Fuelling Road Transport

Implications for Energy Policy

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nsca

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The Energy Saving Trust (EST) is a non-profit company funded by government to deliver sustainable energy solutions to households, small firms and the road transport sector. EST funds a UK wide network of 52 Energy Efficiency Advice Centres (EEACs) offering advice to householders, local authorities and small businesses on energy efficiency and helping with local co-ordination of activities. EST works with over 200 individuals interested in energy efficiency (manufacturers, retailers, local authorities, energy suppliers and community groups) to develop a long term framework for reducing carbon dioxide emissions and tackling fuel poverty in UK homes. EST also manages the *Energy Efficiency* marketing campaign (funded by DEFRA), which aims to raise awareness and influence householders' purchasing decisions of energy efficient household appliances, insulation, lighting, and boilers. EST's *TransportEnergy* is an umbrella brand for EST's environmental transport programmes which include *PowerShift*, *CleanUp* and *BestPractice*. The *PowerShift* and *CleanUp* programmes aim to stimulate market demand for alternatively fuelled vehicles and emissions reduction equipment. *BestPractice* provides authoritative, independent information and advice to help local authorities and businesses implement sustainable road transport initiatives.

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The Institute for European Environmental Policy (IEEP) is a leading centre for the analysis and development of environmental policy in Europe. Its work focuses on European environmental policy, and environmental aspects of other sectoral policies including transport, agriculture, regional development and fisheries. IEEP's transport research covers many of the environmental aspects of transport policy, including climate change and air quality. Over the past 15 years, IEEP staff have undertaken a series of studies of vehicle technology and alternative fuels, including a contribution to the Performance and Innovation Unit's (PIU) recent review of energy policy.

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The National Society for Clean Air and Environmental Protection (NSCA) was founded in 1898 as an anti-smog campaigning group. Today it brings together organisations and individuals across the private, public and voluntary sectors to promote a balanced approach to understanding and solving environmental problems. Its membership includes environmental protection specialists from industry, local authorities, academia and consultancies.

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Executive Summary

There are compelling environmental and strategic arguments for reducing the carbon intensity of the UK energy mix, and in particular the road transport sector, which is uniquely oil-dependent. Long term, the ‘dream ticket’ of vehicles powered by fuel cells using renewably sourced hydrogen offers the prospect of sustainability.

The Government’s forthcoming Energy White Paper provides an opportunity to consider the most beneficial mix of fuels and technologies which might form the intermediate routes leading to that ‘dream ticket’. There are concerns that a premature ‘dash for hydrogen’ might have an environmental downside and preclude the development of other, comparatively beneficial technologies. There is also uncertainty about the optimal use of renewable electricity from the UK grid, and about the likely form and future contribution of biofuels.

This study, by experts from three of the UK’s leading organisations in the transport/energy/environment sector, takes as its terms of reference the optimal role for transport fuels in the future energy mix from an environmental perspective. We have developed a model that assesses a number of possible technological pathways to a future low carbon transport system, measured against a range of energy mix scenarios. The focus is specifically on the relative carbon benefits of hydrogen and bio-energy options, as well as more efficient vehicles. This study is based on a ‘well-to-wheel’ analysis that accounts for emissions both from vehicles and from upstream fuel production. But it also goes beyond traditional ‘well-to-wheel’ studies in considering the alternative options for use of different fuels elsewhere in the energy system. We have also considered the extent to which concerns over security of oil supplies might modify conclusions based primarily on the need to reduce greenhouse gas emissions.

Our conclusions are:

1. Until there is a surplus of renewable electricity it is not beneficial in terms of carbon reduction to use renewable electricity to produce hydrogen – for use in vehicles, or elsewhere. Higher carbon savings will be achieved through displacing electricity from fossil fuel power stations. There would be some carbon savings from hydrogen vehicles using electricity from a power system dependent largely on gas and renewables, if the gas technologies are combined heat and power (CHP). But the supply of hydrogen to mass-market vehicle applications is likely to require more electricity than can be supplied from renewables and CHP alone for at least 30 years.
2. The production of hydrogen from gas offers the cheapest route to hydrogen and some potential carbon benefits if used in high efficiency fuel cell vehicles. There are still benefits, though not as large, when hydrogen fuel cells are compared to diesel and petrol hybrid vehicles. Hybrid vehicles have the potential to halve carbon dioxide (CO_2) emissions compared with current conventional technologies and can offer substantial benefits in the short term for air quality and noise as well. Gaseous fuels also offer some environmental advantages. In the absence of a large carbon reduction benefit, there is no strong environmental case for accelerating the introduction of a large scale hydrogen fuel cell vehicle fleet ahead of the availability of surplus renewable energy sources.

3. Tax breaks for renewable hydrogen in the transport sector could provide some modest stimulus to renewable generation, but this would require a bigger subsidy level and achieve a lower carbon saving than supporting renewables more generally via a mechanism such as the Renewables Obligation.
4. There are substantial uncertainties around the infrastructure issues associated with the introduction of a hydrogen fleet. In particular they depend on whether the hydrogen is produced at local sources, or centrally with distribution through a network. It seems unlikely that these issues can be confidently resolved in the short term. In the meantime, and before a wide-ranging network of hydrogen fuel supply is available, there is the opportunity to proceed incrementally through bi-fuelling and through dedicated depot based fleets meeting niche markets.
5. Developing depot based niche fleets would not substantially increase natural gas demand compared to the expected demand from the domestic, service and industry sectors. Furthermore, any hydrogen production could be designed to draw on a range of different fuels quite quickly in the advent of external disruption to gas supplies.
6. There are some carbon benefits from using biodiesel and bioethanol from annual crop production to substitute for oil-derived fuels. However, using woody biomass for energy could give significant carbon benefits, and offers three routes – hydrogen and methanol or ethanol – to renewably sourced fuels for fuel cells. Biomass offers a cheaper and earlier route than renewable electricity to reducing carbon emissions via a hydrogen fuelled transport system. As an indication of the potential contribution, 25% of UK agricultural land planted with indigenous wood crops converted to methanol, ethanol or hydrogen could in the long term satisfy most, or even all, UK road transport fuel demand. This outcome would, however, be dependent on relative costs and a large number of technical factors.
7. The case has been made for accelerating development of an electrolytic hydrogen fuelled vehicle fleet, ahead of the availability of renewably sourced energy, and even ahead of the use of fuel cells, on grounds of reducing oil dependency. However, aggressive promotion of energy efficiency, combined with the development of hydrogen (or methanol) initially from gas and then from biomass, and more concerted effort to manage demand, could address security of supply concerns equally effectively – and without the need to take a medium term ‘carbon hit’ from the use of fossil fuel electricity-derived hydrogen.
8. There may be other reasons for developing hydrogen powered vehicles in the UK as part of a long term strategic plan for sustainable transport and for helping to build competitive advantage for the UK’s auto industries. It is clearly important to maximise the commercial opportunities inherent in the developing strands of new technologies, and we support a continuing engagement with them. There is a good case for encouraging niche markets in order to develop expertise and experience. This suggests that a medium term strategy should be focused on substantially more efficient use of fossil fuels, combined with the introduction of mass-market fuel cell vehicles at a rate consistent with the ability of biofuels to supply the hydrogen. This offers the more sustainable route to cleaner vehicles.

1. Introduction

In response to the Government's Energy Policy – Consultation Document of May 2002, the Department for Transport (DfT) has invited Nick Eyre of the Energy Saving Trust (EST), Malcolm Fergusson of the Institute for European Environmental Policy (IEEP) and Richard Mills of the National Society for Clean Air and Environmental Protection (NSCA) in an individual capacity, but with the support of their respective organisations, to undertake a tripartite analysis of the implications of future transport demand and technology for the UK energy supply system.

The overall approach is to consider the optimal role for transport fuels in the future energy mix, primarily with regard to minimising greenhouse gas emissions, and to certain other environmental considerations. Vehicle technology and energy scenarios are considered over the period to 2050. The analysis specifically examines the impact on overall UK energy supply of demand for hydrogen fuelled transport in reducing UK carbon emissions. It also addresses the potential contribution of fuels, such as biofuels, to reducing carbon emissions, and technologies such as hybrids and fuel cells, for providing carbon-reducing pathways. The transport sector analysis is based on a 'well-to-wheel' analysis that accounts for both the efficiency of the vehicle and the efficiency of fuel production and transportation. When considering the emissions reductions which could be gained by switching vehicles to renewable fuels, we also consider the benefits foregone of using this fuel in another (possibly more efficient or environmentally more beneficial) way.

Energy security issues are then considered, to see whether these would significantly modify our conclusions based on an 'environmentally optimal' approach.

This paper is restricted to road transport. Rail and shipping are not addressed on the basis that (a) they represent, and will continue to represent, a relatively small share of UK transport energy demand and (b) that relatively straightforward options to improve energy and carbon efficiency (for example railway electrification) are available if needed. We are nonetheless concerned at the lack of attention to energy efficiency or energy supplies in these two subsectors.

