electrovaya already claims an impressive energy density of 225Wh/kg for its lithium-ion-superpolymer technology, with a life time equivalent of 150,000 km of operation. Short term cost targets for these batteries are in the order of £165/kWh. The firm aims at reaching 330Wh/kg for the next generation. Some advanced battery technologies face other challenges, for example Li-ion batteries are

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[7] House of Commons Science and Technology Committee (2006), *Meeting UK Energy and Climate Needs: The Role of Carbon Capture and Storage,* First Report of Session 2005–06; Volume II: Oral and Written Evidence

fragile, requiring protection circuitry to maintain safe operation, and suffer from aging, whether used or not.

Table 3: United States Advanced Battery Consortium goals for advanced batteries for battery electric vehicles.

Parameter of fully burdened system	**Minimum goals for large-scale commercialisation**	**Long term goals**
Power density [W/l]	460	600
Specific power – discharge, 80% DOD/30 sec [W/kg]	300	400
Specific power – Regen, 20% DOD/10 sec [W/kg]	150	200
Energy density – C/3 discharge rate [kWh/l]	230	300
Specific energy – C/3 discharge rate [Wh/kg]	150	200
Specific power/specific energy ratio	2:1	2:1
Total pack size [kWh]	40	40
Life [years]	10	10
Cycle life – 80% DOD [cycles]	1,000	1,000
Power & capacity degradation [% of rated spec]	20	20
Selling price – 25,000 units @ 40 kWh [£/kWh]	<80	55
Operating environment]C]	-40 to +50 20% performance loss (10% desired)	-40 to +85
Normal recharge time [hours]	6 (4 desired)	3 to 6
High rate charge [minutes]	20-70% SOC in <30 min @150 W/kg (<20 min @ 270 W/kg desired)	40-80% SOC in 15 min
Continuous discharge in 1 hour – no failure [% of rated energy capacity]	75	75

Table 4: Main characteristics of various types of current battery technology for battery electric vehicles

Technology	Specific energy [Wh/kg]	Specific power [W/kg]	Life time [cycles]	Optimal working temperature [°C]	Efficiency [%]	Other parameters	Current cost [£/kWh]
Valve regulated Pb-acid	35	250	700	20-40	80-85	low self-discharge rate; maintenance free	80 -105
NiCd	40	200	2000	0-40	70-75	low self-discharge rate; fast charging; toxicity	340 - 500
NiMH	55	250	2000	0-40	70	high self-discharge rate (hydrogen diffusion through the electrolyte); need for thermal management; maintenance free; fast charging	400 - 465
NaNiCl (‘Zebra’)	100	200	1000	250	85-90	high self-discharge rate (heating); need for thermal management (cooling in operation, heating when idling)	310 - 345
Lithium-ion	110	400	3000	0-40	90-95	low self-discharge rate safety issues due to lithium high reactivity; fast charging; low weight	485 - 595

specific energy: the amount of energy that can be extracted from a battery per unit of battery weight
specific power: the amount of power that can be extracted from a battery per unit of battery weight
cycles: number of charge-discharge cycles a battery can last before it must be replaced
optimal working temperature: temperature range within which the battery delivers suitable performance
efficiency: ratio between the energy required to charge the battery and the energy delivered by the battery for one charge-discharge cycle
Source: SUBAT project

Finally, issues other than battery energy density and cost may lower acceptance of electric vehicles. These include the fact that the battery may self-discharge if left unused for a period of time; they have poor performance in cold conditions, particularly below 0°C, battery life-time that strongly depends on how the vehicle is used, and most have long recharging times. The latter is most probably the greatest barrier for a wide diffusion of electric vehicles, as it considerably reduces the flexibility of use. However, this is partly an infrastructure issue, as fast charging of certain battery types is technically achievable, though at a high cost, with appropriate chargers and outlets.

Infrastructure

Conventional charging stations deliver about 10 km per charging hour (8-12 hours in average for complete recharge) and most vehicles include the power conversion equipment onboard. In Europe, cities such as Paris, Athens, Copenhagen, Coventry, London, Palermo, and

Stockholm for example have infrastructure for the ”slow” recharging of electric vehicles. Charging stations may belong to the municipality or to the local electric utility.

Fast charging stations deliver ~10 km per charging minute but are much more costly and expensive due to the power and thermal control systems. Furthermore, current commercial vehicles are not suitable for such charging stations. Semi-fast charging stations deliver ~10 km per 5 to 10 charging minutes.

Within the European project Zeus, the city of Palermo experienced different charging station options: slow recharging posts cost between £35 and £220 to install and a fast recharging post with two points cost between £3,450 and £4,150.

No top-down state planning approach for a comprehensive development of electric vehicles' infrastructure has been conducted so far. The current liberalisation process of electricity markets taking part in many countries do not play in favour of such an approach and state involvement is more likely to occur through financial incentives to encourage demand, pilot & demonstration projects, negotiations for the establishment of common standards and regulations.

If such an infrastructure ever develops, it is likely to develop on a decentralised basis through local initiatives, i.e. at the city or regional level.

1.3.7 Summary

Despite the recent progress reported, BEVs still face significant barriers which are likely to prevent mass production and major market diffusion in the medium term. In the longer term, these barriers could potentially keep BEVs within the niche applications discussed above rather than allow them to enter the mass market, especially if fuel cell vehicles develop as a viable alternative. BEVs are therefore not considered in the modelling later on in this analysis.

Although lithium-ion technology is believed to provide a significant improvement margin in terms of cost and performance, specific energy storage and corresponding range remain relatively limited compared with gasoline or diesel vehicles, and battery charging time is still high for most customer expectations, unless fast charging is used. The latter requires more complex and considerably more costly charging stations and would require very aggressive policies for infrastructure to be put in place.

Hybrid vehicles, and potentially plug-in hybrid vehicles, may well prove to be a preferred alternative to battery electric vehicles for wide market diffusion as they seem to face more manageable challenges.

From the point of view of CO_2 emissions, electric vehicles need to be evaluated on a life-cycle basis. For their large introduction to significantly contribute to emissions reduction, a coherent strategy would have to be pursued in the electricity generation sector, with an increase of renewable or nuclear based power, or the generalisation of carbon capture and sequestration technology.

1.4 Hybrid vehicles

Hybrid technology can mean any combination of drivetrains, but now usually refers to a vehicle concept which combines an engine that burns a fuel (typically an ICE, but increasingly a fuel cell) with an electric power train (electric motors and electricity storage devices, i.e. battery or supercapacitors). The purpose is to combine the range and rapid refuelling of conventional vehicles with the environmental benefits of an electric drive mode and/or with the high torque and acceleration performances of electric engines. The key technical components of a conventional hybrid vehicle are similar to a BEV – the battery and motor – but the control strategy and design are also very important. In this section only ICE hybrids are discussed, as most FCVs are already hybridised.

1.4.1 Technology background and vehicle design

1.4.1.1 Mini and mild hybrids

The least aggressive option for hybrid vehicle architecture, i.e. mini-hybrid, is a concept which shuts down the thermal engine when the vehicle stops, and uses energy stored in the battery to start it again. Citroën (PSA) recently developed and commercialised this for the C3 (2004) and the C2 (2005) under the name of ‘Stop & Start’ technology, a reversible starter-alternator system. CO_2 emissions are reported to be reduced by about 10% compared with the standard C2 model when driven on a US standard combined cycle (reported fuel economy 50.4 (US)mpg, or 4.7 litres per 100 km). Starting price for the C2 in the UK is £10,690 and a cash-back incentive of £1,696 is currently offered – equivalent to a one year’s London congestion charge.

Slightly greater environmental performance can be achieved when the architecture of the hybrid vehicle is such that the braking energy can be partially recovered and stored, to be used for starting the vehicle and assisting drive during acceleration. This is a so-called ‘mild hybrid’.

1.4.1.2 Full hybrids

While mild hybrids do not allow pure electric operating mode, full hybrid vehicles are designed in such a way that they can run for limited distances without operating the main engine. However, current models have very low pure electric ranges, typically less than 1or 2 km, due to limited battery capacity.

Full hybrid concepts use both the main engine and the electric motor to run the vehicle, and those are combined within ‘Series’, ‘Parallel’ or ‘Mixed’ architectures (see Figure 2). Series architecture has typically been used for ‘range extender’ versions of battery electric vehicles. Parallel and mixed architectures allow the downsizing of the thermal engine and its use within a load range where its efficiency remains close to nominal efficiency. When the load is low the main engine still operates at high enough load to maintain a decent efficiency and the excess power is used to charge the battery via an alternator, and when the load is high the main engine is supported by the electric motor using the energy previously stored. The battery is always charged by the main engine.

‘Series hybrids’ are based on electric traction and use the thermal engine as a generator. ‘Parallel hybrids’ are based on mechanical traction and the electric motor is used as a ‘booster’, i.e. both systems usually share the same shaft, operate at identical speed and add their torque – the Honda Insight and Honda Civic are of this type. ‘Mixed hybrids’ combine both modes within a more complex architecture – the Toyota Prius and the Nissan Tino are of this type.

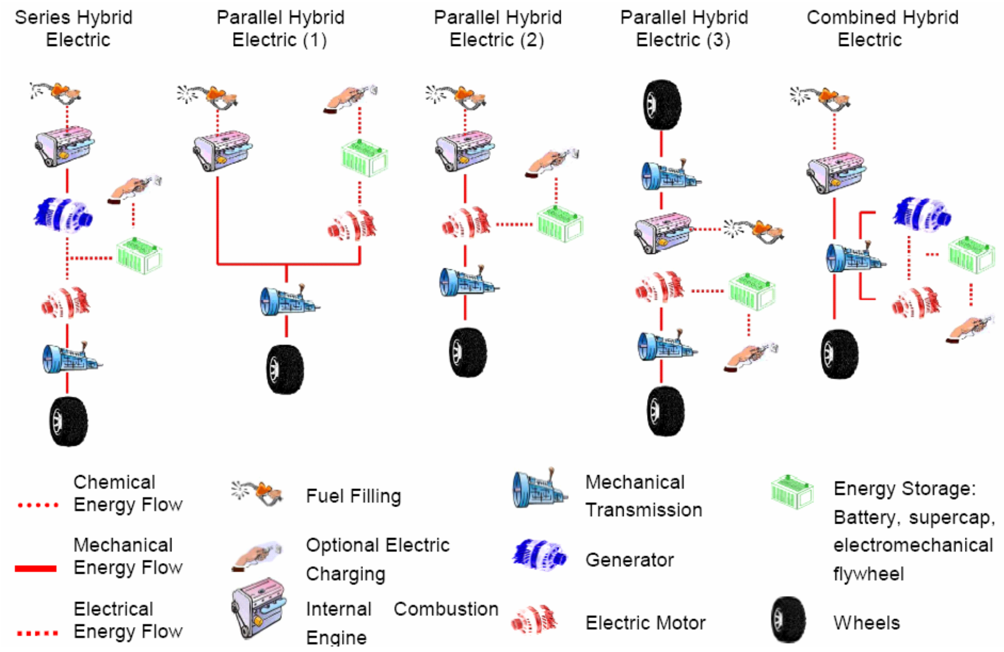

Figure 2: Various possible architectures for hybrid vehicles [Source: TNO]

1.4.1.3 Plug-in hybrids

The problems faced by pure electric vehicles in terms of range and refuelling time have so far been a barrier to their diffusion beyond the limited market of dedicated urban fleets. A plug-in hybrid vehicle would not only use the main engine to recharge, as do most versions, but could also be plugged in to a charging station to augment its range.

Plug-in hybrids offer potentially both the benefit of pure electric vehicle attributes (quiet operation, low operating and maintenance cost, high acceleration from standing start, braking energy recovery, zero local pollution rate and potentially low CO_2 emissions) while providing a range and refuelling time equivalent to conventional vehicles whenever needed. These are sometimes referred to as 'range extender' hybrid vehicles.

An indicative 10% market penetration of plug-in hybrid electric vehicles in Western Europe (a more likely early market than the whole of Europe, given the additional cost of hybrid vehicles) would require an additional 29TWh of electricity generation yearly, i.e. about 1% of current total electricity generation, under the following assumptions: 1) a total fleet of about 200 million passenger vehicles[8], i.e. 20 million electric vehicles, 2) 15,000 km driven per year and per vehicle on average, 3) 12 kWh/100 km average specific energy consumption in pure electric mode, and 4) 80% share of pure electric mode in the total distance driven annually – essentially urban trips.

Most of this additional load would however occur at off-peak hours (overnight recharging typically) and load would be essentially concentrated in urban areas associated with already significant grid capacity. A 10% market penetration of plug-in hybrid vehicles might therefore not have a significant impact on electricity generation and transmission capacity. CO_2 emissions reduction would depend entirely on the region and local charging mix, in addition to the alternative displaced.

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[8] The national fleet in 2004 was 192 million vehicles

1.4.2 Status

Hybrid vehicle technology is generally perceived as a very credible medium term option and has already been commercialised despite the extra cost and constraints related to the added electrical equipment. A large spectrum of technical options is being investigated and associated performances vary from a few percent to about 50% lower CO_2 emission rates compared with conventional gasoline fuelled ICE vehicles when measured for urban cycles. The plug-in hybrid option potentially allows even much greater emissions reduction, depending on the vehicle use and on the carbon intensity of the grid electricity. The expected extra cost for producing the vehicle has been reported to be between a few percent and 20% depending on the type of hybrid vehicle (mini, mild and full-hybrids), but this is obviously very sensitive to assumptions relative to market penetration and corresponding volume of production.

Hybrid technology is often perceived as an alternative to diesel engines in countries such as the United States and Japan, due to the reluctance of American and Japanese authorities to promote diesel for passenger cars because of issues related to atmospheric pollutants. Diesel based hybrid technology is being considered by several automakers as a possible option for the European market. Hybrid vehicles are also often seen as a transition technology on the path towards fuel cell vehicles which, by the way, are likely to be based on hybrid architecture.

The greatest difficulties automakers have to face are the complexity associated with real-time management of dual power trains and the relatively poor performance of battery technology which has so far limited commercial models to so-called mini-hybrids and mild-hybrids, or to very modest versions of full hybrids.

Japanese automakers have been the pioneers with Toyota, Honda and Nissan, who started commercialisation of full hybrid vehicles several years ago. Following the success of the Japanese hybrids on the US market, North American automakers also began to propose hybrid models, essentially with a focus on SUVs so far.

In Europe, where automakers invested heavily in diesel technology and where diesel vehicles are already widely diffused and associated with high fuel economy, enthusiasm about hybrid technology has been lower among automakers. Some are still very sceptical (i.e. Renault) while others see a future for hybrid technology in Europe but only when associated with diesel engines (PSA, Volkswagen).