In contrast, we believe that there are major grounds for concern over the future environmental impacts of aviation, but at this stage we consider that there is little to be added to the Performance and Innovation Unit's (PIU) Energy Review background paper on the subject. That is, we anticipate that energy demands will continue to grow with air travel demand significantly outstripping improvements in more efficient aircraft technologies. It is unlikely that there will be a significant switching away from kerosene much before the 2050 time horizon of this study. Hence carbon dioxide (CO_2) and other greenhouse gas emissions from aviation are likely to increase.

This report represents the authors' personal views, and is without prejudice to responses their organisations have made to the Energy Policy consultation exercise.

2. Considerations in Developing the Scenarios and Analysis

There are a number of broad considerations that have been taken into account in this study, which are outlined below and are further explored later in this report. These are:

- the energy supply implications and carbon benefits of the main energy sources for hydrogen production;
- the energy supply implications and carbon benefits of alternative renewable transport fuels;
- the implications for fiscal policy;
- the role of energy security as a driver for transport fuel policy.

A range of scenarios examining the wide range of options available has been developed covering transport demand, vehicle technology and energy scenarios over the 2010, 2020 and 2050 timeframes. These are explained and analysed in Sections 5 and 6. Some initial assumptions that underlie the development of the model are outlined below, to clarify the scope of the scenarios.

2.1 Environmental Considerations

Currently, oil based transport contributes significantly to UK carbon emissions, so climate policy considerations may drive the demand for alternative fuels including hydrogen. The road transport sector requires premium fuels (currently oil based) with specific characteristics and this sector may become a significant source of demand for future hydrogen and/or other renewable energy supply sources. Nevertheless the range of energy sources available to produce hydrogen or other road fuels have very different environmental benefits, and key aspects of these are considered below.

In the long term, renewably produced hydrogen could allow road vehicles to operate with zero 'well-to-wheel' carbon emissions. In this sense, hydrogen vehicles and renewable energy provide a 'dream ticket' for road transport with minimal climate impact. We critically examine the possibilities for and obstacles to the development of the 'dream ticket' option of fuel cells using renewable hydrogen in road vehicles. In addition, we consider a range of alternative and intermediate low carbon configurations, including hybrid engines, biofuels and hydrogen from non-renewable sources. We also consider the prospects not only for a large-scale switch to hydrogen as a general road transport fuel, but also specialist vehicles and captive fleets, both as niche markets and as possible pathways to broader deployment. For all transport energy supply sources we consider regional and global sources of supply as appropriate; the UK system cannot be considered in isolation.

We take official forecasts of future transport demand as the basis for our analysis. The focus of this analysis is on technical options, not demand management, modal shift, etc. This is not because such options are not important for carbon emissions reduction or improving energy security – indeed they may well prove critical. It is simply that these are not the issues that we have been asked to address in this study.

We anticipate that carbon emissions reductions (and where relevant, the reduction of other greenhouse gas emissions) will be the primary environmental driver of future scenarios, alongside the continuing requirement for fuels and vehicles to meet good local environmental standards (for example air and noise standards). We therefore take into account the latter, and the secondary impacts of renewable power sources, including biofuels and waste materials. Our analysis is based as far as possible on a full fuel cycle (i.e. 'well-to-wheel') analysis of CO_2 and other greenhouse gas emissions where applicable.

2.2 Fiscal Issues

One issue in determining future fuels for road transport systems is the price offered for fuels by each economic sector and the alternatives available. The high prices paid for fuels in the transport sector and the specific and exacting requirements of vehicle fuels are significant considerations. In this respect we note that UK Government has scope to vary the level of taxation for different fuels and different energy sectors, and that this possibility could be a major determinant of the extent to which hydrogen as a road fuel is taken up. This is further explored in Section 6.2.

2.3 Scenario Considerations

We consider a number of possible future transport and energy scenarios, addressing the supply-side implications alongside the demand characteristics of transport. In line with the approach taken in the PIU Energy Review, the scenarios are framed around 2010, 2020 and 2050 timeframes in order to provide short, medium and long term perspectives. For all relevant scenarios, we seek to build on the analysis in IPPR's report H_2: Driving the Future, on the transport background paper to the PIU's Energy Review, on EST's *Pathways to Future Vehicles* report and on AEA Technology's work on *Low Carbon Futures*. Where appropriate we reflect the assumptions and targets of the Government's strategy *Powering Future Vehicles* published in July 2002.

In the scenarios we consider a number of energy supply constraints and implications, but some considerations are outside the scope of this study. Some of the issues taken into account in the report are outlined below:

- we assume for the purposes of this exercise that renewable energy sources represent the sustainable low carbon energy option;
- in considering possible 'high renewable' scenarios, we examine how the distinctive features of renewable energy generation (notably intermittency and the potential for off-grid production) could foster hydrogen production;
- we also look at the energy and carbon implications of the use of renewable hydrogen as a transport fuel compared to the likely alternatives;
- we consider whether development of a strong market for transport hydrogen would utilise renewable energy that would otherwise displace fossil energy use in the stationary sectors – or conversely, whether it would stimulate *additional* renewable capacity, discussing how this effect might work in practice;

- in scenarios involving a major switch to biomass based transport fuels, we consider the implications for biomass heat and power generation and the carbon consequences. We comment on the scope of the potential environmental, agricultural and rural policy implications; a full treatment of such issues is, however, beyond the scope of this analysis;
- we do not anticipate that gaseous hydrogen will fuel significant numbers of stationary fuel cell installations. This is because (a) hydrogen will be a premium fuel, whereas other, lower grade fuels can be used in such installations; and (b) it will probably make little sense to use renewable energy sources to generate hydrogen, and then to use the hydrogen primarily to generate electricity, except as a form of energy storage. However, fuel cells using gas in stationary applications are not irrelevant to the discussion about hydrogen, as they may play a role in developing a low carbon electricity system. This is discussed further in Section 7;
- we recognise that battery electric vehicles in combination with sustainable electricity sources could be an environmentally desirable option, but we support the argumentation of the transport background paper to the PIU's Energy Review. It assumes that the constraints in range and battery performance will not improve with sufficient speed to enable battery vehicles to be widely deployed. Niche uses of battery vehicles may well continue. The recent decision by Ford to cease production of its Think electric car reinforces us in our view, but we still do not rule out this option;
- for each scenario, we consider the implications for security of energy supply as well as environmental considerations (see Section 5.2). We address a number of possible aspects of energy security, noting that security is not synonymous with self-sufficiency, and that the latter should not be an overriding consideration. For this purpose we adopt the framework discussed in the PIU's Energy Review, and consider whether different aspects of security of supply suggest or favour different outcomes.

3. Hydrogen and Renewables: Key Issues

3.1 Sources of Hydrogen

In the long term, renewably produced hydrogen could allow road vehicles to operate with zero 'well-to-wheel' carbon emissions. The technologies are available or under development, and there are sufficient renewable energy resources available in the UK, provided that these can be harnessed in a manner that is economic and publicly acceptable.

However the situation for the foreseeable future is more complex, as renewables are currently only a minor component of electricity supply in the UK. Electrolytic hydrogen would effectively rely initially on fossil fuelled electricity generation. Renewable hydrogen could also be produced directly from biomass, rather than via renewable electricity.

Even if electricity from renewable sources of electricity were contractually committed to hydrogen supply, there would be a requirement for more electricity from fossil sources for other uses. Similarly biomass can be used for heat and power as well as transport fuels and so a similar issue regarding optimum use arises. Moreover, the cheapest source of hydrogen is currently reformation of fossil fuels, which would result in carbon emissions. 'Well-to-wheel' emissions depend on the type of primary fuel as well as the efficiency of the vehicle and the upstream energy conversion.

This basic analysis raises three problems:

- **energy system carbon emissions**. For the foreseeable future, the contribution of hydrogen powered vehicles to carbon reduction is an empirical issue. It requires quantitative analysis of both transport and energy systems to identify the overall impacts of using hydrogen in vehicles on the UK energy system and therefore on total UK carbon emissions;
- **the conditions for renewable electricity-based hydrogen**. The use of large amounts of renewable electricity from the grid for hydrogen production would, at present, lead to a requirement for more fossil fuelled electricity. But this is not necessarily true under all conditions in the future. The key issue is under what circumstances might truly 'renewable hydrogen' be produced;
- **how best to use biomass**. The question also arises whether biomass is best used for heat and power, or for transport. And, if the latter, which biomass feedstocks and biomass-derived fuels are preferred?

3.2 Energy Security: an Additional Concern

Aside from environmental considerations, the international political situation may result in oil and/or gas resources becoming insecure or too expensive. This may then lead government to accelerate the development of a vehicle fleet fuelled from alternative fuels, either in anticipation of or in response to such events. However, there are similar energy security issues for gas as for oil, and gas is likely to be the major short-term source of hydrogen.

Oil Supplies

Oil is currently overwhelmingly the dominant fuel in the transport system. It is the fossil fuel with the lowest global reserves to production ratio and potentially 'in short supply' before 2050 even without political disruption. In contrast to the position in recent years, the UK will increasingly become a net importer of oil over the next 10 to 20 years. Imports are expected to come increasingly from the Middle East, with the possibility either that OPEC could again become an effective cartel, or that disruption of supply through political or military upheaval could become more likely. Risks are however offset by the existence of large 'unconventional' reserves of oil, for example in central America and Canada, which are increasingly close to being economic to exploit, and probably would become so with any future politically driven price increase.

Gas Supplies

Natural gas is scarcely used in transport in the UK, but is the biggest single input to the energy system as a whole. It is also a relatively new major player on the global energy scene and there is a commonly held view that the search for reserves has been less intensive than for oil, and therefore that there is greater potential for major new discoveries. Currently there are adequate resources in the continental shelf (UK and near neighbours, especially Norway), but western Europe as a whole is becoming increasingly dependent on key regional exporters, especially north African countries and Russia. Imports from further afield are currently limited as this requires the use of liquefied natural gas (LNG), but a global market may develop. The risk of an effective cartel is more limited than for oil. Political disruption is however possible, related to similar risks as with oil, or possibly others. Russia has been a very reliable exporter through difficult internal political changes – larger threats perhaps arise from instability in the intervening countries and the susceptibility of pipelines to terrorist attack.

Categories of Risk: Oil and Gas

There is no risk-free fuel supply system. The security issue is best considered in terms of the amount of 'insurance' that society is willing to pay to reduce specific risks.

For both oil and gas there seem to be two broad categories of risk:

- long term trends of growth in demand leaving increasing economic power in the hands of exporting countries, or threatening restriction to supply; and
- sudden risks of disruption, at any point in the future, arising from political instability, hostilities or terrorist activity.

These risks need to be considered separately. The former may be addressed by:

- technological development to improve energy efficiency or develop new fuels; and
- socio-economic measures to reduce dependence on the more energy intensive transport modes (for example air and individual road transport).

Either or both these approaches will reduce dependence on imported fuels in general or on specific fuels identified as risky. However, in general, these measures do not provide effective options for dealing with short term disruption. In this case it is necessary to substitute completely, or largely, for a fuel, source or route of transit on much shorter timescales. Relevant options in this case include:

- infrastructure redundancy (e.g. in pipeline capacity); and
- alternative suppliers in different geo-political regions.

Diversity of fuel sources provides some security to reducing the risk of specific threats. However, owing to the slow turnover of vehicle stocks, technological options only offer protection to the extent that they allow different primary energy sources to be used for the same vehicle. Relevant options here include:

- bi-fuelled vehicles, e.g. gas and oil, or hydrogen and oil; and
- secondary fuels that can be derived from a number of primary fuels, notably hydrogen, methanol and ethanol.

Bi-fuelling would not be likely to prove a sensible option across the fleet at large, but might prove useful if focused on emergency services, delivery vehicles, etc.

4. Modelling The Scenarios

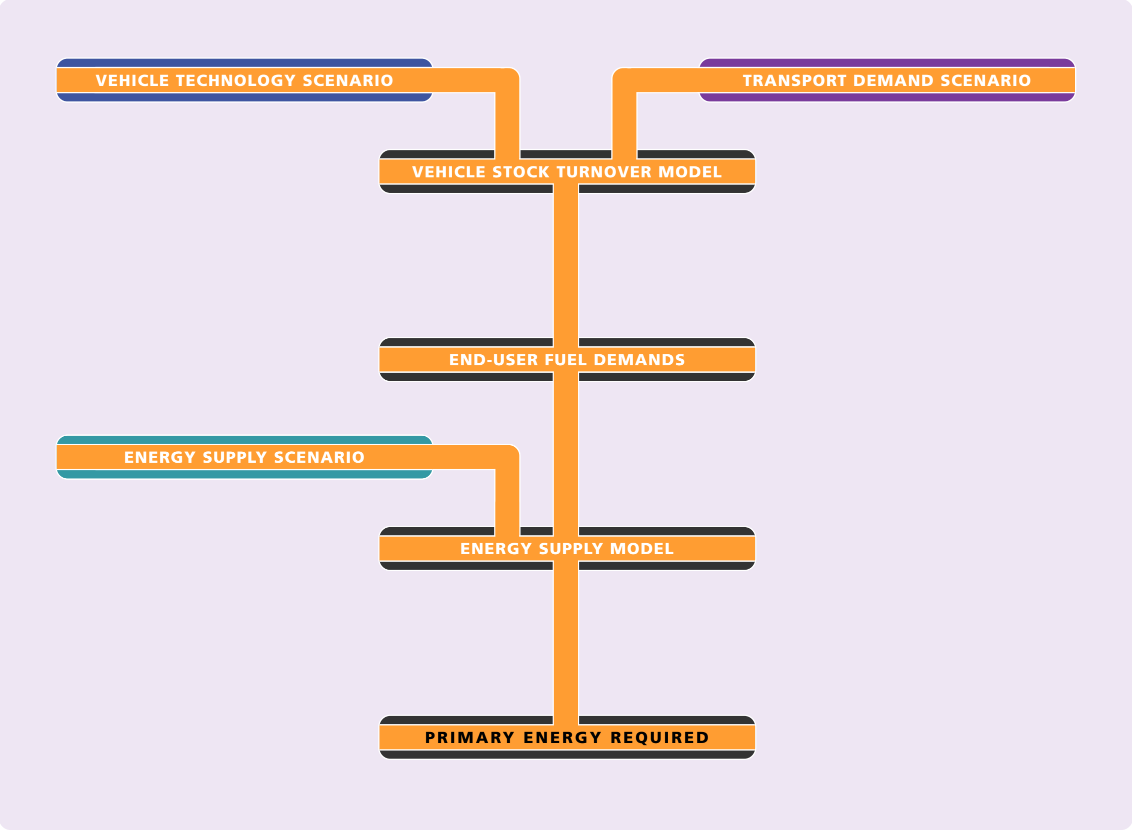
4.1 Overview of Modelling Approach

In order to explore the energy implications of future transport demand and technology scenarios, the project team developed a model in an Excel workbook. This is in essence a physical model of the UK road transport sector coupled to a model of the relevant elements of the energy supply system (i.e. a partial model of the energy system). It is a 'bottom up' model which derives a detailed vehicle stock profile from a combination of transport demand (i.e. traffic) and vehicle technology development scenarios. From this basis end user fuel demands in each modelling year are calculated, and then translated into primary energy demands and corresponding CO_2 emissions.

The model is structured to have separate scenario data for each year modelled in each of the following categories:

- traffic demand by class – for example car, bus, light goods vehicles (LGV), heavy goods vehicles (HGV);
- vehicle technology developments – for example percentage hybrids, fuel cells, etc;
- energy supply characteristics – for example electricity generation mix.

For each of these scenario areas we have developed specific cases to illustrate possible outcomes. These are described in turn below. A diagrammatic representation of the model is as follows:



The configuration of results from the model is very flexible, but the key outputs are:

- final energy demand by vehicle class;
- primary energy demand by fuel type; and
- carbon emissions by fuel type and year.

In addition, it is possible to distinguish energy demand and carbon emissions by vehicle class and this information is also given in selected cases. Results are available for each of the six model years (2010 to 2050 in ten year intervals) but the results for 2010, 2020 and 2050 are considered the key years, representing short, medium and long term perspectives respectively.

We would emphasise from the outset that the point of the modelling exercise and scenario development is to illustrate and explore some of the key issues, not to try either to predict the future or to generate results for endless different permutations of the scenario cases.

4.2 Transport Demand Scenarios

Transport demand scenarios give the total national traffic level in billions of vehicle kilometres (bvkm) for each modelling year and for each of the four vehicle classes.

We already have three 'ready made' scenario cases for traffic demand, based on the work of the UK Foresight Programme as adapted by AEA Technology for their *Low Carbon Futures* analysis[1]. This latter also forms a basis for many of the energy demand characteristics of vehicle classes which are built into the model, supplemented by additional data sources. The three scenarios presented are as follows:

- ***Baseline;***
- ***World Markets;***
- ***Global Sustainability.***

Of these, the *Baseline* case represents a broadly 'business as usual' future, with economic growth continuing at historic levels and no particular measures to pursue sustainable development or tackle traffic growth. However, traffic growth tails off in the medium term anyway to reflect capacity constraints and saturation effects. *World Markets* represents a globalised future with high consumption of goods, faster economic growth and ever-growing mobility. Additional road building is assumed to meet demand, and no measures are taken to curb traffic levels. *Global Sustainability* reflects a future with growing concern for environmental issues and strong societal action to curb the adverse impacts of traffic and other activities. The result is a lower rate of traffic growth, and some shift to environmentally-friendly modes.

These three in a sense correspond to a medium, high and low demand case respectively. However, to generate these scenarios AEA Technology had to extrapolate the official transport forecasts out to the year 2050, which is inevitably a rather speculative process. As a result they reflect a quite extreme range

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[1] Low Carbon Futures, AEA Technology, Crowthorne, 2002

of possible futures which may not be credible; the *World Markets* case reflects a virtual doubling of traffic from 2000 levels by 2050 while, in contrast, *Global Sustainability* envisages a modest decline in car traffic from the middle of the period, along with very substantial increases in public transport use.