Toyota commercialised the first mainstream hybrid technology in 1997 after about ten years of research, the Prius. The chosen system is complex (mixed architecture) but nevertheless reliability and feasibility have now been proven with total sales to date of about 450,000 vehicles worldwide. Toyota claims the Prius has 40% lower CO_2 emissions than an equivalent conventional gasoline fuelled vehicle, over a standard driving cycle. The CO_2 emissions rate has been measured to be 104 g per km on a European cycle, though real-world emissions are probably higher. A more powerful car, the Toyota Camry Hybrid will soon be available in the US at a retail price of £14,500, which is a premium of about £3,600 over the cost of the four-cylinder Toyota Camry LE. The Camry Hybrid is expected to achieve 40 (US)mpg in the city and 38 (US)mpg on the highway, for a combined fuel economy of 39 (US)mpg (6 litres per 100 km), a 40% improvement over the standard four-cylinder Camry.

Sales of hybrid vehicles currently represent about 6% of Toyota's total sales in the US. Toyota expects hybrid vehicles to represent 10% of its worldwide sales by 2012, i.e. 1 million hybrid vehicles sold per year. Toyota claimed in an article in the Japanese newspaper *Nihon Keizai Shimbun* that the current cost of its hybrid models is, *on average,* about £2,245 greater than an equivalent vehicle of conventional type. Their plan is to lower the price of hybrid technology and reduce the equipment size (notably by switching from nickel metal hydride to lithium-ion batteries) by more than 30% in order to make it available for cheaper models.

The new Prius, to be commercialised in 2008, is intended to deliver much greater fuel economy than the current model, i.e. 94 (US)mpg (2.5 litres per 100 km). Its electrical system has been redesigned and Toyota is working on a prototype that runs solely on the electric motor in slow traffic.

Honda also recently announced that it would cut the extra cost of the Civic hybrid power train by a third within 5 years, down to about £955. The current version of the Civic emits 116 g/km CO_2 on a European cycle. The two seat Honda Insight is currently the most efficient hybrid vehicle on the US market, at 62 (US)mpg (3.8 litres per 100 km).

Mitsubishi and Fuji Heavy Industries (owner of Subaru) both plan to commercialise hybrids before 2010. Mitsubishi released a mixed hybrid prototype early in 2006, the Concept-CT. This vehicle is based on the In-wheel Electric Hybrid System developed by the firm which associates an electric motor to each one of the four wheels, and uses lithium-ion battery technology.

In North America, GM and DaimlerChrysler, together with BMW, are in collaboration on the development of the so-called ‘two mode’ system which will equip the Chevrolet Tahoe in 2008. GM and DaimlerChrysler are also working on a diesel hybrid concept for the Opel Astra for a possible future introduction on the European market. This vehicle is equipped with the ‘two-mode’ full hybrid system and NiMH battery technology, and reaches a fuel consumption below 4 litres per 100 km (MVEG cycle), i.e. 25% below comparable diesel models.

PSA is working on a hybrid diesel concept to be commercialised by 2010, and has just presented its 307 CC Hybrid HDI, using NIMH batteries. The electric motor operates at low vehicle speed and during deceleration, while the ICE operates at high speed. Both motors operate together during strong acceleration phases. The fuel economy is 4.1 litres per 100 km for a mixed cycle, i.e. 30% less than the current diesel 2.0l HDI FAP model with similar performance. PSA also works in collaboration with Ricardo Ltd and QinetiQ on advanced hybrid technology to develop an ultra-low CO_2 emission car, the Efficient-C. The CO_2 emissions target is 89.5g/100 km.

Although Volkswagen is focused on advanced diesel technology for the European market, it intends to make a diesel hybrid technology available in the short term for its Beetle and Jetta models with a targeted fuel economy close to 3 litres per 100 km, and has also started collaboration with Shanghai Automotive for the development of hybrid vehicles and commercialisation by 2010 on the Chinese market. Their recently demonstrated Golf ECO.Power has a 62 (US)mpg fuel economy average (3.8 litres per 100 km). Note that Volkswagen released a diesel hybrid vehicle prototype in 1991 with an impressive fuel economy of 2 litres per 100 km.

Fiat has been working on full hybrid vehicles for several years using the Multipla platform, but no plans for commercialisation have been announced.

Table 5: Examples of hybrid vehicles currently proposed by automakers for the US market

Vehicle	Automaker	Fuel economy (US combined driving cycle) [(US)mpg] / [litres per 100 km]	Starting price [£]	Vehicles sold per month on the US market
Prius	Toyota	55 / 4.3	11,880	~ 7,900
Camry	Toyota	39 / 6.0	14,180	
Civic	Honda	48 / 4.9	12,155	~ 2,200
Insight	Honda	62 / 3.8	10,950	~70
Saturn VUE (SUV)	GM	29 / 8.1	12,595	
Escape (SUV)	Ford	33 / 7.2	15,055	~ 1,600[9]
Highlander (SUV)	Toyota	30 / 7.8	18,065	~ 3,000
Lexus RX 400h (SUV)	Toyota	30 / 7.8	26,555	~ 2,500

The concept of plug-in hybrid vehicles has gained momentum in the United States recently among policy makers. The new industrial ‘Plug-in Hybrid Development Consortium’ has also been created, with the goal of developing technologies required for plug-in hybrid vehicles to reach a fuel economy between 100 and 200 (US)mpg (1.2 to 2.4 litres per 100 km) and a pure electric range between 20 and 50 miles (40 to 80 km).

In Japan, hybrid technology providers have previously emphasised the fact that their technology did *not* require plugging-in, to differentiate themselves from poorly perceived pure electric cars. Their marketing strategy seems to have changed recently and some Japanese automakers are reconsidering the plug-in concept as a possible option for their portfolio, essentially in relation with the expected developments in the US market.

In Europe, some R&D activities in the field of plug-in hybrids have been undertaken by major automakers (PSA – ‘Dynalto’, Renault – ‘ElectRoad’, Fiat – ‘Multipla’) in the recent past. Range extender versions of previously developed electric vehicles have been tested, and even briefly commercialised in the case of Renault. Pure electric ranges between 40 and 100 km are typical, with ICEs used to allow total ranges between 150 to 400 km depending on the operating mode and model. However, most of them have cancelled these programmes in the last two to three years due to inadequate battery performance and low market potential. DaimlerChrysler is one exception; it is still investigating the relevance of a plug-in version of its Sprinter van for near term commercialisation, in collaboration with EPRI. However, this is essentially driven by Californian rather than European market requirements.

Some know-how has nevertheless been gained by European automakers, which could be a basis for new momentum in the case of a potential breakthrough in battery technology.

From an early niche market point of view, activities are undertaken by specialised firms such as Dassault-Heuliez SVE, supported by on-going testing programmes in France in collaboration with EDF and the mail delivery service. This firm is the closest to a commercial version for dedicated fleets which could be released in the very near term, with characteristics as shown in Table 6.

EnergyCS (US) have started commercialising a retrofit plug-in version of the Toyota Prius under the brand name ‘Edrive’ in California for £6,730 in addition to the original model price, and plans to deliver plug-in kits in the UK soon in collaboration with Amberjac. The battery can be recharged overnight with a normal house outlet for a cost of about £0.60, and the Edrive is said to reduce the fuel consumption by half over a distance of at least 50 miles (80 km). Hymotion (Canada) also proposes plug-in kits for the Toyota Prius and the Ford Escape.

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[9] including Mariner model

Ricardo and AFS Trinity are developing a plug-in hybrid concept, the ‘Extreme Hybrid’, based on lithium-ion batteries and ultracapacitors which is expected to deliver a fuel economy as high as 250 (US)mpg (less than 1 litre per 100 km) and be able to reach 50 miles (64 km) on a pure electric mode.

In the UK, Zytek is working on a diesel plug-in hybrid prototype in the context of the Energy Saving Trust’s Ultra Low Carbon Car Challenge project. The vehicle is based on a 1.5 litres turbo-charged diesel engine and two permanent magnet electric motors. Batteries are of lithium-ion technology (from Lithium Technology Corporation) with a 25 kW maximum power output. Electric range is very modest as the battery pack delivers 2.2 kWh (288 V, 7.5 Ah).

Table 6: Characteristics of the ‘Cleanova II’ plug-in hybrid electric vehicle)

Pure electric range	200 km
Full range	400-500 km
Max speed in electric mode	130km per hour
Full recharge	8 hrs (70% after 0.5 hrs, with high power fast charger)
Energy storage	Lithium-ion, 25 kWh, 200 kg
Electric motor nominal power	35 kW
Thermal engine nominal power	15 kW
Acceleration	8 sec. from 0 to 50 km per hour

1.4.3 Vehicle sectors

Hybrid systems are being investigated for passenger cars, light-duty vehicles, heavy duty vehicles, and even locomotives. Hybrid technology is easiest to implement on passenger cars and light-duty vehicles. As described above, mild hybrid systems are already part of automakers’ commercial plans and are becoming available on the market, together with modest versions of full hybrid vehicles.

High mileage and power requirements make it more challenging to equip trucks and buses with hybrid systems. However, hybrid buses have been developed notably by GM and commercialised since 2004. About 500 hybrid buses have been delivered on the North American market so far, and GM has just announced the delivery another 250 buses by the end of 2006. GM claims the buses provide 50% greater acceleration than conventional diesel buses. In Japan, Hino is producing a diesel parallel hybrid bus which reduces fuel consumption by 10-20% compared with conventional diesel buses. However, hybrid buses remain associated with substantial initial cost premiums (up to £85,000-115,000 over the £195,000 average cost) and their greater fuel economy does not offset this over their lifetime.

Commercialisation of hybrid trucks started in 1993 in Japan, and Hino Motors Manufacturing has sold more than 15,000 of its hybrid system developed in collaboration with Toyota. This vehicle reduces fuel consumption by 30% compared to the diesel version, but is about £5,000 more expensive. Yearly sales are 1,500 units, and Hino wishes to reach 2,000 to 3,000 units per year by decreasing the cost by 30-40%. Isuzu Motors and Mitsubshi are about to make similar vehicles available on the market. In the United States, development and demonstration of prototype trucks is ongoing, notably within the ‘National Hybrid Truck Users Forum’ bringing together truck users, truck providers, and the U.S. military. Results have shown between 40 and 60% lower fuel consumption than conventional trucks. ‘International Truck and Engine’ announced it may start commercialisation of trucks soon.

The Volvo Group is working on the development of diesel hybrid trucks based on bi-polar lead-acid batteries, a technology associated with very high cycling capability which has been developed within a project funded by the European Union. Volvo plans commercialisation of such trucks by 2009 and claims its technology can achieve up to 35% fuel consumption reduction depending on use.

Note that mechanical hybrid systems (such as flywheels) represent a valid alternative to electric hybrids in HGVs due to the greater power and energy density and the much greater lifetime of mechanical systems compared with battery technology.

Diesel hybrid technology is also being investigated for railways in North America (Railpower) and Japan (Mitsui).

In Europe, the high additional costs are likely to preclude widespread diffusion of hybrid technology into the HGV and bus sectors, though by 2020 some penetration is possible. These are not considered in detail in the modelling.

1.4.4 Key issues

A large market diffusion of full hybrid vehicles essentially relies on substantial improvements in battery technology. The challenge is to come up with battery technology associated with greater power density (or energy density in the case of plug-in hybrids), reliability and cycle life at an acceptable cost. In Europe, the cost must allow hybrid vehicles to be delivered at prices competitive enough with advanced diesel technology, which already has major market share and similar economy. This assumes that consumers would be willing to pay a small premium for a more efficient car, similar to what has happened in some European countries as regards diesel versus gasoline versions of the same vehicle.

Recent claims of progress in advanced battery technology tend to indicate that the required levels of power and energy density for full hybrids and plug-in hybrids to offer acceptable usability are likely to be achieved in the medium term.

The main remaining issue is therefore whether substantial enough diffusion on the North American and Asian markets will occur that would provide the required economies of scale to bring down the cost at levels competitive with advanced diesel power trains in Europe. If this does happen, it needs to be early enough for full hybrid and plug-in hybrid technology to acquire a significant share before fuel cell technology, for example, makes its way to commercialisation.

As for battery electric vehicles, the development of less CO_2 intensive electricity generation is implicitly required for the plug-in hybrid option to deliver substantial benefits.

1.4.5 Possible market share

Various near-term market prospects for hybrids have been formulated by US based market research firms. The most optimistic scenarios (high uptake) see hybrid vehicle technology as 20% of the US market by 2010 and 80% by 2015 (Booz Allen Hamilton), while much more conservative views give it no more than 3% by 2010 (J.D. Power). Longer term perspectives have also been formulated: Exxon Mobil forecasts a 30% share in the North American market by 2030 in its last Energy Outlook, and the EIA (Annual Energy Outlook 2006) expects 1.5 millions sales per year by 2025 with only 7% of the new vehicle market. JRC suggests market shares of hybrid vehicles in EU25 could be between 5 and 14% by 2010, and between 9 and 24% by 2020 (for oil prices of US$20 and US$120 per barrel, respectively).

In 2004, NREL (the US National Renewable Energy Laboratory) investigated the public’s willingness to pay a premium for a more efficient car in the US. About 49% of respondents said they would be willing to pay an extra £550 or more (and 21% would be willing to pay an extra £1,100 or more) for a car that would save £220 each year. Most of the models proposed on the market by 2010 are therefore likely to be of mild hybrid type (‘stop & go’ systems) as this technology is closer to prices expected by most consumers and at lower risk for automakers.

Full hybrids and plug-in hybrids need battery technology to reach greater power density and energy density respectively, at an acceptable cost.

Market diffusion is expected to be slower in Europe than in North America or Asia due to already highly competitive advanced diesel technology, although diesel hybrid systems which show benefits compared with diesel power trains may gain momentum after 2010. Unless a significant breakthrough occurs some time soon in battery technology, hybrid systems are more likely to end up being a ‘transition’ technology in Europe, with a significant use of its ‘mild’ version in ICE vehicles in the medium term and in fuel cell vehicles for energy recovery in the longer term. Plug-in hybrids might play a role within a dedicated fleet as they do overcome some of the barriers faced by battery electric vehicles. In such a vision, there does not seem to be a need for specific policies in favour of hybrids as mild versions are already part of automakers short term commercial plans. Public procurements could help plug-in hybrids to overcome the otherwise limited market of dedicated fleets.

Based on the market forecasts cited above and assuming that market diffusion in Europe will be initially slower than in North America and Asia, but also assuming that fossil fuel prices will be high, shares of 5% in 2010 and 20% in 2020 might reasonably be expected for ICE mild hybrid electric vehicles in the European market for new passenger cars. By 2050, the share could possibly reach 80%, but only if fuel cell technology is not successful. In the longer term, a fleet of full hybrid passenger cars might have average gasoline consumption as low as 2.5 litres per 100 km.

1.4.6 Implications

Again, considering about 29.3m passenger cars on the road in the UK in 2004, average new registrations of passenger cars of 2.5m per annum, and a 5% share of plug-in HEVs between 2007 and 2009, followed by a 10% share 2010-2014, and 20% 2015-2020, this leads to about 4.625m hybrid electric vehicles on the road in the UK by 2020 (6.9% of the total passenger car fleet). These would require about 6.7TWh of electricity, i.e. about 1.7% of the DTI total electricity demand forecast of 399TWh , assuming that each vehicle is driven 15,000 km per year on average, that average specific energy consumption is 12kWh/100 km, and that electricity is used for 80% of the total driving distance.