These results were therefore compared to the results of the RAC Foundation's recent scenario analysis[2] which is arguably more robust in terms of methodology and hence probably more realistic for longer term car use figures. The RAC Foundation's unconstrained case corresponds quite closely for cars to the *Baseline* case above; however, this assumes sufficient road construction to contain congestion at current levels, which appears unlikely and is considerably above what is currently envisaged. An alternative constrained case is also presented, in which a latent demand growth of 50% to 2031 is cut back to an actual growth rate of 33%, and this appears more realistic. On the other hand the RAC Foundation projects no growth in public transport use, and that goods traffic will grow only in line with car use, both of which assumptions appear likely to be too low. In particular, most projections suggest that the intensity of freight traffic and light van traffic with respect to GDP will remain higher than that of private car traffic. In the likely advent of road pricing over the coming decades, it strongly suggests that commercial traffic will grow more rapidly than car traffic. We have therefore developed a composite *Central* case as follows:

- car use growing by 33% over the first three decades as in the RAC Foundation's constrained case, and more slowly thereafter;
- bus and coach public sector vehicles (PSV) use increase modestly, as in the *Baseline* case;
- goods vehicle traffic growth also reflects the *Baseline* level, resulting in a doubling of heavy goods traffic by 2050 relative to 2000, and a slightly higher growth rate for light goods vehicles (LGVs).

We have run all four of these transport demand cases against one standard set of technologies (the *Modest Progress* case below, see Section 4.3) and energy supply (the *Business as Usual* case below, see Section 4.4), to illustrate that:

- there is a very wide range of outcomes to the various cases, and that these reflect substantial uncertainties; and
- that a great deal more energy will be needed, from whatever source, if we allow traffic levels to grow in an unconstrained manner.

We have also combined the high demand case with the limited technical progress case to illustrate a 'worst case scenario'. Beyond this, however, we have used only the *Central* transport demand case throughout in order to aid comparisons between different technology pathways and to avoid a proliferation of sets of results.

4.3 Vehicle Technology Scenarios

Vehicle technology scenarios specify which technologies will be added to the vehicle stock, and in what proportion, for each year. They also include a stock profile for each vehicle class to illustrate its typical longevity.

[2] Motoring towards 2050, RAC Foundation, London, 2002

We have developed five cases of future vehicle technology developments as follows:

- a **Limited Progress** case, with only modest technical change in car fleets except dieselisation, and no switch to hybrids or fuel cells;
- a **Moderate Progress** case, incorporating the Powering Future Vehicles targets for cars and buses and some Energy Saving Trust targets and other background research, and building on continuous progress;
- a **Rapid Progress** case with early introduction of hybrids and then of fuel cells for cars, with progress on buses and vans equally rapid, and hybrids gradually penetrating the HGV fleet as well;
- a **Biomass Alternative** case reflects an alternative possible future where hydrogen fuel cells do not make a significant impact on the vehicle market. Instead there is a rapid switch to methanol, first in conventional engines, then in hybrids and possibly fuel cells. This scenario is deployed in conjunction with the High Biofuels energy supply scenario (see Section 4.4);
- a **Combined H_2/Methanol** case combines elements of the previous two, using methanol in goods vehicles where fuel cells make less headway.

These five cases are set out in greater detail below:

Limited Progress

- internal combustion engine (ICE) car fleet dieselisation increases to 30% of new cars by 2010 and remains at that level; light van sales increasingly switch to diesel by 2020. Note that this implies a better than 30% improvement in conventional new car fuel efficiency between 2000 and 2050. This amounts to the Association of European Automobiles Manufacturers (ACEA) agreement plus very limited progress thereafter, plus significant improvements in light vans;
- no switch to hybrids or fuel cells;
- liquefied petroleum gas (LPG) retrofits reach equivalent of 2% of new car and van sales in 2010 and 3% by 2030, then remain at that level thereafter;
- progress in fuel economy is rather faster in LGVs, but much slower for HGVs.

Moderate Technical Progress

- incorporates the *Powering Future Vehicles*[3] targets for cars and buses, then continuous progress from this point, reflecting the cautious end of the spectrum of possible development paths set out in the transport paper published by the PIU[4];
- petrol and diesel hybrids together make up 10% of new car sales from 2012; diesels dominate from 2020 onwards, superseding petrol and rising to 70% of new cars by 2050;
- 3% of new cars are hydrogen fuel cells by 2020, rising to 30% by 2050;
- LPG levels as above, but superseded by 2050;
- one in ten new buses from 2010 is powered by compressed natural gas (CNG);
- the *Powering Future Vehicles* strategy recommends 600 low carbon buses by 2012. Although not fuel or technology specific, we assume that this will be largely met by the introduction of diesel

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[3] Powering Future Vehicles: The Government Strategy, Department for Transport, London, 2002

[4] Fergusson M, Analysis for PIU on Transport in the Energy Review, Cabinet Office, London, 2001

hybrid buses. This figure is about 20% of new bus registrations, but a much lower share (around 8–9%) of the total PSV fleet.

- rates of hybrids for LGVs reflect those in diesel cars;
- limited penetration of hybrids into captive truck fleets from 2020; rising to 30% of new trucks by 2040; and
- steady increase in use of CNG in HGVs, reaching 30% of new vehicles in 2050.

Rapid Progress

- early introduction of hybrids and then of fuel cells for cars, reflecting the optimistic end of the range from the PIU paper;
- 5% of new cars are fuel cell from 2010; 20% by 2020 and 100% by 2050;
- 10% petrol and 5% diesel cars are hybrids from 2010, with diesel capturing the remainder of the car fleet thereafter;
- equally rapid progress on buses and vans;
- 20% of new HGVs and PSVs are CNG powered from 2010 through 2030, reflecting its growing use in captive fleets;
- hybrids gradually penetrate the HGV fleet to reach 80% of new trucks by 2050, with the remainder running on hydrogen fuel cells.

Biomass Alternative

- some biofuel from annual crops blended into petrol and diesel as a fuel extender (see High Biofuels energy scenario in Section 4.4);
- petrol and diesel hybrids deployed as in Moderate Technical Progress;
- methanol ICEs capture 10% of new car fleet from 2010, increasing to 30% by 2030. Growing switch to methanol from diesel hybrids by 2020;
- from 2040 also 30% of new cars run on direct methanol fuel cells, rising to 50% in 2050;
- heavy diesels are progressively displaced by conventional methanol ICEs from 2010, then hybrids from 2020, and direct methanol fuel cells appearing by 2040.

Combined H_2/Methanol

- reflects hybrid and fuel cell developments of rapid progress case;
- combined with methanol substitution of biomass alternative for HGVs and, to a lesser extent, LGVs.

4.4 Energy Scenarios

The energy component of the model calculates primary energy use, and hence carbon emissions, arising from the road transport sector[5]. It takes as inputs the demands for transport fuel. The energy component of the model comprises two elements:

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[5] It is important to note that this is not a UK energy system model. It differs in two important ways. It excludes energy use required for purposes other than road transport. And it includes fuels that might be produced overseas and imported into the UK road transport sector.

- technical data on conversion of primary fuels to transport fuels (conversion efficiencies, ancillary fuel inputs etc); and
- energy scenarios containing the shares of different primary fuels used to manufacture the different transport fuels.

The outputs of the model are primary fuel demands of the road transport sector. This allows the calculation of associated carbon emissions (i.e. 'well-to-wheel' emissions).

The key components of the energy scenarios are:

- methanol, ethanol and rape methyl ester (RME) additive contents of 'conventional' liquid fuels – petrol and diesel;
- shares of different feedstocks (coal, gas and biomass) for manufacture of alcohols;
- feedstocks used for the (offboard) manufacture of hydrogen – gas, coal, fuel oil, light distillates, biomass and electricity); and
- fuel inputs to electricity generation.

There are four scenarios reflecting developments in the energy system over the next 50 years that would have significant ramifications for fuelling of the transport (and other) sectors. These may be qualitatively described as follows:

- **Business as Usual (BAU)** – there is continuing technological progress, but no sudden breakthroughs. Key decisions are made primarily on economic grounds;
- **High Renewables** – high rates of technological progress in low carbon technologies result in the rapid penetration of renewable energy sources, particularly in the generation of electricity[6];
- **Electrolytic Hydrogen** – the availability of large quantities of clean and low cost[7] electricity, plus wide availability of fuel cell vehicles, stimulates the development of hydrogen from electricity;
- **High Biofuels** – stimulated by a policy objective of wider use of alternative fuels[8], but with hydrogen vehicles not becoming widely available. There is rapid development of the use of biomass resources, in the UK and elsewhere, for liquid fuels.

We do not claim that this a complete set of all possible energy futures. However, we believe it represents a reasonable range of the key determinants of road transport energy fuels – notably the key sources for electricity, hydrogen and liquid biofuels.

The key characteristics of each scenario are described below:

Business as Usual

- additive contents of petrol and diesel remain low over the whole period to 2050 as oil derived fuels are the cheapest option;

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[6] For carbon emissions, the key issue is the carbon content of electricity. Zero carbon electricity can come from renewables, nuclear or fossil fuels with carbon sequestration. We here assume electricity is from renewables, based on the PIU Energy Review conclusion that these are likely to provide the cheapest long term source and avoid the serious environmental concerns associated with other options.

[7] The low cost of electricity for the transport sector may result from low production costs, or differential fiscal treatment.