As an indication, generating 6.7TWh of electricity under the grid electricity mix assumptions given earlier[10] would produce between 1.3Mt and 1.6Mt of CO_2, or around 4% of road transport emissions.

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[10] House of Commons Science and Technology Committee (2006), *Meeting UK Energy and Climate Needs: The Role of Carbon Capture and Storage,* First Report of Session 2005–06; Volume II: Oral and Written Evidence

FUELS

The primary alternative fuels associated with major potential reductions in CO_2 emissions are different liquid biofuels and hydrogen. Conventional alternatives, such as LPG, are not considered to offer sufficient opportunities and are not evaluated here.

Biofuels are considerably more commercially developed than hydrogen, and so more data are provided as to their exact costs and status.

1.5 Hydrogen

Hydrogen must be produced from other resources, using energy in the process, but can act as a common 'currency' for different energy sources. This enhances energy diversity and also potentially allows low-carbon production routes to be used. Hydrogen production is done industrially today at large volumes, resulting in hydrogen at the production plant with a similar cost per unit energy to gasoline at the same point, pre-tax. However, transporting and storing hydrogen is expensive and can consume considerable amounts of energy. Whether hydrogen contributes to reducing emissions depends entirely on its production route and the end-use technology.

Production routes to hydrogen are many and varied, with the potential for energy from any source to be used. For hydrogen to meet key UK goals of energy security and CO_2 emissions reduction, only a few routes are applicable[11], i.e. hydrogen from:

- renewable electricity,
- nuclear electricity,
- natural gas with carbon capture and storage (CCS),
- coal with CCS,
- biomass (with optional CCS), and
- 'novel' hydrogen production technologies (fermentation etc)

These 'few' cases nevertheless include a significant number of different specific pathways as biomass, for example, can include many raw resources. CCS routes of course depend on the successful development and commercialisation of the relevant technologies, in addition to those for hydrogen production.

In the timeframe to 2020 the most likely of the routes above are natural gas-based (without CCS in the near term) and some regional renewable routes, both electricity and biomass. Dedicated coal or nuclear routes are unlikely, given that a small volume of hydrogen will be required, while these plants are typically very large. Use of current nuclear or coal capacity would entail simply connecting to the existing grid and effectively using the electricity as part of the overall mix, which would have both high CO_2 emissions and cost.

While technology continues to develop, no substantial changes have been made to those technologies and costs already outlined in previous work for the DfT[12], as reproduced below. This range of costs is used in the subsequent sections.

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[11] E4tech, Element Energy, and Eoin Lees Energy (2004), A strategic framework for hydrogen energy in the UK. A report for the Department of Trade and Industry, London, UK

[12] E4tech (2004), Liquid biofuels and hydrogen from renewable resources in the UK to 2050: a technical analysis. Department for Transport, London, UK

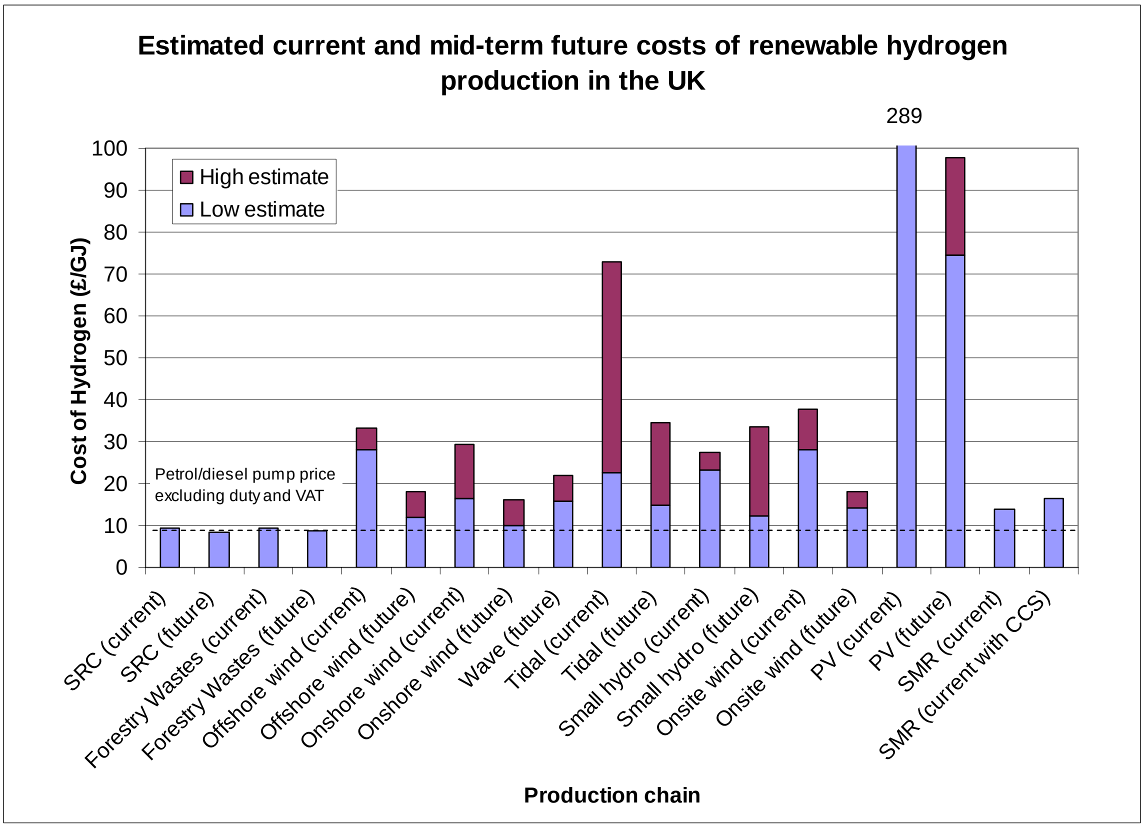

Figure 3: Comparison of estimated costs of renewable hydrogen for the UK, as delivered to the user (includes distribution costs and profit)

In considering CO_2 emissions reductions for the long term, it is important to note that short term increases may nevertheless lead to long term decreases. Using the most cost-effective hydrogen in the near-term in order to build a supply chain and infrastructure would open the way for lower carbon options in the longer term. While the volume of hydrogen being used is small (during the early period of uptake), any possible increase in CO_2 emissions from a small fleet of vehicles will be negligible, relative to total emissions.

1.5.1 Hydrogen technologies

The state of development of hydrogen technologies is considerably different for different scales and conversion routes. Industrial steam reforming of natural gas is a well-understood process, as is large-scale electrolysis using comparatively constant power. Small-scale technologies and varying duty cycles require the greatest development support and offer the greatest potential for improvement, as these are relatively novel applications.

An important consideration for the development of hydrogen production technologies is the need for hydrogen demand. If hydrogen is required for industrial or transport applications then technology development will continue, but support for the supply side in the absence of demand will very likely be of limited success, as technologies try to reach commercial targets without adequate commercial pull. Technologies for low carbon hydrogen production, e.g. low-cost electrolyser units capable of operating under intermittent conditions such as those often created by the use of renewable energy, may require specific support for their low carbon benefits.

1.5.1.1 Electrolysers

Conventional electrolysers are well-established and unlikely to benefit from major reductions in cost, though increasing demand for hydrogen may result in some improvements. However, small-scale electrolysers capable of working well on intermittent electricity supplies could begin to emerge, as could alternative types of electrolyser. High temperature electrolysis, where some of the energy is supplied through heat, can be cheaper than conventional low-temperature systems.

The implications of deriving all future transport fuel from renewable resources are documented in much greater detail in the previous work for DfT[13]. It is important to note that not all of this resource must be converted into electricity before hydrogen is generated, as hydrogen can be produced directly from other resources such as biomass.

1.5.1.2 Natural Gas Reformers

Small-scale technologies for the production of hydrogen from natural gas may also play an important role in enabling hydrogen to be supplied to local demand centres in the near term. Conventional production units are large and hydrogen has to be transported to the point of use, while on-site production may be more cost-effective in the near term. As demand grows and economies of scale begin to become important, large-scale production may take over. This must always be balanced against distribution costs from a single centralised site, but analysis of the true costs depends heavily on the specific local situation. Economies of scale in steam reforming are considerable, but must be balanced against additional requirements for transportation of the centrally produced hydrogen. The following figures give an indication of the implications of using only natural gas to produce hydrogen for transport, which is unlikely in any case.

For reference, approximately 464PJ of hydrogen is required to fuel the 2004 UK fleet of cars and light goods vehicles. 605PJ is needed for the buses, coaches and heavier goods vehicles, making a total of 1,069PJ, or 8,894kt hydrogen. To make this amount of hydrogen using steam reforming, using average efficiencies, would require 715PJ of natural gas for the cars; 929PJ for the heavier vehicles. Total gas use would be 1,644PJ.

The UK used 1127TWh of natural gas in 2004. This is equivalent to 4,057PJ – or 2.5 times the amount that would be required for transport use under this scenario. Conversely, producing hydrogen for all road transport from natural gas in the UK could increase consumption by about 41% over 2004 figures.

1.5.1.3 Hydrogen from other renewables and waste

Hydrogen production from renewable energy sources in general is often dependent on the electrolysers mentioned above, as much of it will be renewable electricity from a variety of primary sources. The majority of the remainder will be biomass-based, with some coming from wastes such as municipal solid waste and from sewage management. As part of an integrated waste management strategy, the potential for waste-to-energy using hydrogen to fuel vehicles is potentially attractive. However, much of the technology required for this is still in development, and considerable cleaning of the waste is typically required in order to ensure that the product is suitable for conversion. Strong technology parallels can be drawn between this and many routes for the production of biofuels.

1.5.2 Summary

The production of hydrogen to fuel either fuel cell or ICE vehicles is unlikely to be the main barrier to their introduction. Developing a cost-effective supply infrastructure will be important, and incentives for low-carbon hydrogen will be important at a later stage of introduction to ensure that the desired policy objectives are achieved.

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[13] E4tech (2004), Liquid biofuels and hydrogen from renewable resources in the UK to 2050: a technical analysis. Department for Transport, London, UK

In view of the close link between development of infrastructure and introduction of vehicles, it may be important for targeted and structured incentives to be put in place to ensure that both are available in the same place, at the same time. Seeding the infrastructure in this way, providing suitable policy support across different jurisdictions, and maintaining this for an appropriate period of time will be essential if fuel cell vehicles are to be introduced as early as possible.

To ensure that CO_2 emissions reductions result from the use of fuel cell vehicles, it will be essential to put in place policy measures to move hydrogen production towards low carbon sources. This should neither hinder early hydrogen provision from higher carbon sources while the markets are evolving, nor be done without considering the wider implications of the use of those resources, for example renewables that could be used directly. Support for fuel cells should be combined also with support for low carbon hydrogen production technologies.

1.6 Biofuels

Biofuels production can be classified under three principal routes:

- fermentation routes for ethanol production,
- vegetable oil and animal fat routes to biodiesel, and
- pyrolysis and gasification routes for the production of a range of synthetic fuels.

Biofuels could be used in road, rail, marine and air transport applications.

The range of feedstock, conversion process and transport fuel options are illustrated in Figure 4. Ethanol production from sugar and starch crops, such as sugar cane, sugar beet, wheat and corn, and biodiesel production from vegetable oils and animal fats, such as rape seed, soy bean, palm oils and tallow, are commercial processes and are known as ‘1st generation biofuels’. However, research and development is underway to improve these processes and reduce their costs. The production of fuels from lignocellulosic[14] biomass, such as wood, straw and components of municipal solid waste, is under development, with a range of processes at the research, development, demonstration and pre-commercial stages. These are considered ‘2nd generation biofuels’.

It is also possible to produce a range of fuel additives from biomass that could be blended with petroleum-derived gasoline and diesel as octane and cetane enhancers. The chemical synthesis of fuel additives from biomass is at the research stage.

Biorefinery concepts, where biofuels and other chemical and energy products are produced, are at a concept stage, mainly based on lignocellulosic biomass feedstocks. The driver behind biorefineries is to maximise the value of biomass conversion through a mix of low volume high value chemicals and high volume lower value energy products.

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[14] Lignocellulosic biomass consists of a combination of lignin, cellulose and hemicellulose that provides the structural framework of plants and makes up most plant matter.

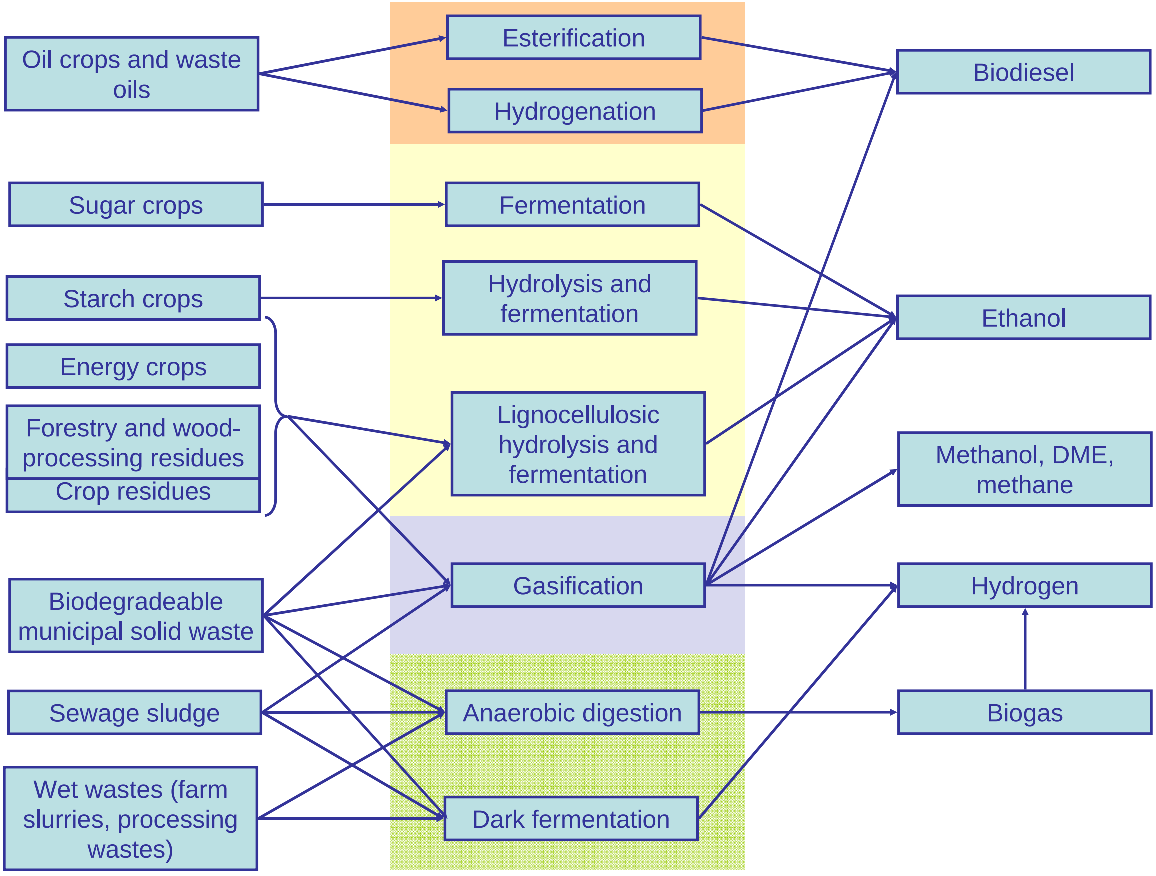

Figure 4: The main feedstock, conversion and product options for biofuels

Biofuels can be used blended with gasoline or diesel, or unblended, depending on the type of biofuel. In Europe, biofuels are generally blended at levels below 5% in gasoline and diesel. This is due to the early stages of development of the biofuels sector in Europe, as well as fuel standards that limit the proportions, and vehicle warranties[15]. In the US, ethanol is generally blended at a 10% level with gasoline; biodiesel is generally used in vehicle fleets at around a 20% to 30% levels, and low blends (below 5%) are starting to be introduced more widely in the retail market. In Brazil, ethanol is blended with gasoline at a level between 20% and 25%, and neat ethanol is also sold at refuelling stations for use in an increasing number of flex-fuel vehicles (about three-quarter of new vehicles sold in Brazil are flex-fuel).

The technical potential for biofuels depends on the amount of biomass resources available or selected for production and the conversion route efficiency and yield (i.e. transport fuel vis-à-vis other co-products). The previous work for DfT has considerably more detail in this regard[16]. We consider that the technical potential from EU27 resources, based on energy crops, agricultural and forestry residues, and the organic fraction of municipal solid waste, is roughly between 20% and 30% of EU27 road transport fuel in 2030 for bioethanol **or** biodiesel (including advanced biofuel routes; the lower end of the range depends on the fraction of synthetic diesel relative to other Fischer-Tropsch products (60% is assumed here)). This potential would be higher if hydrogen were produced and used in fuel cell vehicles, at

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[15] Gasoline vehicle warranties could probably be changed to accept 10% ethanol blends 'overnight'. Going beyond 5% biodiesel blends and 10% bioethanol blends would require some minor changes in the vehicle manufacturing supply chain. However, these could be achieved easily and at very low cost. As a note, a carbon reduction target of 5% would probably require more than a 6-8% blend, based on current biofuels and processes. A 5% target by proportion of energy would roughly require the volumes mentioned.

[16] E4tech (2004), Liquid biofuels and hydrogen from renewable resources in the UK to 2050: a technical analysis. Department for Transport, London, UK

around 50%. This potential does not consider alternative uses of the biomass for other fuels, for electricity and / or heat. However, it does consider land-use and residue & waste recovery constraints (e.g. energy crops are assumed to be planted on a maximum of 14Mha, corresponding to 5% of current arable land and 12% of current pasture land).

For the UK, the technical potential from UK resources, based on energy crops, agricultural and forestry residues, and the organic fraction of municipal solid waste, is between 20% and 30% of UK road transport fuel in 2030 for bioethanol, or between 10 and 20% for biodiesel, or 30 to 40% for hydrogen. This assumes a land area available for energy crops of 1.6 Mha (equivalent to around 30% of the current arable area), 40% of energy crop residues, 12% of residues from the 6 principal food crops, 50% of fellings from forestry and 20% of wood processing residues, and 70% of the organic and paper fractions of municipal solid waste. Note that these potentials are exclusive – the resources given could be used to produce this amount of ethanol or biodiesel or hydrogen, assuming no use for other fuels or power – and depend on the availability of second generation technologies.

Despite this relatively high levels of UK technical potential, UK biofuels demand will not be supplied by UK production alone. The uptake of fuels from different sources will depend on their relative price, and on their availability. In the short term, UK supply will be limited to that provided by the plants currently in planning, whose total production is projected to be 360,000t by 2008 for ethanol (about 2% by volume of 2004 gasoline consumption) and 750,000t for biodiesel (about 4% by volume of 2004 diesel consumption), irrespective of the Obligation level set.

The production of transport fuels from biomass faces a number of challenges. These include: the need for cost reductions, in order to be increasingly competitive with petroleum-derived alternatives; the commercialisation of lignocellulosic conversion technologies (2nd generation technologies), in order to increase the resource base and possibly reduce costs; improvements in the GHG balance of conventional bioethanol and biodiesel routes, in order to maximise the environmental benefits from these routes; ensuring sustainable practices are followed along the entire fuel chain, in order to ensure the sector's long-term viability; improvement of the integration of biofuel into fuelling infrastructure, in order to facilitate their introduction and reduce their costs.

The announcement of the RTFO and changes in the EU's agricultural policy have generated a significant interest in biofuels. As a result, a number of plants are in the planning and under construction in the UK.

1.6.1 Ethanol via fermentation routes

Bioethanol routes based on fermentation of sugars from crops such as sugar cane or sugar beet, and routes based on hydrolysis[17] and fermentation of starch crops such as corn and wheat are commercially available now. Lignocellulosic biomass-based routes, which involve pre-treatment to break down the cellulose, hemicellulose and lignin components, hydrolysis and fermentation are at the research, demonstration and development stage, with first-of-a-kind commercial plants in the planning. Lignocellulosic biomass could offer the potential for a broader and larger resource base for bioethanol production, low well-to-tank emissions, and potentially lower long-term bioethanol production costs.

The UK has no current ethanol plants, however one is under construction and others are in the planning, with a combined production capacity of 360,000t by 2008 if all are constructed as planned.

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[17] Hydrolysis is a process by which the starch is broken down into fermentable sugars.

1.6.1.1 Ethanol from sugar crops

Sugar cane is the largest source of biofuel worldwide, with most of the production concentrated in Brazil (approximately 15 billion litres per year) and growing rapidly (Brazilian sugar cane area could grow from 5.5Mha to 8-9Mha over the next ten years). Brazilian bioethanol is also the cheapest crop-based biofuel production route, with production costs as low as R¢60/l (equivalent to 16p/l at an exchange rate of R$3.8/£). Ethanol is also produced in other sugar cane growing countries such as India, Australia and Thailand, and there is potential for expanding ethanol production from sugarcane, e.g. in southern Africa (see recent work commissioned by UK Office of Science and Innovation[18]).

In Europe, ethanol is produced from sugar beet, mainly to diversify out of sugar production. There is also the potential to produce ethanol from sorghum in Southern Europe. Production costs are estimated at about £0.27 per litre of ethanol (based on feedstock cost of £22 per tonne of beet, and assuming revenue from the sale of pulp pellet feed). Ethanol yields per hectare of land are high, about 6,000 litres per hectare for a beet yield of 60 tonnes per hectare, and there is some potential for expanding sugar beet production. However, this is unlikely to be the case, as ethanol production costs from sugar beet tend to be higher compared with the alternative commercial route based on wheat grain, unless integrated with sugar production plants, mainly as a result of higher plant capital costs and lower revenues from co-products, based on current practices. Sugar beet is grown on about 135,000 hectares in the UK, producing about 9 million tonnes of beet; converting all land area to ethanol would produce over 700,000 tonnes of ethanol. This corresponds to 3.5% of 2004 gasoline consumption on a volume basis.

The GHG balance of ethanol from sugar cane is very good as a result of high sugar cane productivity and the use of bagasse[19] to fuel the processing plant energy requirements. The well-to-tank GHG emissions are estimated at 20g/km resulting in an 88% reduction in GHG emissions compared with gasoline (or similar compared with a mixed baseline). In the case of ethanol from sugar beet the results depend heavily on the use of the co-product pulp. The well-to-tank GHG emissions are estimated at 58g/km when the pulp is used for process heat, or 111g/km when the pulp is used for animal feed, resulting in a 64% or 32% reduction in GHG emissions respectively compared with gasoline (or similar compared with a mixed baseline). This illustrates the importance of energy efficiency and renewable fuel use at biofuel processing plants.

One UK plant producing ethanol from sugar beet is under construction by British Sugar in Wissington, Norfolk, with production expected to start early in 2007. The plant will have a capacity of 55,000t (70 million litres) of ethanol and is sited at British Sugar's Wissington beet processing factory, which is the largest in Europe and processes about 2.4 million tonnes of beet. British Sugar operates all six sugar beet processing plants in the UK. British Sugar have stated that their future feedstock approach will be flexible and they will consider starch-based feedstock for future investments.

1.6.1.2 Ethanol from starch crops

Corn (maize) is the second largest source of ethanol production worldwide, with most production concentrated in the US (approximately 15 billion litres produced in 2005). The cost of ethanol production from corn is estimated at about £0.18/l (US¢32/l). Ethanol production in the US has been expanding rapidly. Current ethanol capacity is about 4.5 billion gallons (17 billion litres) annually, compared to 1.9 million gallons (7 billion litres) in 2001. Furthermore, ethanol facilities under construction, or being expanded, could add an additional 2 billion gallons of capacity. Ethanol is also produced from wheat grain, mainly in Europe, at

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[18] E4tech (2006), Technical analysis document for Brazil : UK : Africa Partnership on Bioethanol – Scoping Study on behalf of UK Office of Science and Innovation. Available from OSI (chris.d.miles@dti.gsi.gov.uk)

[19] Cane residue left over after sugar extraction.

a cost of about 29p/l (based on feedstock cost of £97 per tonne of wheat – estimated cost of producing winter wheat – and assuming revenue from the sale of DDGS[20]). However, commodity wheat prices are about £70 per tonne. At this feedstock price, ethanol could be produced for about 0.22p/l. In the UK, ethanol yields per hectare are estimated at about 2900 litres per hectare for a wheat grain yield of 8 tonnes per hectare. The UK has a surplus wheat production of about 3 million tonnes from about 350,000ha. If this wheat were used for ethanol production, the UK could produce about 800,000 tonnes (1 billion litres) of ethanol. This corresponds to 3.9% of 2004 gasoline consumption on a volume basis. Wheat is grown on about 1.9 million hectares in the UK. Technically, there is potential for expanding area under cereal production, given that over the last two decades the area planted with cereals has decreased by over 1 million hectares. However, the relatively low ethanol yields that can be obtained per hectare based on wheat grain, may make this route unattractive. The picture may change if straw-to-ethanol processes become commercial (see following section). Its use could lead to an additional 1,500 litres of ethanol per hectare (based on about 5 tonnes of straw per hectare).

The well-to-tank CO_2 emissions from starch to ethanol routes are heavily dependent on the production process used, and on the use of co-products. In the US, where CO_2 emissions reduction has not been the driver for bioethanol development, some ethanol plants have very poor CO_2 balances, as a result of the significant use of fossil fuels to power the plant. A report by the LowCVP in 2004 showed that the range of carbon savings from wheat to ethanol chains in the UK could range from 77% for the very best plants, where straw-fired combined heat and power (CHP) is used to provide energy, to 7%, where grid electricity, produced from a mix including fossil sources is used. It is therefore very important that the use of plant technologies with low carbon emissions is stimulated: for example through carbon certification of fuels, or through increased ECAs for plants using CHP or renewables for energy.

Technical improvements can be made to commercial ethanol production routes, for example through improved enzymes for starch-based feedstocks, membrane technologies for ethanol distillation, modelling and data acquisition for process and plant optimisation, and improved quality of co-products.

Two UK plants producing ethanol from wheat are planned:

- A 40,000t plant in Norfolk, to start production in late 2007
- GreenSpirit fuels' 100,000t plant in Henstridge, Dorset, to start production in mid 2007

1.6.1.3 Ethanol from lignocellulosic materials

Routes from lignocellulosic materials to ethanol are more complex than those from sugar and starches, as lignocellulosic materials contain more complex sugar polymers, such as cellulose and hemicellulose, which are more difficult to break down chemically, together with lignin. Processes being developed involve first separating the biomass into cellulose, hemicellulose and lignin, then hydrolysing the cellulose and hemicellulose to produce sugars, followed by fermenting those sugars to produce ethanol. The hydrolysis stage can be carried out by chemical routes, such as acid hydrolysis, which is a well known process, or by biological routes, using enzymes, which are in development. The key areas for RD&D are enzymatic hydrolysis, and fermentation of some of the sugar types produced.

The most promising technology is considered to be enzymatic hydrolysis. This technology is currently more expensive than the other hydrolysis technologies, but is thought to have the greatest potential for cost reduction, to a level competitive with ethanol from other sources.

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[20] Dried distillers grains with solubles.

The key to commercially viable processes is low cost cellulase production, an area where there is significant potential for cost reduction.

Ethanol costs from enzymatic hydrolysis processes are estimated to be of the order of 25-31p/l in 2010 based on wood feedstock costs of £34-52/t. By 2020 these could reduce to 19p/l based on wood feedstock costs of £28/t. These cost estimates are based on engineering modelling studies of possible commercial plant configurations. The competitiveness of lignocellulosic ethanol will depend strongly on the availability of low cost feedstocks. GHG emissions from lignocellulosic chains vary depending on the feedstock. The well-to-tank GHG emissions are estimated at 10-40g/km, resulting in a 73-94% reduction in GHG emissions compared with gasoline (or similar compared with a mixed baseline).

There are few commercial plant developers currently. Most commercial activity is in the US, Canada, Spain and Scandinavia, however there are also UK companies involved in this area:

- Acid hydrolysis
  - Arkenol (focus on agricultural residues as feedstock) and Masada (focus on MSW as feedstock) in the US;
  - Losonoco (focus on MSW as feedstock) in the UK.
- Enzymatic hydrolysis
  - Iogen in Canada (Built largest current demonstration plant. Cooperating with Shell on development and commercialisation since 2002. The company is expecting construction of commercial scale facilities in 2007);
  - Abengoa Bioenergy in Spain and US (Building first-of-a-kind 5 million litre commercial plant in Spain);
  - BC International (focus on bagasse), Cargill Dow, Dupont Biofuels in the US;
  - Etek Etanolteknik AB (Developed pilot plant in Sweden).

Plant developers may have their own enzymes (e.g. Arkenol, BCI) or may license these enzymes from their developers (e.g. Novozymes, Genencor, Roal). Microorganisms for fermentation of sugars produced from lignocellulosic hydrolysis would be needed regardless of the hydrolysis technology used. In the UK, TMO Biotech is developing a bacterium for fermentation of these sugars.

Large public and private RD&D efforts are directed to lignocellulosic ethanol development, and rapid technical progress is being made. Worldwide, progress in some pilot scale facilities is at a level where first-of-a-kind commercial scale plant is expected by 2008, possibly leading to a limited number of early commercial facilities producing ethanol and polymers in operation by 2010. By 2015, further facilities are expected to have been built and early adopters technology development to be complete.

Early commercial scale plants are likely to be developed in areas where there is an established demand for ethanol fuel, a suitable biomass resource base, buy-in from other stakeholders involved in the chain, and economic incentives for plants and for ethanol as a fuel. Several years ago, it was thought that siting of these first commercial scale plants in the UK would be unlikely, as a result of lower levels of market and support for ethanol than in other countries. However, the RTFO, and the activity of UK players over the last few years has changed this.