[8] Possibly driven by oil security concerns.

- gas remains the feedstock for methanol production, and annual crops for ethanol;
- hydrogen is manufactured exclusively from natural gas; and
- gas takes a large share in the market for power generation; existing coal and nuclear stations are not replaced when they close; the share of renewables rises to 10% in 2010 and thereafter modestly to 20% by 2050[9].

High Renewables

- biofuels rapidly penetrate as additives – with a 5% biodiesel mixture and a 5% ethanol contribution to petrol by 2020;
- gas remains the feedstock for methanol production and annual crops for ethanol;
- hydrogen is manufactured exclusively from natural gas until 2040, after which intermittent renewables contribute – rising to a 20% market share in 2050; and
- renewable electricity production rises very rapidly to 30% of UK electricity in 2020 and most of UK demand by 2050. Gas takes a growing share to 2020, but falls thereafter; existing coal and nuclear stations are not replaced when they close[10].

Electrolytic Hydrogen

- biofuels rapidly penetrate as additives – with a 5% biodiesel mixture and a 5% ethanol contribution to petrol by 2020;
- gas remains the feedstock for methanol production and annual crops for ethanol;
- from 2020, hydrogen is manufactured exclusively from electricity; and
- renewable electricity production rises very rapidly to 30% of the UK total in 2020. It continues to grow thereafter in line with the same assumptions as '*High Renewables*'. However, due to the large scale use of electricity in hydrogen manufacture, the percentage contribution is somewhat lower – only 60% of total demand by 2050. Gas takes a growing share to 2030, and continues to contribute to 2050; existing coal and nuclear stations are not replaced when they close[11].

High Biofuels

- biofuels rapidly penetrate as additives – with a 5% biodiesel mixture and a 5% ethanol contribution to petrol by 2020;
- woody biomass takes over from gas as the feedstock for methanol production, and from annual crops for ethanol, by 2020;
- hydrogen (to the limited extent it is used) is manufactured initially from natural gas, but increasingly from woody biomass; and
- gas takes a large share in the market for power generation; existing coal and nuclear stations are not replaced when they close; the share of renewables rises to 10% in 2010 and thereafter modestly to 20% by 2050[12].

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[9] Based on the PIU Energy Review 'World Markets' scenario.
[10] Based on the PIU Energy Review 'Global Sustainability' scenario.
[11] Based on the PIU Energy Review 'Global Sustainability' scenario.
[12] Based on the PIU Energy Review 'World Markets' scenario.

4.5 Combined Scenarios

Using these three sets of scenarios to reflect the main components of the transport energy system, we were able to use different permutations to illustrate a very broad range of possible outcomes. The permutations which we have modelled are summarised in the table which follows:

Scenario Name	**Demand Scenario**	**Technology Scenario**	**Energy Scenario**	**Notes**
BAU with Central Demand	Central	Limited Progress	Business as Usual	Business as usual case
Worst Case	World Markets	Limited Progress	Business as Usual	Worst case modelled – but does assume technical progress
Central Case	Central	Moderate Progress	Business as Usual	Central demand case with modest technical progress
High Demand Case (World Markets)	World Markets	Moderate Progress	Business as Usual	High demand case with modest technical progress
Low Demand Case (Global Sustainability)	Global Sustainability	Moderate Progress	Business as Usual	Lowest demand case with modest technical progress
Vehicle Innovation with BAU Energy	Central	Rapid Progress	Business as Usual	Rapid technical progress in vehicles, but little change in energy supply system
Vehicle Innovation with Renewables	Central	Rapid Progress	High Renewables	Rapid technical progress in vehicles, plus high input of renewables to energy supply
Vehicle Innovation with Electrolytic Hydrogen	Central	Rapid Progress	Electrolytic Hydrogen	Rapid technical progress in vehicles, with hydrogen generated by electrolysis
Vehicle Innovation with Biomass H_2	Central	Rapid Progress	High Biofuels	Rapid technical progress in vehicles, with hydrogen generated from biomass
High Biomass Case	Central	Biomass Alternative	High Biofuels	Progress towards hydrogen fuel cells falters, so methanol from biomass is progressively substituted as a road fuel. NB ethanol could give similar results to methanol
Biomass Combination	Central	Combined H_2/Methanol	High Biofuels	Combines elements of previous two: rapid technical progress in most vehicle classes using biomass hydrogen, plus methanol from biomass in goods vehicles. NB ethanol could give similar results to methanol

5. What the Scenario Model Shows

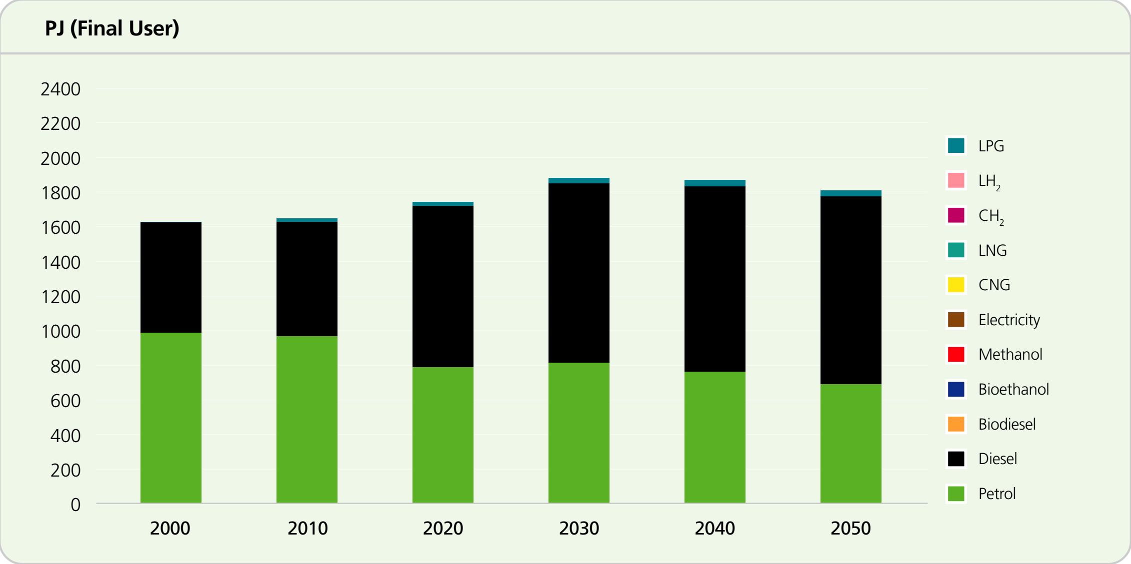
In the sections which follow, selected results of the modelling exercise are presented and briefly characterised. Three main parameters are considered in these descriptions: final end user fuel consumption (i.e. 'tank-to-wheel') for each fuel; the primary fuel demand required to supply this fuel (i.e. 'well-to-wheel'); and the CO_2 emissions which result expressed as million tonnes of carbon (MtC). This reflects the order in which the model calculates the results.

However, in the interests of space, not all three sets of results are presented for each scenario and only the most salient points are presented. In the first case, for example, where petrol and diesel remain the completely dominant fuels, the trend in primary fuel supply and carbon emissions, not surprisingly, closely follows the trend in final user energy. In some other cases, the primary demand is identical in several scenarios because the technology and demand scenarios are the same; it is the energy system which determines differences in outcome between these cases, and hence the primary energy demand and emissions are highlighted instead.

5.1 Characterisation of the Modelling Results

The sections which follow briefly and selectively characterise the main features of the results of each modelling run, in terms of end user energy demand, primary fuels used, and resultant CO_2 emissions. The results are presented in detail in Annex 2 to this report.

5.1.1 BAU with Central Demand

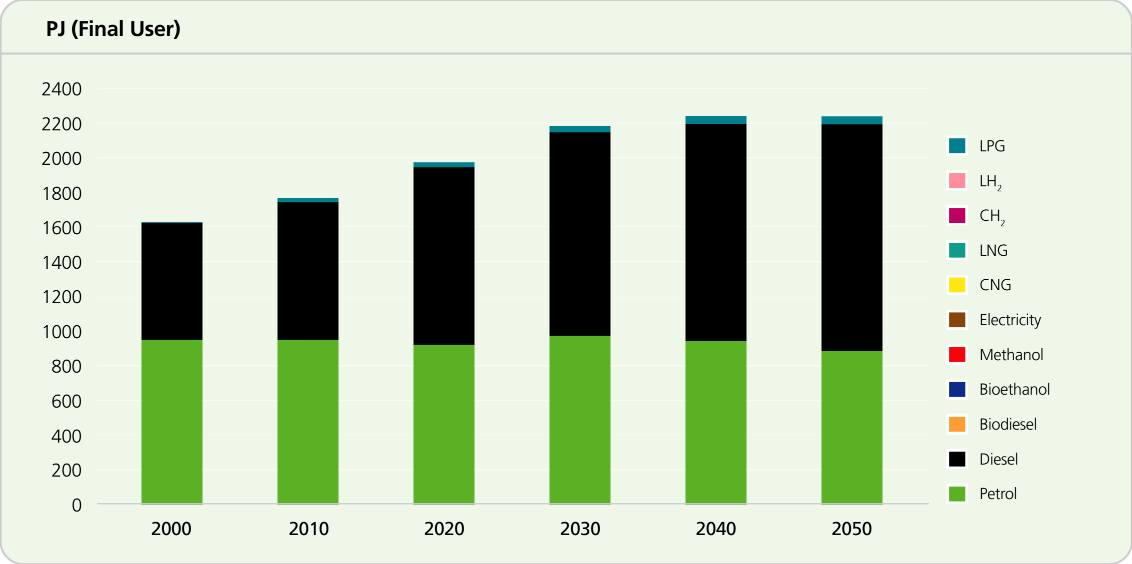


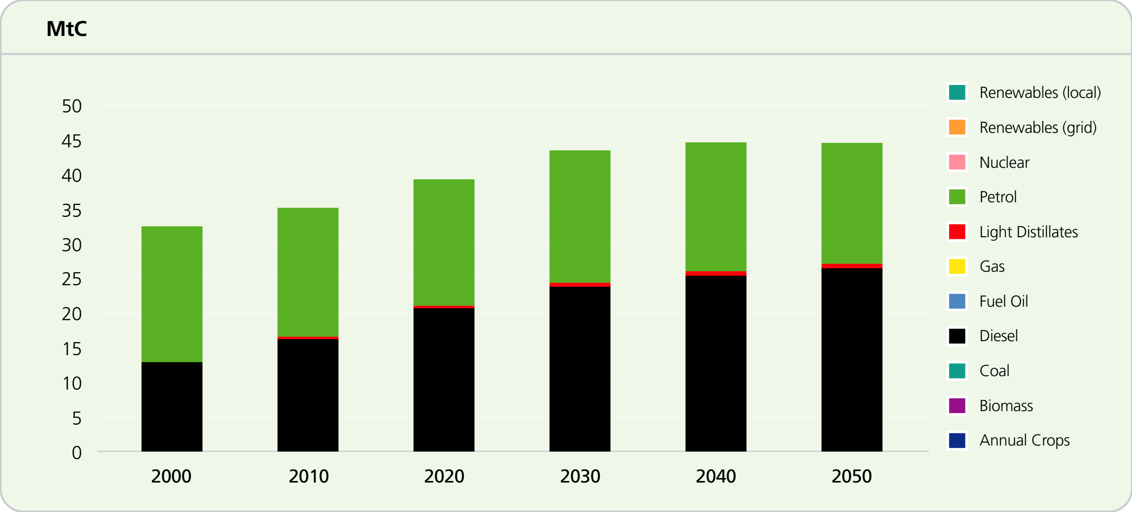
BAU with Central Demand

- continues fully oil-dependent;
- petrol demand gradually reduces as demand shifts to diesel;
- technical progress outstripped by transport demand 2010–2030, then levels off;

- voluntary agreement reduces car energy demand in 2010, but rises thereafter;
- improvements in cars more than offset by increases elsewhere, mainly in goods vehicles;
- goods vehicles constitute a growing share of energy demand; and
- CO_2 follows a similar trajectory.

5.1.2 Worst Case

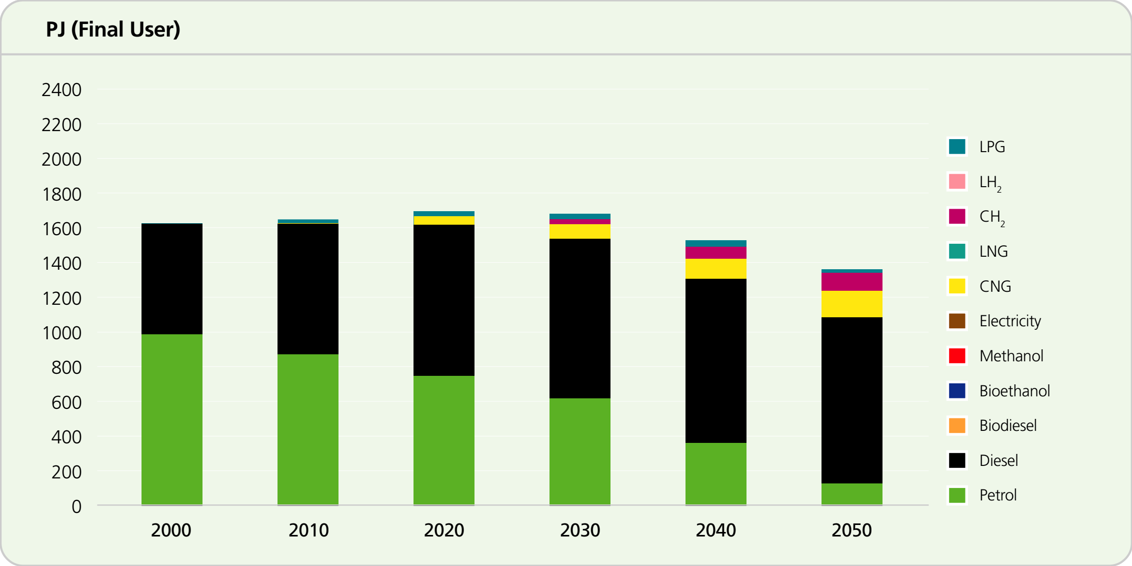


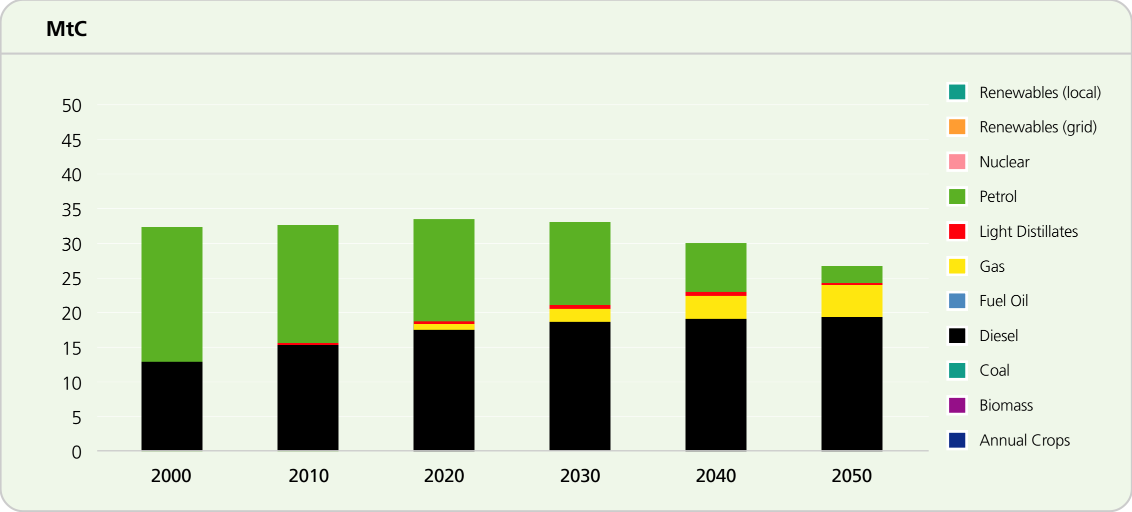


Worst Case

- continues fully oil-dependent;
- petrol demand level to 2040, then falls slightly, as demand shifts to diesel;
- technical progress outstripped by transport demand until after 2040, then levels off;
- energy demand rises consistently in all classes, except that car energy peaks by 2050;
- goods vehicles constitute a growing share of energy demand; and
- CO_2 follows a similar trajectory.