Losonoco is planning plants based on dilute acid hydrolysis of waste lignocellulosic materials including biodegradeable municipal solid waste, combined with proprietary fermentation bacteria from UK-based TMO Biotech. Losonoco has submitted a planning application for two ethanol facilities:

- A 90,000t plant in Ince, Cheshire using wood, paper and straw, planned for production in late 2007.
- A 75,000t plant planned for Edmonton, London, using urban waste.

In the previous report[21], the following biomass resource potentials were given: 155PJ from agricultural and wood residues; 288PJ from MSW; and 270PJ for 1 million hectares of woody energy crops (based on 15 dry tonnes per hectare yield). Assuming a 35% lignocellulose to ethanol conversion efficiency, the following technical potentials can be derived: 2.5 billion litres of ethanol from agricultural and wood residues; 4.7 billion litres from MSW; and 4.4 billion litres from 1 million hectares of woody energy crops. The technical potential for ethanol is large: 10% of current gasoline from agricultural and wood residues; 18% from MSW; and 17% from 1 million hectares of woody energy crops. However, only a fraction of the residues and wastes will be recoverable. While biofuel yields from woody or grass energy crops per unit area planted are potentially much higher compared to starch and oil crops, the development of these crops is at a relatively early stage, and uptake has been slow. Significantly higher yields and lower costs[22] than those achievable today would be required for ethanol to be viable compared to petroleum-derived fuels at oil price of $50/bbl. Furthermore, there may be competition for lignocellulosic resources for other uses, such as heat and electricity generation, the production of other transport fuels, such as synthetic diesel and hydrogen (systems currently at the pilot / demonstration stage), and chemicals. The use of the feedstock will depend on the value that different products can attract. Lignocellulosic ethanol plants may be attractive as they are a type of biorefinery, where heat, electricity and other products can be produced alongside ethanol, from the different biomass constituents.

1.6.1.3.1 Infrastructure

Ethanol is hydrophilic, therefore its transport and distribution requires care to avoid water contamination, if it is to be used as a gasoline blend. Its hydrophilic nature also has raised concern over its transport in fuel pipelines used for other fuels, because of possible contamination of jet fuel. Therefore, ethanol may require dedicated transport to the fuel terminals, where it is stored and blended with gasoline. Another option is to convert the ethanol to ETBE, in which case water contamination issues are avoided. Transport of ethanol in multi-fuel pipelines does however occur in Brazil.

Blending ethanol with gasoline at blends below 5% increases the fuel’s Reid Vapour Pressure. This means that at certain times ethanol blends would exceed the RVP limits on fuels in the UK. There are a number of ways in which this issue can be dealt with, such as modifying the gasoline base, modifying the RVP limits without necessarily leading to an increase in VOC emissions, or using ETBE or higher ethanol blends.

Blends up to 10% ethanol do not require changes in vehicles or infrastructure equipment. Above 10% some vehicle modifications or flexi-fuel vehicles are required.

None of the above infrastructure issues are serious barriers to the introduction of ethanol. Although the introduction of ethanol requires some investment in infrastructure, these investments can be made in a short timescale and make a very small contribution to the fuel cost.

1.6.2 Vegetable oil or animal fat derived fuels

1.6.2.1 Transesterification[23] of vegetable oils and animal fats

Biomass-derived diesel substitutes can be produced from vegetable oils and animal fats in commercial processes. Germany is the leading biodiesel producer with an installed capacity in

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[21] E4tech (2004), Liquid biofuels and hydrogen from renewable resources in the UK to 2050: a technical analysis. Department for Transport, London, UK

[22] Cambridge Land Economy Research Group estimates current costs at £45/dry tonne, excluding land rent, which could add an additional £20/dry tonne

[23] Transesterification consists of reacting oils and fats with an alcohol (e.g. methanol) in the presence of a catalyst. Its purpose is to reduce the viscosity of liquid fuels derived from vegetable oils and animal fats.

excess of 2 million tonnes, largely based on oil seed rape as feedstock. A palm oil-based biodiesel industry is growing rapidly in Malaysia. Biodiesel production based on soy bean is also growing in Brazil and the US. Jatropha is being studied as a potentially interesting crop for dry climates and low quality soils. BP has recently announced a £10 million research programme on Jatropha in India. The UK produces biodiesel from rapeseed oil and from waste vegetable oils and waste animal fats, with current production capacity of about 70,000 tonnes of biodiesel per year. Oil seed rape is grown in the UK on about 600,000 hectares of land. Using all this land area for biodiesel production would provide about 600,000 tonnes of biodiesel (680,000 litres), corresponding to about 3% of 2004 diesel consumption on a volume basis. There is some potential for expanding oil seed rape area.

Main UK plants:

- BIP Sustainable Energy 12,000t plant in the West Midlands – rapeseed oil
- Global Commodities UK 10,000t plant in Shipdham, Norfolk – waste vegetable oils
- Argent Energy 45,000t plant in Motherwell, Scotland – waste oils and fats
- 2,500t plant in Northwich, Cheshire – waste vegetable oils
- 300t plant in Hull – rapeseed oil

In a conventional base catalysis process biodiesel can be produced from rapeseed oil at a low cost of about 35p/l, based on a rapeseed cost of £150/t and assuming revenue from the sale of straw, glycerine and rape meal. Well-to-tank GHG emissions for biodiesel are estimated at 83g/km, resulting in savings of 46% compared with diesel. This is estimated to vary between 38% and 57%, depending on whether rape meal is used for animal feed or for energy, respectively.

Technical improvements can be made to commercial biodiesel production routes, for example through the development of better catalysts and catalytic processes to increase the yield and reduce the process costs, modelling and data acquisition for process and plant optimisation, and improved quality of co-products.

There are several plants under construction and planned in the UK:

- Greenergy Biofuels 100,000t plant under construction in Immingham on the east coast of England (Expected start date Q3 2006). There are plans to double the production capacity of the plant. Will use rapeseed oil and imported oils.
- Biofuels Corp 250,000t plant under construction in Teesside. Will use rapeseed oil and imported oils.
- Global Commodities UK / Rix Biofuels expansion of plant in Hull to 150,000t.
- Global Commodities UK plans for 180,000t plant in Lowestoft, Suffolk.

There is potential for some further exploitation of oil seed rape in the UK, though biofuel yields on a per unit land area basis are relatively low. However, most plants will rely heavily on imported vegetable oils, which raises concerns over the sustainability of the feedstock, especially as demand for vegetable oils for food consumption is also growing rapidly and concerns have been raised over the use of land for palm oil crops, in particular. Current biodiesel use generally results in GHG emissions savings, but better savings could be achieved if improvements in feedstock production and process plants were made. Some of these improvements can be achieved through improved practices, the rest will require further R&D. The increase in biodiesel supply will also lead to an increase in the supply of its associated co-products. As a result, their value may decrease and alternative uses, for energy for example, may need to be considered.

1.6.2.1.1 Infrastructure

Biodiesel from transesterified oils and fats is corrosive to certain plastics. While this is not a problem at blends below 5%, some vehicle and infrastructure equipment needs to be adapted at higher blends.

1.6.2.2 Hydrogenation of vegetable oils and animal fats

A diesel fuel, similar to petroleum-based diesel, can be produced by hydrogenation of vegetable oil and animal fat. The technology is at the demonstration stage, and requires integration with an oil refinery to avoid building a dedicated hydrogen production unit and to maintain a high level of fuel quality. It is promising in terms of feedstock flexibility and costs. Current demonstration and pilot project should demonstrate the technical viability of the process, as well as generate the information required to understand its cost effectiveness and performance in terms of energy and greenhouse gas balances. UK refineries have been assessing the option, and BP is installing an animal fat hydrogenation facility at refinery in Australia, based on proprietary technology. The UK government has encouraged the piloting of hydrogenation.

Other hydrogenation technologies of interest are:

- Neste NExBTL process – plant is planned for operation in 2007, with annual capacity of around 170,000 tonnes per annum.
- CETC process – developed by CANMET.

1.6.3 Syngas derived fuels

The gasification of biomass can lead to a range of liquid and gaseous fuels for transport applications, as illustrated in Figure 4. Some of the fuels that can be produced are: synthetic diesel and gasoline, methanol, ethanol, dimethylether (DME), methane, and hydrogen. The fuels are generally produced by chemical synthesis of a syngas, consisting mainly of carbon monoxide and hydrogen, in a catalytic process under certain temperature and pressure conditions.

Biomass gasification technologies are commercially available, at different scales and with different designs. Similarly, syngas conversion technologies have been demonstrated at commercial scale for the fuels mentioned above. Synthetic fuels are produced commercially today mainly from natural gas or the gasification of coal e.g. Sasol plants in South Africa. However, there is very limited commercial experience integrating biomass gasification with downstream processes for the production of liquid or gaseous transport fuels. The only experience involves the gasification of mixed feedstocks, including biomass, at the Schwarze Pumpe plant in Germany for the production of methanol.

A number of companies and research organisations are developing systems for the production of transport fuels from biomass-derived syngas, in Europe in particular. The European Commission is currently funding two major projects. The CHRISGAS project aims at producing hydrogen-rich syngas from biomass suitable for the synthesis of transport fuels at a demonstration plant in Sweden. The RENEW project aims at assessing different biomass-to-liquids production routes, and at producing synthesis fuels at different pilot and demonstration sites. Companies involved in the development of biomass-to-liquid systems are: Choren, Future Energy (linked to Lurgi), TPS Termiska Processer, Lurgi, Chemrec (focused on black liquor gasification) in Europe; Dynamotive, Startech / Future Fuels in North America; JFE (focused on DME) in Japan. Choren, in partnership with Shell, is planning a first-of-a-kind commercial biomass-to-liquids plant at a scale of 15,000 tonnes of diesel per year.

Companies and research organisations are addressing a number of issues en route to the commercialisation of biomass-to-liquids systems, some key issues being: syngas quality, product selectivity in chemical synthesis, process integration, and scale. Scale in particular may determine the type of gasification system used, which in turn may determine the share of different products produced (i.e. transport fuels, electricity and heat).

DaimlerChrysler, Renault, Royal Dutch Shell, SasolChevron and Volkswagen have launched an Alliance for Synthetic Fuels in Europe to promote synthetic fuels in Europe and to support research, demonstration projects and public-private cooperation in the area. The focus of the alliance is on natural gas, coal and biomass-to-liquids.

Given the early status of the technology, only estimates are available for the cost of producing fuels from biomass-derived syngas. These estimates are based on techno-economic assessments of envisaged commercial systems. The cost of producing synthetic diesel is estimated at about 40p/l for a biomass feedstock cost of £28 per dry tonne and a relatively large-scale 400MWth plant. Therefore, cost competitiveness will depend on significant cost reductions in the process, or if these cannot be achieved, lower feedstock costs and revenues for co-products such as electricity and chemicals. The well-to-tank GHG emissions are estimated at 9g/km, resulting in a 94% reduction in GHG emissions compared with diesel (or similar compared with a mixed baseline, such as detailed in the next section). Similarly to lignocellulosic ethanol, syngas-derived fuel could make a significant contribution to UK transport fuels.

Other processes exist that convert biomass, though a liquefaction process, into a ‘biocrude’ product that can be further refined to produce liquid transport fuels. An example of such a process is the HTU process developed by Biofuel BV in the Netherlands, which involves treating a biomass feedstock in liquid water at 300-360C and 100-180 bar to produce a product oil. Biofuel BV estimates that HTU diesel could be produced for about £8/GJ for a biomass feedstock cost of £1.4/GJ.

Biomass-to-liquids processes can also be used for the production of fuels suitable for aircraft transport, in particular in jet engines. Synthetic kerosene from biomass-to-liquid plants, and possibly hydrogenated oils, may be the only viable option for displacing petroleum-based kerosene, because of the very stringent energy density and fuel property requirements of jet fuel.

The quality of the fuels that can be obtained, the range of fuel products and co-products, and the efficiency of syngas-based systems make them particularly attractive. However, there are uncertainties with regard to, for example, the availability of feedstock for a single plant necessary to achieve sufficient economies of scale, and plant designs at different scales that may be economically viable. There is strong interest in developing this route, in Europe in particular. However, there is very limited research and development activity in this area in the UK, essentially related to some biomass pyrolysis and gasification research.

TECHNOLOGY AND COST ISSUES AND OTHER BARRIERS

The sections prior to this have outlined in more or less detail, the technologies and status of relevant possible routes for CO_2 reductions in the transport sector. Where possible, we have highlighted issues still to be resolved.

Cost remains a fundamental issue for both fuel cell vehicles and battery technologies. Hybrid vehicles, though intrinsically more expensive than engine-only vehicles, appear to have some chance to approach cost parity, or at least come close enough to make them saleable.

Costs for hydrogen are very varied, with many of the low-carbon routes (largely renewable) suffering from high costs. Costs of developing infrastructure in the short term will also be an issue, though amortising the infrastructure costs in the longer term will not add considerably to the basic production costs.

The different biofuels and their production routes also have very varied costs, each of which also varies to some extent based on location.

Technology status is also quite different for the different vehicles. Fuel cells themselves require some fundamental research and development support in addition to demonstrations if they are to achieve performance targets that will make them attractive. Battery vehicles are more advanced, but also appear to have reached a point at which technology is unlikely to be sufficient for full commercialisation. Hybrid vehicles are considerably more likely to be commercialised in large numbers, though their long-term uptake will depend on the success of the fuel cell.

1.7 Barriers

This section gives a summary of the main barriers to development and widespread deployment of the technologies and fuels, drawn from the information in previous sections.

1.7.1 Biofuels

The barriers to the introduction of biofuels include:

- The need for cost reduction in conventional biofuels to compete with petroleum-derived alternatives
- The high cost and relative technological immaturity of second generation biofuels with the potential for lower carbon emissions and a larger resource base
- Uncertainty over carbon and wider environmental benefits or impacts of biofuels, leading to investor and policy uncertainty and the risk of negative public perceptions
- Uncertainty and perceived uncertainty over the best use of land and of biomass resources leads to inaction
- Limits to blending percentages for ethanol and conventional biodiesel reduces their potential in the near term
- Resistance by some fuel suppliers to inclusion of ethanol in fuel infrastructure
- Lack of vehicle availability and need for additional infrastructure for biogas vehicles
- Higher cost of biogas compared with CNG and lack of recognition of significant environmental benefits
- Low levels of awareness in the waste management community of biofuels options, uncertainty over their viability, and public acceptance, once technologies reach commercial status.

1.7.2 Hydrogen

As previously explained, the production of hydrogen to fuel either fuel cell or ICE vehicles is unlikely to be the main barrier in their introduction.