5.1.3 Central Case

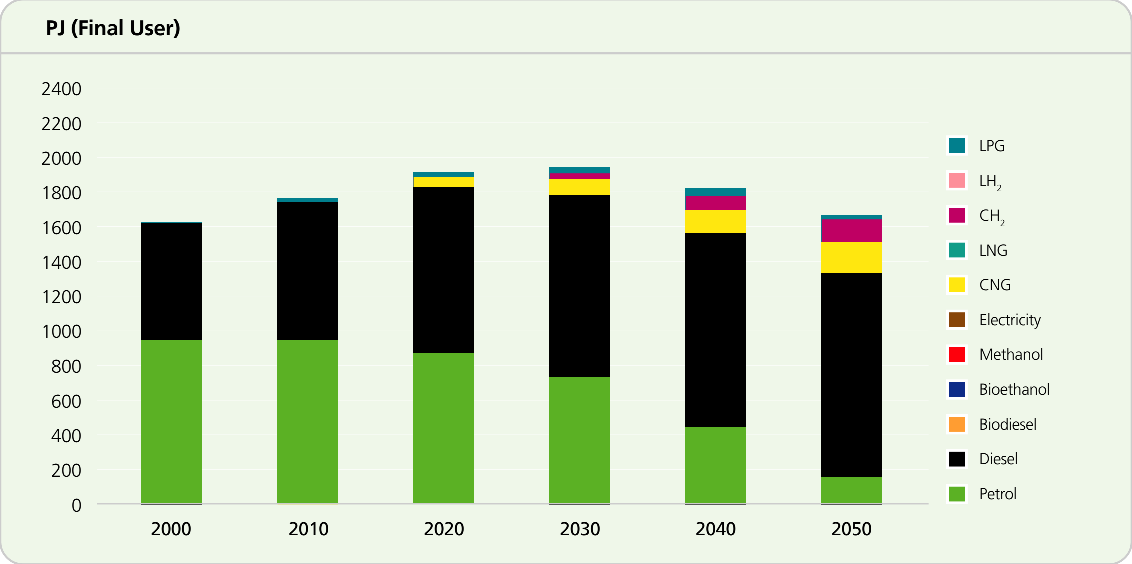


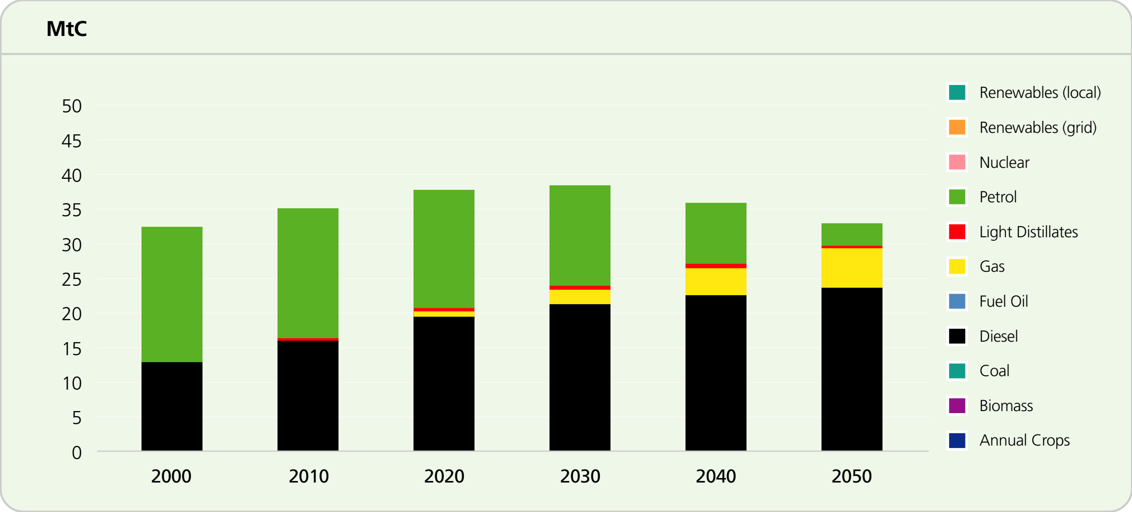


Central Case

- continues largely oil-dependent;
- petrol demand more rapidly shifts to diesel;
- growing use of gas, and latterly hydrogen;
- goods vehicles constitute a growing share of energy demand;
- energy demand curbed earlier (2020 or soon after);
- CO_2 follows a similar trajectory;
- modest reduction in net CO_2 by 2040 relative to 2000.

5.1.4 High Demand Case (World Markets)

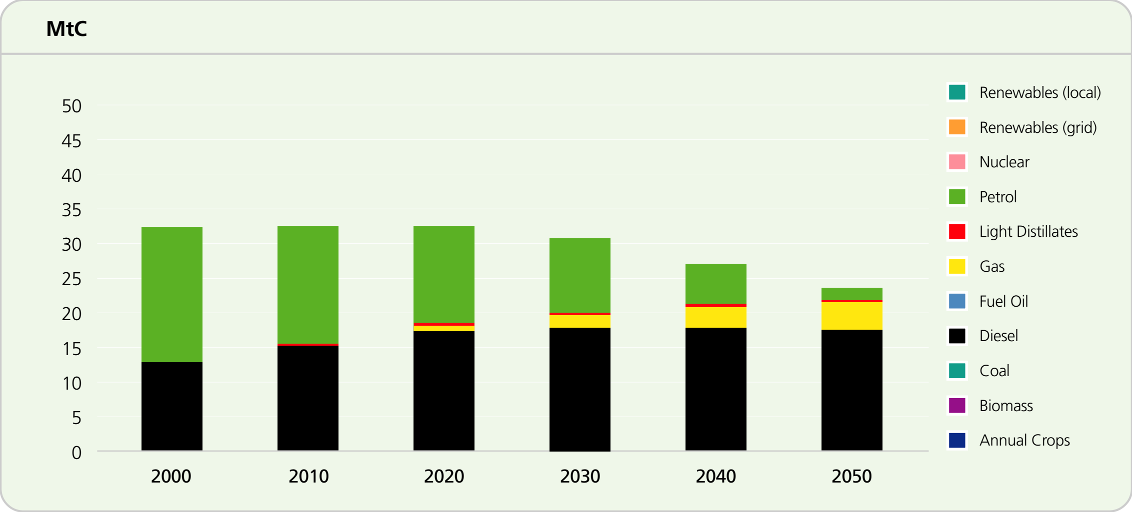




High Demand Case (World Markets)

- fuel mix as previous, but with more marked contribution from gas by 2050;
- energy demand and CO_2 both rise sharply, especially up to 2020;
- no return even to 2000 levels by 2050.

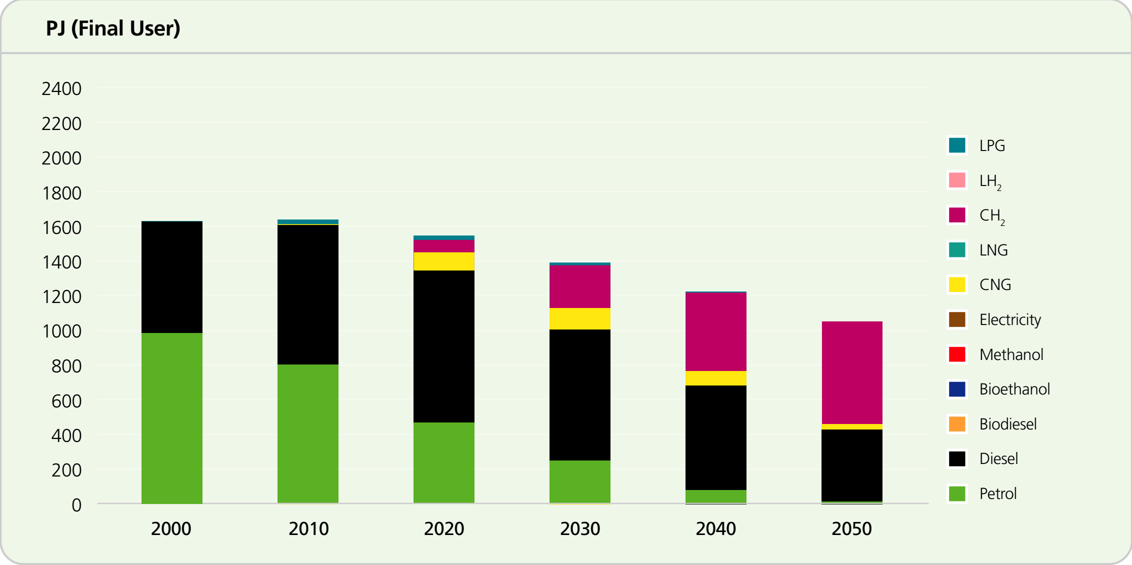
5.1.5 Low Demand Case (Global Sustainability)

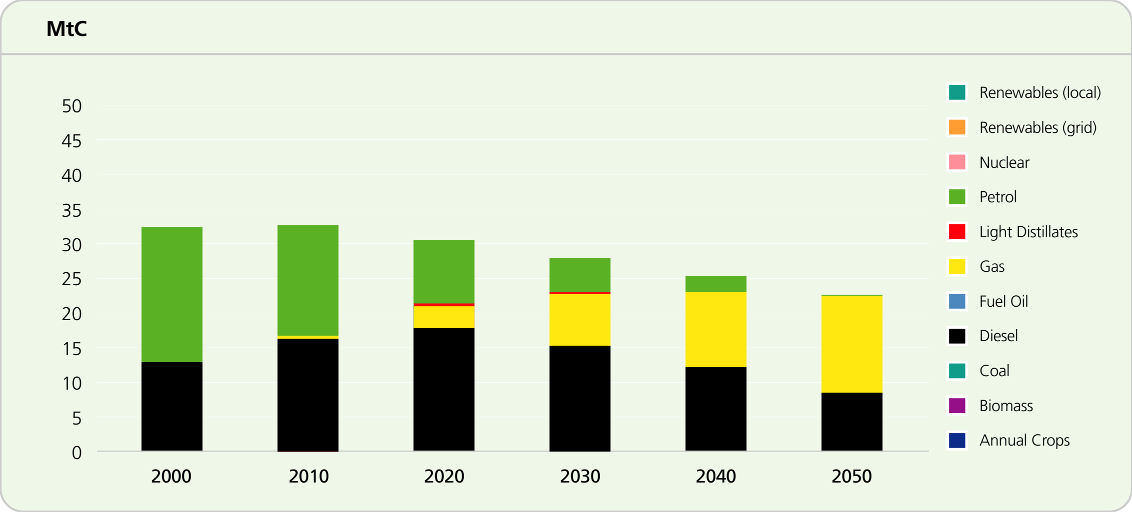


Low Demand Case

- lower demand leads to lower energy use profile, after small initial rise;
- falling energy demand and CO_2 after 2020;
- energy demand and CO_2 down more than 25% in 2050 relative to 2000; and
- energy demand and CO_2 in 2050 28% lower than in World Markets case.