- Performance improvement (reliability, durability, hydrogen storage) and cost reduction in fuel cell vehicles is required
- Poor availability of vehicles (ICE or FCV) for demonstration limit options for uptake
- It is unclear how simultaneous development of infrastructure and provision of vehicles at a rate which enables all actors to receive an adequate return on investment could occur
- Technology development and cost reduction is required in some low carbon hydrogen production technologies (small scale electrolysis, biomass routes, chains using CCS)
- Uncertainty exists over how to clarify and manage the carbon benefits of different hydrogen fuel chains
- Confusion over the best use of resources – renewable energy, biomass – leads to inaction
- Public and policy-maker perception of hydrogen technologies shows limited knowledge and typically an overly conservative approach

1.7.3 Hybrid vehicles and plug in hybrid vehicles

Barriers to the uptake of hybrid vehicles include:

- Low consumer awareness of the relative emissions of vehicles, which, coupled with little willingness to pay additional capital cost for vehicles with lower emissions, leads to low demand for full hybrid vehicles in the UK
- In the UK and Europe, other low carbon emission vehicle options exist, e.g. advanced diesel options which furthermore still have a significant margin for improvement
- Advanced battery technology development is required: for greater power density, and for greater energy density for plug-in hybrids, to improve the performance of full hybridisation
- Uptake of plug-in hybrids could benefit from any development of infrastructure for fast charging of batteries – appropriate chargers and outlets – which are much more expensive than slow charging facilities

1.7.4 Battery-electric vehicles

Battery electric vehicle uptake is limited primarily by technology issues:

- In addition to high cost, batteries do not yet have competitive lifetime, power or energy density characteristics
- In particular, there is a need for development of advanced battery technology for greater range and faster charging
- Infrastructure for the fast charging of batteries is required – appropriate chargers and outlets – which are much more expensive than slow charging facilities
- Development of large urban electric passenger car fleets is seen as unlikely, as other issues such as congestion or parking space availability may well tend to promote public transportation instead
- Poor public perception of electric vehicle performance

COSTS OF ENERGY USE AND CO_2 EMISSIONS REDUCTION

A wide range of sources for cost data exist. We have taken as our primary reference for modelling the CONCAWE/EUCAR/JRC analysis of full fuel cycle emissions for Europe[24]. Slightly different assumptions, such as are made in the ongoing MARKAL modelling work undertaken by FES are equally valid. Unfortunately, small differences in cost and CO_2 emissions, and in the baseline used for comparison, can have significant implications for the apparent cost of CO_2 reductions. For example, we have used a low additional cost for fuel cell vehicles, as discussed in 1.1.1.2, which we have taken to be equivalent to the incremental cost for a diesel hybrid. Assuming cost parity with conventional vehicles would result in a zero cost of carbon reduction, while higher additional costs would result in concomitantly higher carbon reduction costs.

Using the data for technologies and fuels described above, we have modelled both energy costs and CO_2 emissions for key future pathways. These are described in Table 7 and Table 8. A range is given for different pathways and to show possible variation within pathways. A negative cost is given when the life cycle cost of the option (vehicle cost plus running cost) is less than the baseline. The amount of that negative cost is not given, as it is misleading. Greater negative costs per tonne of CO_2 can either mean much lower costs than the baseline, or very small reductions.

The values are compared against baselines that are a weighted mix of the current diesel and petrol emissions in the UK. Choosing a baseline is a complex issue and no baseline can be found against which all options will actually be compared equally. For example, the comparison of a diesel hybrid against a part-petrol baseline makes it appear more favourable – what the vehicle may actually displace might be diesel vehicles, which already have lower emissions than the mix.

The cost of CO_2 emissions reduction shown below also does not split out the costs between vehicle and infrastructure, while the policies required to support them may be considerably different.

Furthermore, cost of CO_2 reduction is a blunt instrument for comparison. Some more expensive options may offer much greater overall potential for reductions than cheaper ones, due to resource availability. Equally, some options that appear logical and favourable may not be taken up for other reasons. Smaller, more efficient cars would make a significant impact in CO_2 emissions from the sector at lower cost than almost any other option, but are unlikely to be chosen by the majority of consumers.

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[24] EUCAR/CONCAWE/JRC Well-to-Wheels analysis of future automotive fuels and powertrains in the European context, *WELL-to-WHEELS Report Version 2a*, December 2005. http://ies.jrc.cec.eu.int/wtw.html

Table 7: Summary of fuel chain costs and emissions

Fuel chain		**Fuel cost (£/GJ)**	**Cost driven (p/km)**	**Carbon emissions (g/km)**	**Cost of carbon saving (£/tC)**	**Cost of carbon saving (£/tCO$_2$)**
Gasoline	**2010**	3.4-6.1	7.8-9.2	155-171	n/a (baseline)	n/a (baseline)
	2020		7.7-9.0	140-155		
Diesel	**2010**	3.4-5.8	5.7-6.8	147-162		
	2020		5.7-6.7	133-147		
Gasoline hybrid	**2010**	3.4-6.1	8.7-9.4	133-147	1629-5089	444-1388
	2020		8.6-9.2	111-122	1523-3280	415-895
Diesel hybrid	**2010**	3.4-5.8	6.2-6.8	121-134	negative	negative
	2020		6.2-6.7	101-112	negative	negative
Bioethanol	**2010**	7.9-13.8	9.1-10.2	20-114	405-1673	125-456
	2020	7.9-13.8	8.9-9.9	9-114	485-2647	138-722
Biodiesel	**2010**	11.3-16.9	7.5-8.4	8-83	negative -222	negative-61
	2020	11.0-16.9	7.2-8.1	8-83	negative -5	negative-66
Hydrogen	**2020**	6.0-22.3	8.2-14.2	8-97	334-4461	91-1217

Table 8: Specific fuel chain costs and emissions

Fuel chain		**Fuel cost (£/GJ)**	**Cost driven (p/km)**	**Carbon emissions (g/km)**	**Cost of carbon saving (£/tC)**	**Cost of carbon saving (£/tCO$_2$)**
Gasoline	**2010**	3.4-6.1	7.8-9.2	155-171	n/a (baseline)	n/a (baseline)
	2020		7.7-9.0	140-155		
Diesel	**2010**	3.4-5.8	5.7-6.8	147-162		
	2020		5.7-6.7	133-147		
Gasoline hybrid	**2010**	3.4-6.1	8.7-9.4	133-147	1629-5089	444-1388
	2020		8.6-9.2	111-122	1523-3280	415-895
Diesel hybrid	**2010**	3.4-5.8	6.2-6.8	121-134	negative	negative
	2020		6.2-6.7	101-112	negative	negative
Bioethanol	**2010**	7.9-13.8	9.1-10.2	20-114	405-1673	125-456
	2020	7.9-13.8	8.9-9.9	9-114	485-2647	138-722
Wheat – energy from grid	**2010**	10.8	9.6	114	1673	456
	2020		9.4		2647	722
Wheat – energy from gas CHP	**2010**	9.5	9.4	90	972	265
	2020		9.2		1321	360
Wheat – energy from straw CHP	**2010**	11.7	9.8	49	752	205
	2020		9.6		898	245
Brazilian sugar cane	**2010**	8.9	9.3	20	405	125
	2020		9.1		485	147
Sugar beet – pulp as animal feed	**2010**	10.9	9.6	111	1581	431
	2020		9.4		2421	660
Sugar beet - pulp used for heat	**2010**	11.9	9.8	58	832	227
	2020		9.6		1007	275
Wood	**2010**	13.8	10.2	40	812	222
	2020	9.0	9.1	9	507	138
Corn	**2010**	7.9	9.1	111	1152	314
	2020		8.9		1396	381
Biodiesel	**2010**	11.3-16.9	7.5-8.4	8-83	negative - 222	negative-61
	2020	11.0-16.9	7.2-8.1	8-83	negative - 5	negative-1
RME - glycerine as animal feed	**2010**	11.3	7.5	83	negative	negative
	2020		7.3		5	1
FT biodiesel	**2010**	16.9	8.4	8	222	61
	2020	11.0	7.2	9	negative	negative
Hydrogen used in a fuel cell vehicle	**2020**	6.0-22.3	8.2-14.2	8-97	334-4461	91-1217
H$_2$ gas, central plant	**2020**	6.9-8.3	8.2-12.9	78-87	550-3641	150-993
H$_2$ gas onsite	**2020**	6.0-9.2	8.2-13.0	86-97	582-4461	159-1217
H$_2$ renewable electricity	**2020**	13.4-22.3	8.8-14.2	8-9	418-1890	114-516
H$_2$ gas, central plant, CCS	**2020**	7.4-9.0	8.3-12.9	29-33	334-1879	91-513

CHP – combined heat and power; RME - Rape methyl ester; FT - Fischer-Tropsch; CCS – Carbon capture and storage

Figure 5 to Figure 8 show the same data, but plotted such that relative cost of emissions reduction is shown in addition to the amount of reduction (per km driven) for each option. The charts show both the low and high estimates of emissions, in 2010 and 2020. Petrol and diesel costs correspond with an oil price of $31/bbl, as used in the Concawe report – which is 40.3$/bbl gasoline or diesel or 14.1p/l.

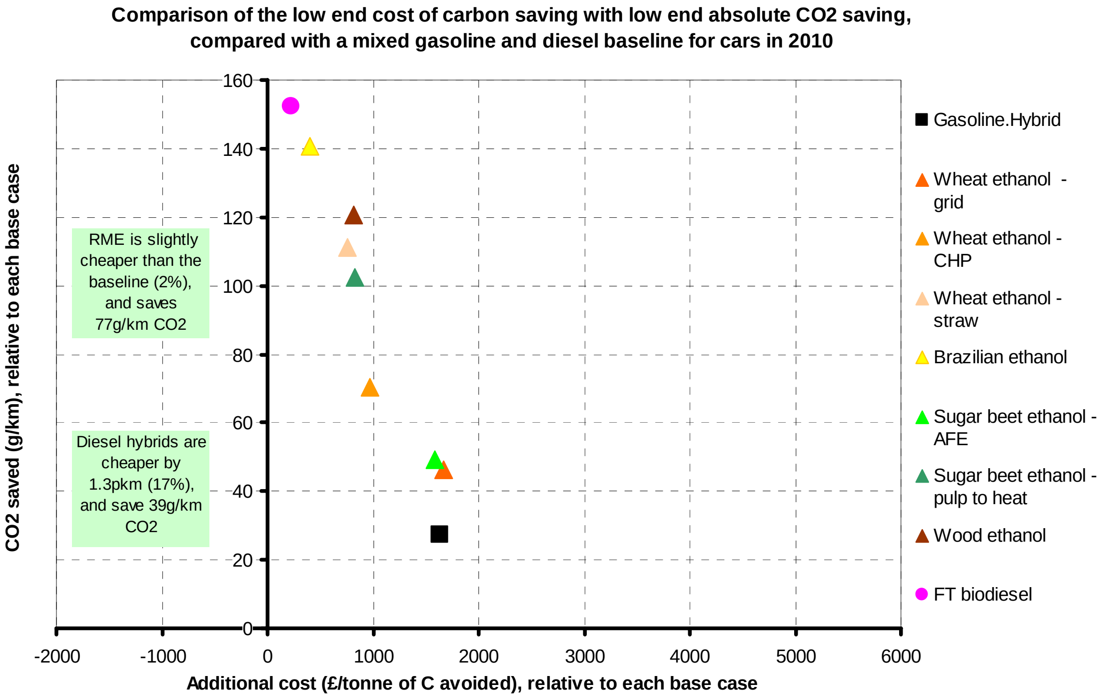
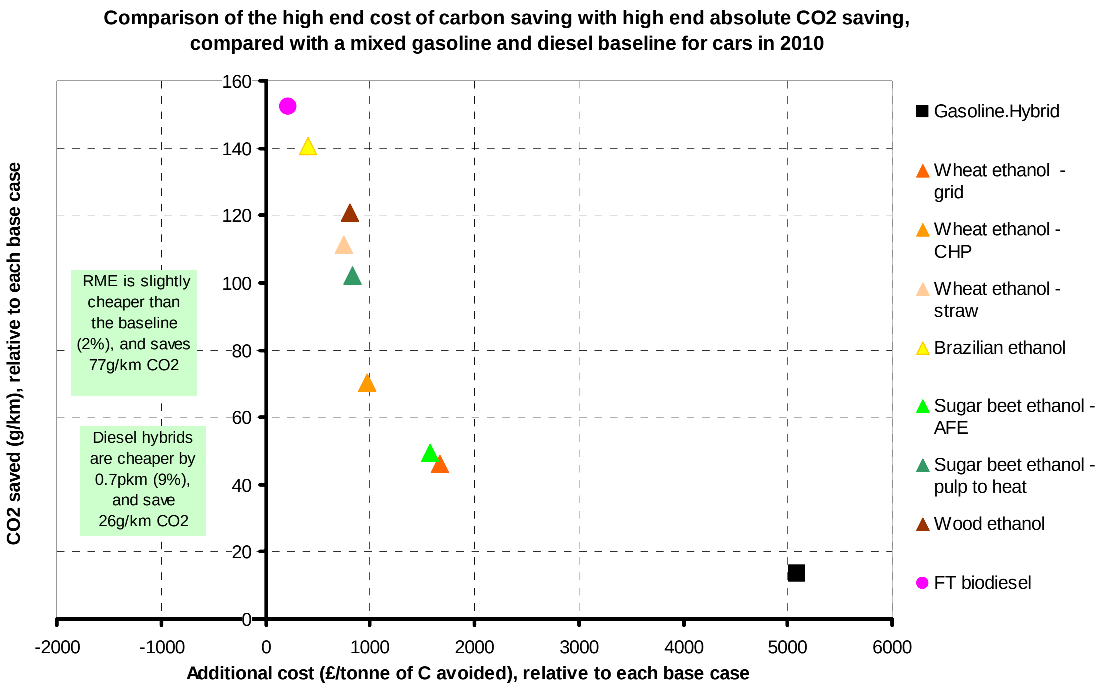


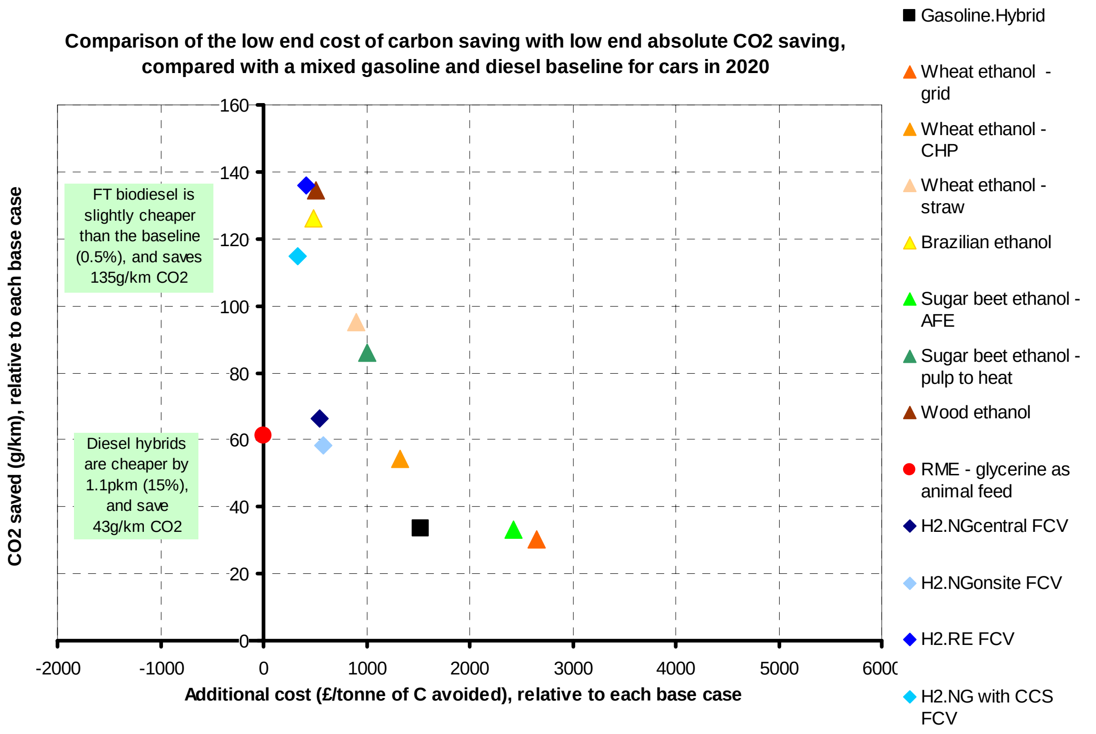
Figure 5: Cost of carbon emissions reduction in 2010 (low)


Comparison of the high end cost of carbon saving with high end absolute CO2 saving, compared with a mixed gasoline and diesel baseline for cars in 2010

RME is slightly cheaper than the baseline (2%), and saves 77g/km CO2

Diesel hybrids are cheaper by 0.7pkm (9%), and save 26g/km CO2

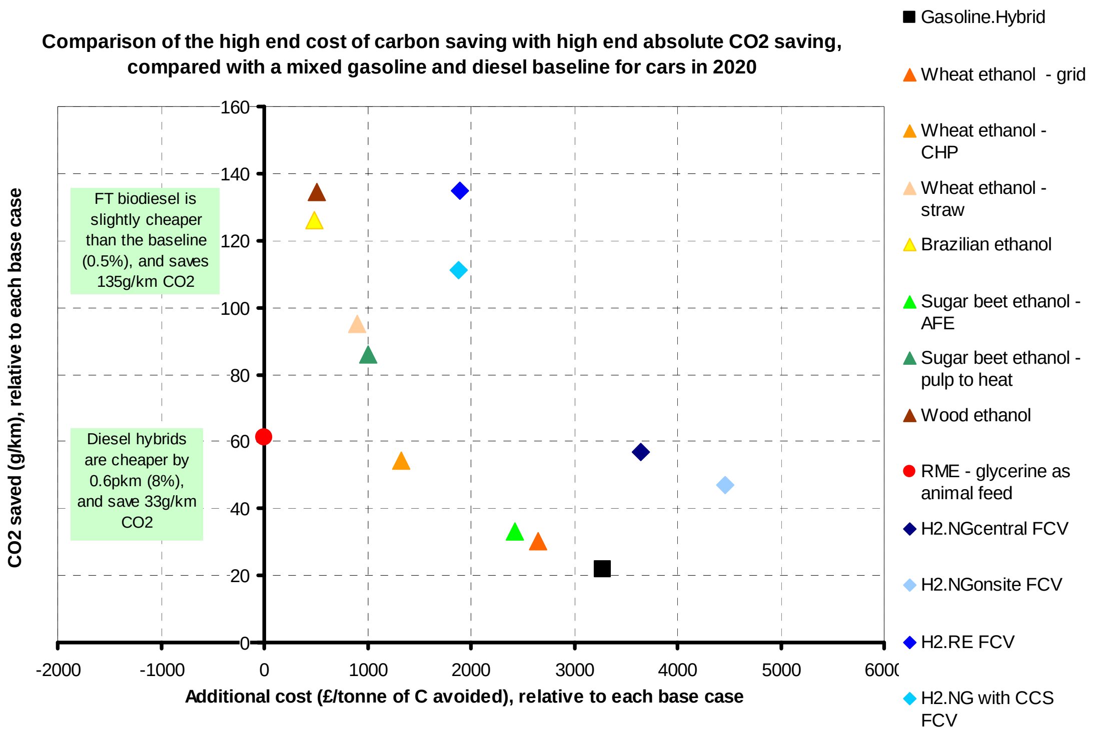
Figure 6: Cost of carbon emissions reduction in 2010 (high)


Comparison of the low end cost of carbon saving with low end absolute CO2 saving, compared with a mixed gasoline and diesel baseline for cars in 2020

FT biodiesel is slightly cheaper than the baseline (0.5%), and saves 135g/km CO2

Diesel hybrids are cheaper by 1.1pkm (15%), and save 43g/km CO2

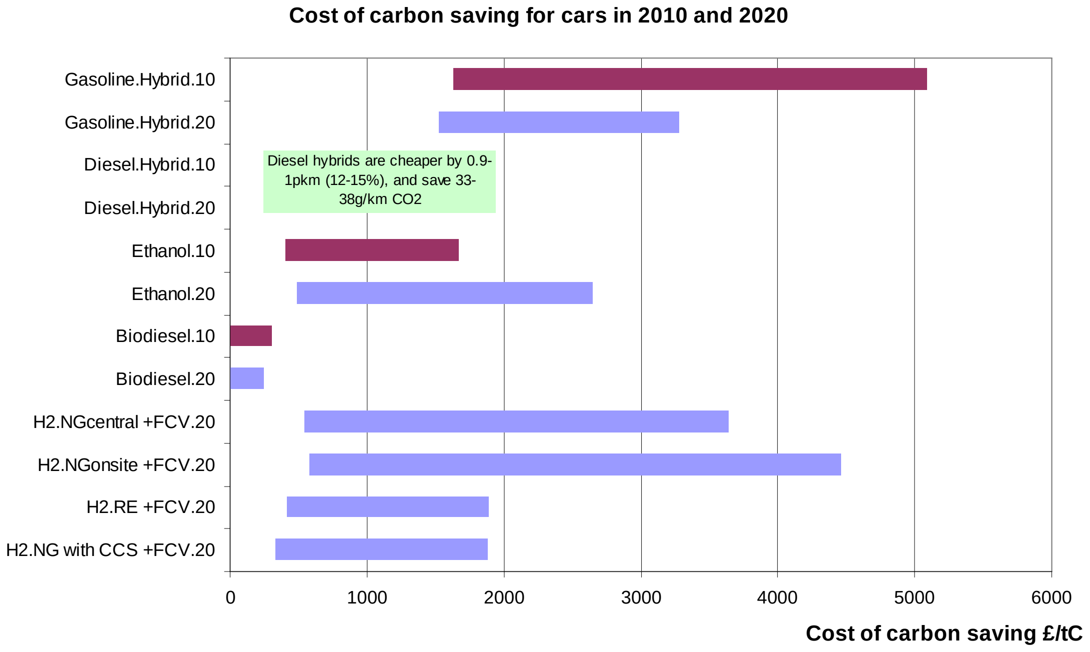
Figure 7: Cost of carbon emissions reduction in 2020 (low)



FT biodiesel is slightly cheaper than the baseline (0.5%), and saves 135g/km CO2

Diesel hybrids are cheaper by 0.6pkm (8%), and save 33g/km CO2

Figure 8: Cost of carbon emissions reduction in 2020 (high)



Diesel hybrids are cheaper by 0.9-1pkm (12-15%), and save 33-38g/km CO2

Figure 9: Range of costs of carbon emissions reduction for cars (2010 and 2020)

POLICY

1.8 Existing policies and their effects

1.8.1 Fuels – demand side

1.8.1.1 Renewable Transport Fuel Obligation (RTFO)

The RTFO will oblige transport fuel suppliers to show that a defined percentage of their fuel sold is a renewable transport fuel. In the Energy Act 2004, a renewable transport fuel is defined as:

> (i) biofuel,
>
> (ii) blended biofuel,
>
> (iii) any solid, liquid or gaseous fuel (other than fossil fuel or nuclear fuel) which is produced:
>
> a) wholly by energy from a renewable source; or
> b) wholly by a process powered wholly by such energy; or
>
> iv) any solid, liquid or gaseous fuel which is of a description of fuel designated by an RTF order as renewable transport fuel.

This would mean that any biofuel, including second generation biofuels and biogas, and hydrogen from electrolysis using renewable electricity, from biomass routes, or produced directly from sunlight would be included in this definition, and should therefore count towards RTFO targets, and so be supported by the Obligation. Hydrogen from fossil or nuclear energy sources would be excluded.

Despite the fact that the second generation biofuels would qualify under the RTFO, the RTFO in its current form is unlikely to provide an incentive for their development or use. This is because the current plans for the RTFO include mandatory reporting of the well-to-tank carbon intensity of fuels, but do not distinguish between fuels on this basis when awarding RTFO certificates. As a result, the RTFO will stimulate use of currently available biofuels, but will not promote investment in second generation biofuel technologies, which have lower carbon intensities, but are also currently more expensive. A solution to this would be to award a higher number of certificates to fuels with lower carbon intensity or set carbon targets, as is being considered post-2010. This type of approach is being taken in the US, where lignocellulosic ethanol receives additional credit under the Renewable Fuel Standard (albeit for resource use and technology support, rather than CO2-linked reasons).

Only hydrogen produced wholly from renewables or biomass (presumably with wholly renewable inputs) would be included at this juncture, which may be excessively strict. Note, however, that the Energy Act allows for the RTF order to be amended to include other renewable transport fuels ((iv) above), or to make provisions on how different fuels are to be counted towards the discharging of an obligation, relating, amongst other things, to fuel descriptions, specific substances, sources of energy, methods and processes.

Biogas is included in the RTFO, although there appears to be some uncertainty over how the distinction between biogas-derived methane and methane from other sources will be made at the duty point for the purposes of awarding RTFO certificates. A similar issue applies to ethanol from biomass and ethanol from other sources. Given that certification is likely to be needed in the future to distinguish between chemically identical biofuels from different sources, and between renewable and non-renewable hydrogen, then it would be useful to develop a proper framework now.

The level of obligation will be 2.5% in 2008-09, 3.75% in 2009-10, and 5% in 2010-11. RTFO levels beyond 2010-11 are intended to be raised beyond 5% by 2010-11 “so long as infrastructural requirements and fuel and vehicle technical standards allow, and subject to the costs being acceptable to the consumer.”

It is not explicit how renewable electricity used to power battery electric or plug-in hybrid vehicles would be considered under the RTFO, but it seems likely that it would not benefit from the policy; electricity is not a ‘solid, liquid or gaseous fuel’, and electricity suppliers fall under the RO, not the RTFO. Further consideration is required if renewable electricity to be used in electric vehicles is to be given incentives under this scheme.

Some of the more complex, crossover areas of the RTFO would hence potentially benefit from further analysis or development.

1.8.1.2 Fuel duty reduction or exemption

Current fuel duty reductions for biofuels of 20p/l are to be gradually reduced, with the support mechanism for biofuels shifting toward the RTFO, with accompanied raising of the buy-out price to 2008-9 (Budget 2006). Current duty reductions for biofuels are therefore unlikely to promote or hinder second generation biofuels. Additional support for second generation biofuels would be better provided through RTFO-linked mechanisms than through maintaining separate duty reductions.

There is currently no distinction between biogas and CNG for the purposes of fuel duty exemption, although some biogas trials currently have a fuel duty exemption.

Budget 2005 announced that the Government was also considering the use of duty reductions to support hydrotreated bio components in diesel. It would be sensible to treat biofuels where the bio component is included at the refinery in the same way as biofuels that are blended afterwards.

Pilot projects for the use of hydrogen in transport have been exempted from fuel duty, with the intention of maintaining this exemption “for a limited period to encourage its further development and early take-up”. This includes hydrogen from any source. In principle, setting a limited period of time for duty exclusion is unhelpful, and stronger signals could be sent to existing and potential users of hydrogen if a volume of hydrogen were used instead. In this way the exemption could be either stopped or tapered off as the use of the fuel became more widespread, allowing those involved the time to anticipate and develop their supplies.

1.8.1.3 Public procurement

Procurement of biofuels by local authorities and other public bodies can build experience and confidence in biofuels use, and support the developing industry and UK market. For example, Southwark Council converted 70 vehicles to biodiesel in June 2005. These will use 300,000 litres per year of a biodiesel blend of up to 30% and relies on PSA Peugeot Citroen honouring the warranties on the vehicles.

Public procurement of fuels and vehicles could be particularly important, however, for fuels requiring more significant infrastructure and vehicle changes, such as biogas and hydrogen. There has been considerable work done on the infrastructure that would be needed to supply London buses with hydrogen, building on the experience from the CUTE trials. However, public procurement is generally a regional or local decision, and hence a secondary policy issue. In principle, central government could consider in more detail ways to encourage greater local public procurement of vehicles that contribute to national policy objectives.

1.8.2 Fuels – supply side

1.8.2.1 Enhanced Capital Allowance for plants

UK Government has applied for State aids clearance for a scheme to support innovation and help develop the lowest-carbon biofuels production methods. This would be through a 100% first-year allowance for biofuels plant that meet qualifying criteria and which give a good carbon balance inherent in the design. The scheme is envisaged to be put in place early in 2007.

The qualifying criteria are a) use of CHP, b) use of renewable sources to produce energy specifically for the plant or c) use of advanced processes – currently defined as lignocellulosic hydrolysis routes to ethanol and lignocellulose to liquid fuels through gasification. The scheme covers production of ethanol, biodiesel and biogas, but currently does not include any other fuels, e.g. hydrogen. The value of an ECA is about estimated at about 4% of the capital cost of the plant.

This will help promote low carbon biofuels pathways, including second generation biofuels. However, the effectiveness of ECAs, in conjunction with the RTFO, in enabling cleanest biofuel plants and second generation technologies remains to be seen. The regulatory impact assessment for the ECA scheme (Dec 2005) states that: “An ECA or similar measure would though provide a useful additional signal and could tip the balance of investment towards cleaner processes at the margin, particularly CHP”. It would not, however “tip the balance towards the very cleanest technologies at today’s prices”.

1.8.2.2 Refuelling infrastructure grants and ECAs

The refuelling and recharging network scheme, run by EST and funded by the Department for Transport, with support from the Scottish Executive and the Welsh Assembly, offers grants to organisations to help them install refuelling or recharging stations for alternative fuels (non-diesel or petrol). The organisation must also run vehicles on the fuel supplied, and these stations must be open to third parties. The levels of the grant are:

- Grants of 40% of eligible costs are permitted for electric recharging points.
- Grants of 30% of eligible costs are permitted for natural gas/biogas, hydrogen and bioethanol refuelling stations, pumps and dispensers.
- Additional support: an additional 5% or 10% in some UK regions, an additional 10% where the owner of the refuelling/recharging point is an SME

It is not clear what the total allocated to this measure is, or whether it could be taken up by some fuels to the exclusion of others.

Enhanced capital allowances (ECAs) for new refuelling equipment for compressed natural gas (CNG) and hydrogen at refuelling stations, were announced in Budget 2002. The refuelling station does not need to be open to the public, and can be for any vehicle type. This measure supports the use of biogas or hydrogen.

1.8.2.3 Fuel standards

Bioethanol can be used as a 5% blend with petrol under the EU standard EN 228. The British/European Standard for diesel, BS EN 590, allows up to 5% esterified vegetable oil, meeting the biodiesel standard BS EN 14214, to be mixed with conventional diesel without affecting the manufacturer’s guarantee. BS EN 14214 will ensure that biodiesel meets the requirements of modern diesel engines. This standard requires both new and used vegetable oil to be processed so that at least 96.5 per cent of the oil is converted to methyl esters.

These standards are acceptable for allowing use of blends up to 5%, but would need to be modified to allow higher blends without invalidating vehicle warranties.

1.8.2.4 Renewables Obligation and CCL exemption

Electricity exported to the grid from renewable transport fuel production plants should be CCL exempt and qualify for ROCs, as it is produced from renewable sources.

1.8.2.5 Waste policy

The waste hierarchy that has become widely used in decisions on waste management, setting out the order in which options for waste management should be considered based on environmental impact, places composting above energy recovery. Although the hierarchy is not treated as a hard and fast rule, this could lead to the impression that biofuels production from MSW has lower environmental benefits than composting, which is not always the case. It would be beneficial if the information provided to waste managers through activities such as the Environment Agency's WRATE tool also included transport fuel production options as they become available.

1.8.2.6 Agricultural policy

The DEFRA-administered Energy Crops Scheme provides establishment grants for two energy crops, short-rotation coppice (SRC) and miscanthus, and aid to help SRC growers set up producer groups. However, crops must be used for heat, power or CHP at a plant within 10 to 25 miles of the farm – use for transport fuels is not covered. The best use of biomass in terms of lowest costs of carbon saving is more likely to be in heat, power or CHP than in transport fuel production in some cases. However, there may be instances where it would be beneficial to include transport fuel production, such as where there is no local heat or electricity demand, or where a polygeneration[25] approach is used – for example generation of ethanol from wood with the lignin used to produce heat and electricity. The choice of energy end-products is probably best left to the market, within an appropriate policy framework aimed at meeting environmental and energy objectives.

The recent EU sugar reform has led sugar producers to consider ethanol as an alternative product. While some sugar production will be displaced by ethanol, unless there are further changes in the sugar regime, it is likely that the majority of the sugar beet produced in the UK will continue to be used for sugar production.

1.8.2.7 Research funding

The level of support for research in conventional and advanced biofuels, hydrogen production, fuel cell vehicles, hybrid and electric vehicle research, and battery development is low in the UK compared with several other EU countries and with the US, Canada, and Japan. However, the innovation systems in all these areas are global, and it is not necessary or beneficial for research to be conducted in the UK alone in order for technologies to be successfully commercialised worldwide.

Nevertheless, uptake of technologies is frequently linked to support for research and development, as financial organisations and corporations tend to view them as an indicator of a positive climate for investment in these areas. Early demonstration projects with comprehensive monitoring and evaluation provide useful feedback and also develop local knowledge and acceptance.

Funding for research and development should be considered as art of a strategic whole, in which investment in demonstrations, and near-commercial policy incentives such as the RTFO all play a part.

1.8.3 Vehicles

1.8.3.1 Company car tax and capital allowances

Company car tax is based on carbon emissions, and this approach has been shown to be successful in achieving carbon reductions of around 15g/km per car on average (Budget 2006). Budget 2006 introduced a reduction in the threshold for the minimum percentage charge rate

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[25] Simultaneous production of more than one useful output – e.g. electricity and heat; electricity and fuel; heat, fuel and chemicals.

for calculating benefit in kind from company cars from 140g /km to 135g/km, together with a new lower 10% band for company cars with carbon dioxide emissions of 120g/km or less for 2008-09. The Government is also considering options to encourage the purchase of cleaner cars, through a range of first-year allowances for cars depending on CO_2 emissions, building on the existing 100% first-year allowance for cars (or taxis, but not vans or motorcycles) with emissions under 120g/km.

Several of the fuels and vehicle type combinations we are considering have well to wheel emissions under 135g/km or 120g/km (see Table 8), but the type of measures above are only likely to promote use of hybrid vehicles, with lower well to wheel emissions irrespective of the fuel used, rather than flex fuel vehicles for biofuels, or hydrogen vehicles, where the emissions can vary considerably depending on fuel origin. If combined with a successful RTFO or other fuel incentive mechanism, or linked to measures that ensure they are actually using greater shares of renewable fuels (e.g. refuelling infrastructure grants), they could encourage those with company cars to become early adopters of flex fuel or hydrogen technology. Battery electric vehicle technology qualifies for the ECA irrespective of the electricity source, and therefore whilst this will promote uptake of the technology, it will not reduce carbon emissions where grid electricity is used. It is not clear how plug in hybrids would be treated.

1.8.3.2 Variable vehicle excise duty (VED)

Budget 2006 announced the reduction of the VED rate to zero for cars in band A, together with reductions for bands B and C, increases for band F and a new higher band G. There will also be a reduced rate of VED for cars that can run on E85. The level of the reduction for the cars in the lower bands, however, is unlikely to be sufficient to be sufficient incentive for the purchase of hybrid, hydrogen or battery electric vehicles with higher costs.

1.8.3.3 Car labelling

Energy efficiency labels for vehicles introduced in the past year to raise consumer awareness of the fuel savings from lower emissions vehicles, are a useful method of informing the consumer about the environmental impacts of the vehicle, and could support use of hybrids. However, they are unlikely to provide enough information and impact to influence consumers to buy flex-fuel, hydrogen or electric vehicles, particularly given the complexities of emissions generated by different production routes.

1.8.3.4 Vehicle grants

No grants for cleaner vehicles have been available from Powershift since March 2005. This means that there is currently no financial support for individuals wishing to buy hybrid, battery or flex fuel vehicles.

The DfT has been answering a number of questions from the European Commission on the other grant programmes that were submitted for approval, including the Low Carbon Bus Programme (grants to bus operators for purchasing low carbon buses) and the Low Carbon Vehicle Programme (grants to encourage the purchase of low carbon cars and car derived vans).

1.8.3.5 Vehicle emissions standards

Vehicle standards for regulated pollutant emissions are not designed as to be sufficiently stringent as to require use of alternative fuels or vehicles

1.8.3.6 Public procurement

Public procurement vehicles could be particularly important for fuels requiring infrastructure and vehicle changes, such as biogas, hydrogen, plug in hybrids, electric vehicles, and flex fuel vehicles that allow use of higher ethanol blends.

1.8.3.7 Congestion charging

Vehicles on the Powershift register (LPG, NG and hybrid) and electric vehicles are exempt from the London congestion charge. This is potentially a significant amount of money (up to £1600 per annum), and may influence vehicle purchase.

1.9 Further policy needs

In general, policy seems to be short-term focused and often overly specific. Support for fuels and vehicles available at present is significant in some areas but less so in others, leading to imbalances. To encourage long-term fuel or vehicle options that could provide a large impact on emissions but only after an introduction period would require considerably stronger support.

1.9.1 Biofuels

The cumulative effect of the policies above will:

- Promote conventional biofuels adequately to meet RTFO targets and potentially further, up to the blending limits set by vehicle warranties, and potentially a little further if hydrogenation of vegetable oil is successful technically and is included in the RTFO and duty reduction
- Support a UK biofuels industry in conventional biofuels
- Potentially improve the integration of biofuel into the fuelling infrastructure, though not at a high level.

However, the policies would not be sufficient to:

- Bring in second generation biofuels, especially those produced in the UK. The carbon and resource base benefits of second generation biofuels are not currently recognised by the RTFO. There is relatively little RD&D activity and company presence in these areas in the UK compared with Spain, Germany, Sweden, the Netherlands, US and Canada.
- Increase blending percentages above current blending limits. This would require changes to vehicle warranties, introduction of vehicles with some modification or flex fuel vehicles (already the case in other countries), some changes to fuel and refuelling infrastructure.
- Avoid actual or perceived negative environmental impacts of biofuels.
- Clarify the best use of land or biomass in the UK.
- Support the use of biofuels across different transport modes.

To overcome this, further policy could include:

- Linking carbon intensity to the RTFO, or redefining the RTFO to be about low carbon fuels and not a defined list of ‘renewable’ fuels.
- Ensuring sustainable practices are followed along the entire fuel chain, through environmental certification, and clear statement of this to reassure consumers.
- Increasing the levels of support (e.g. ECAs) for ethanol and biogas
- Stimulation of UK RD&D activity in second generation biofuels. Also, stimulating RD&D of biofuels in other applications such as biodiesel in trains and biokerosene production RD&D for aviation.
- Engagement with vehicle manufacturers to change vehicle warranty limits.
- Ensuring the effectiveness of different policy mechanisms in stimulating change in biomass production, conversion, end-use, and related infrastructure that contributes in an optimal way to meeting environmental and energy objectives.

1.9.2 Hydrogen

The cumulative effect of the policies above, together with the activity stemming from the UK hydrogen strategy and from strong local governments, may be enough to support initial demonstrations of hydrogen in transport. Inclusion of renewable hydrogen in the RTFO and ECAs for refuelling infrastructure may be sufficient to sustain use of hydrogen in transport *once it is well established and widespread*. However, the policies above are very unlikely to move hydrogen from the initial to the well established stage.

Achieving this will rely on:

- Clear signals from Government that hydrogen is considered a long-term option
- Support to encourage demonstrations including vehicles in the UK - either through support for demonstrations or signals of long term commitment
- Support in the early, but post-demonstration, stages, including a continued duty exemption and ECAs for hydrogen refuelling stations
- Promotion of strong co-ordination between authorities, automotive and energy companies to orchestrate a successful simultaneous roll-out of fuel and vehicles
- Evaluating and addressing regulations and legislation to ensure no unnecessary barriers e.g. overly onerous safety
- Standards development for hydrogen as a road fuel
- Work on public acceptance, of vehicles, refuelling, infrastructure and production plants

1.9.3 Hybrid vehicles and plug in hybrid vehicles

Hybrid vehicles uptake will rely on consumer awareness of the benefits, fuel prices, vehicle availability, and willingness to pay additional capital costs.

- It remains to be seen whether car labelling and company car benefits will be sufficient to promote consumer awareness, and what impacts schemes such as congestion charging may have. Further clear policies, such as allowing hybrid vehicles to be parked in priority areas or to pay reduced fees, or to drive in multiple occupancy lanes
- Vehicle availability depends largely on the manufacturers, but could potentially be improved by sending strong policy signals, such as commitments to public procurement
- Company car policy could overcome some of the cost barrier for stronger hybrids and plug-ins. In private cars, the lack of grants for purchasing may not prove a barrier to early adopters, or those seeking congestion charge exemption, but is likely to inhibit wider uptake of the vehicle types above, as cost will be a barrier to most consumers

1.9.4 Battery-electric vehicles

The policies above seem sufficient to overcome the barrier of the cost of recharging infrastructure, and to support companies wishing to use electric vehicles. However, the key barrier here is one of technical performance and so policy is in any case likely to be ineffective.

Specific urban policies such as zero emission or low noise zones, congestion charging or exemption from parking fees can make battery vehicles much more attractive, though they will frequently be competing with public transport options. It would also be desirable to design policies to promote the use of low carbon electricity in battery electric vehicles and plug-in hybrids.

1.10 Policy integration

An integrated approach to policy is essential for many of these technologies and fuels to be introduced, given that both they and the benefits they could achieve are interdependent. It is also important to recognise that all fuels and vehicle technologies can contribute towards emissions reduction, and that no single solution is likely. Policy analysis and discussion should therefore always include representatives from the relevant departments.

Policies that avoid technology lock-in should be promoted where possible, though an inevitable transition from a near-term partial solution, such as certain biofuels, to a longer-term and more complete one will mean inevitable changes in the market.

The best use of land is an issue that will continue to require monitoring and evaluation as conditions change. Land could be used to provide food or energy crops, and in some cases both, but the energy and CO_2 emissions reduction potential will change with time according to competing options, such as the mix of generating technologies and fuels used to produce grid electricity. Equally, the best use of biomass in terms of CO_2 reductions will vary depending on these factors and on technology development. In this case the relative impacts of the RO and the RTFO should be evaluated, for example on the eventual use of lignocellulosic biomass.

Similarly, renewable electricity could be used in displacing conventional power, which is generally considered to give the greatest CO_2 reductions when compared with the current grid mix, or in producing hydrogen, which could become the lowest CO_2 option if the grid has lower CO_2 emissions in the future. Ideally, integrated and flexible policies will enable the market to choose the optimum solution.

Links between traditional policy areas such as vehicle and fuel taxation could be made to newer areas such as road pricing. As technology becomes available to track vehicles and charge according to location and time, a charge based on fuel and/or emissions could also be included.

Policies such as ‘feebates’ could be considered for the support of newer and more expensive technologies. A small fee is charged on conventional technologies, and the money is used directly to give rebates for the new technology. The resulting mechanism is revenue neutral, and has only a small impact on the large number of conventional vehicles, yet provides a large amount of support for the very few new vehicles.

The issue that CO_2 emissions must be considered from the whole fuel chain leads to further policy complexity but also interesting opportunities. Fuel cell vehicles, for example, require low-carbon hydrogen production to reduce emissions, but the vehicles themselves emit no CO_2 regardless of the hydrogen source. An area that may benefit further analysis is therefore one where tradable CO_2 permits allocated to vehicle producers could be traded with infrastructure providers. In this way, some level of market involvement in balancing the costs of infrastructure with vehicle investment could be engineered.

The complexities of resource use, real-world CO_2 emissions, monitoring and supporting the long-term optimum technologies are significant, and no single organisation currently has even an overview of these sectors. A small but dedicated unit constituted for the purpose of following in detail the various strands of this debate, including both fuels and stationary heat and power, could assist policy makers considerably.

SUMMARY

All fuels and technologies capable of contributing significantly to CO_2 emissions reductions in the transport sector face considerable challenges. However, these do not appear insurmountable. In the near term, hybrid vehicles and biofuels are expected to be the main contributors to reductions in emissions, which demonstrates consistency with the previous work for DfT. The environmental impact of biofuels is complex and care should be taken in evaluating and monitoring their real-world effects, especially if either raw materials or finished fuels are imported.

Fuel cell vehicles offer possibly the best long-term potential given the extremely wide range of possible hydrogen sources, but require support in research, development and demonstration in the short term, and in the initial stages of commercialisation in the long term. Again, monitoring and careful policy are required to ensure that low-carbon hydrogen is used when appropriate.

For fuel cell vehicles in particular, their early introduction into the UK will depend heavily on strong policy support, as no indigenous manufacturers exist. A considerable difference in the time the first small fleets arrive will have a concomitant impact on the time of uptake. Delays in this area could result in a 5-10 year lag in the UK in comparison with other regions. Of course, this support should only be given if the potential of fuel cell vehicles is considered achievable, but demonstrations will be needed, short-term, for evaluation.

This area is complex and increasingly overlaps with other power and energy options for the UK (the use of biomass for heat and power, the potential for renewable electricity to be used for hydrogen production, and the incentives given by the RO and RTFO). A dedicated unit that tracks and measures these different variables would provide an invaluable input to ensuring that policy-making responds both to technology developments and to the latest thinking in terms of resource allocation.