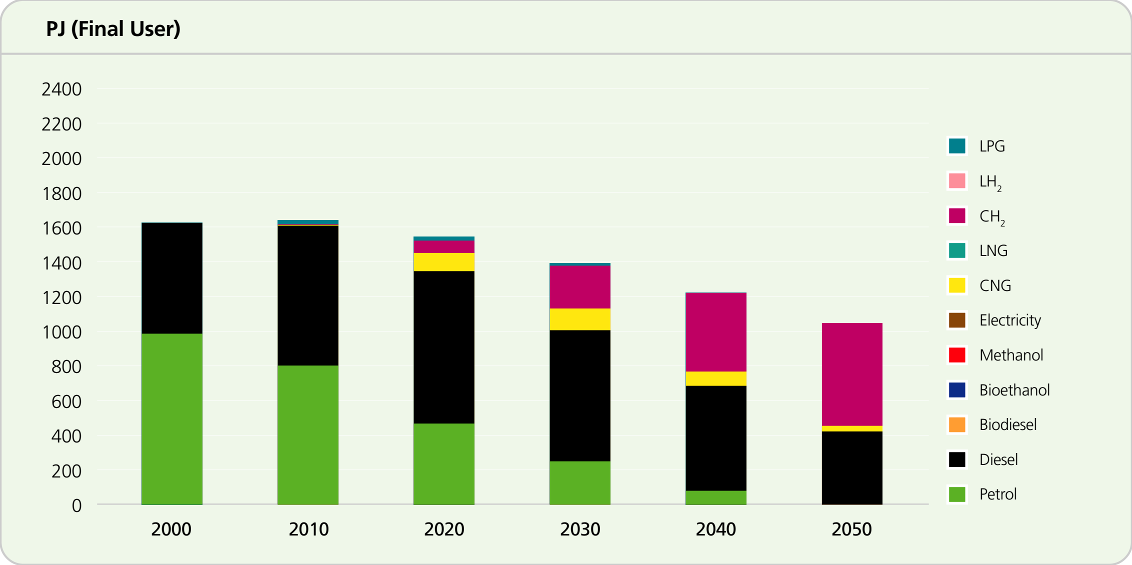
5.1.6 Vehicle Innovation with BAU Energy

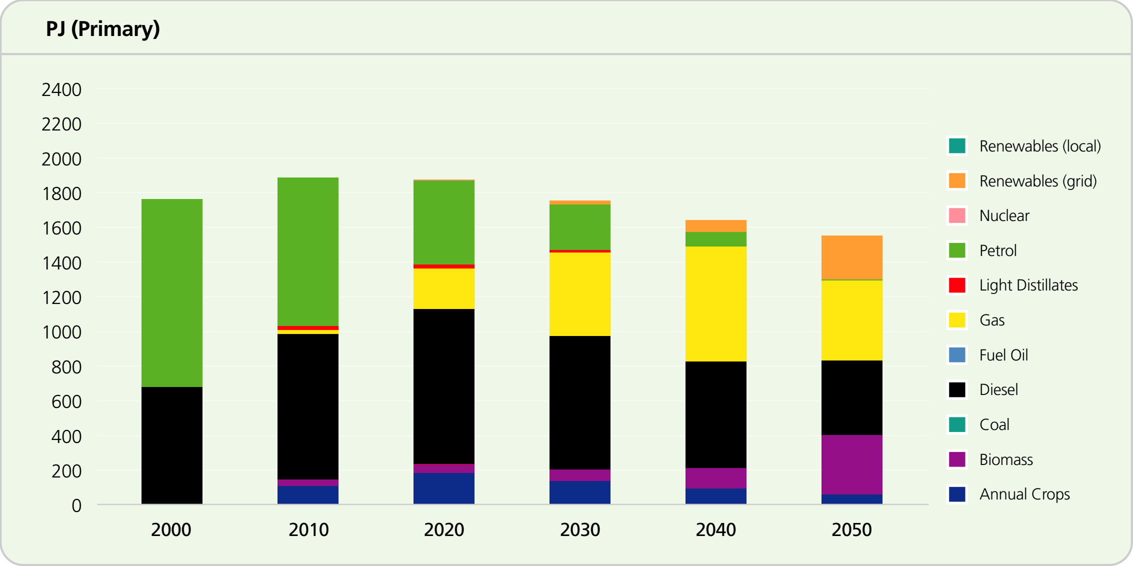


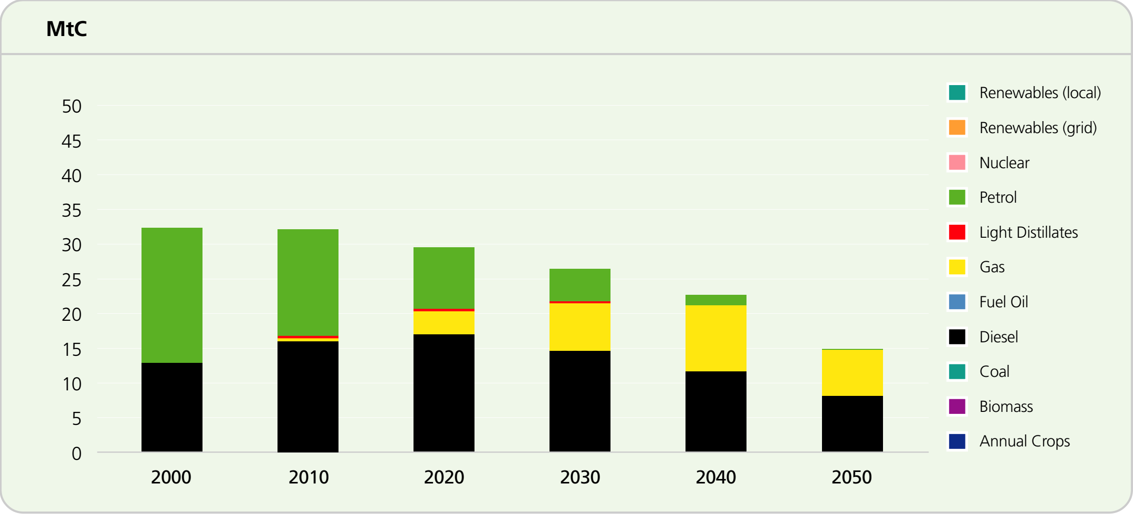


Vehicle Innovation with BAU Energy

- more radical shift away from petrol, and subsequently also diesel;
- substituted by gas, then predominantly hydrogen;
- much less progress in goods than personal travel: goods account for 50% transport carbon by 2050;
- gas initially used as a road fuel in its own right, but then increasingly as a feedstock for hydrogen;
- Gas supersedes petroleum as main fuel feedstock by 2040;
- energy demand in steady decline by 2020; and
- CO_2 on similar trajectory owing to greater energy efficiency combined with shift to gas – reduced almost to two-thirds of 2000 level by 2050.





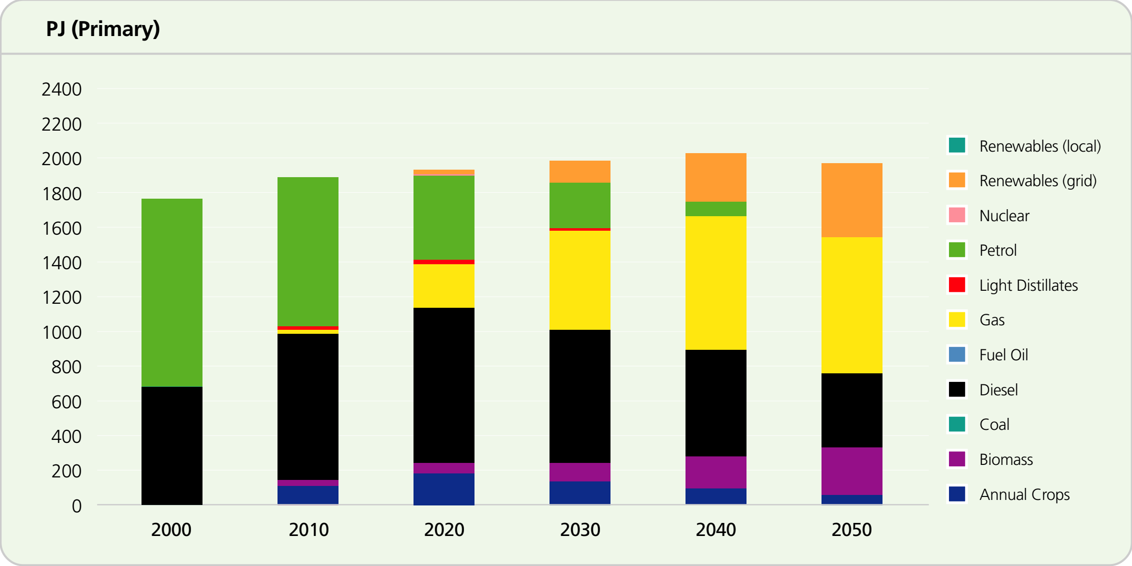


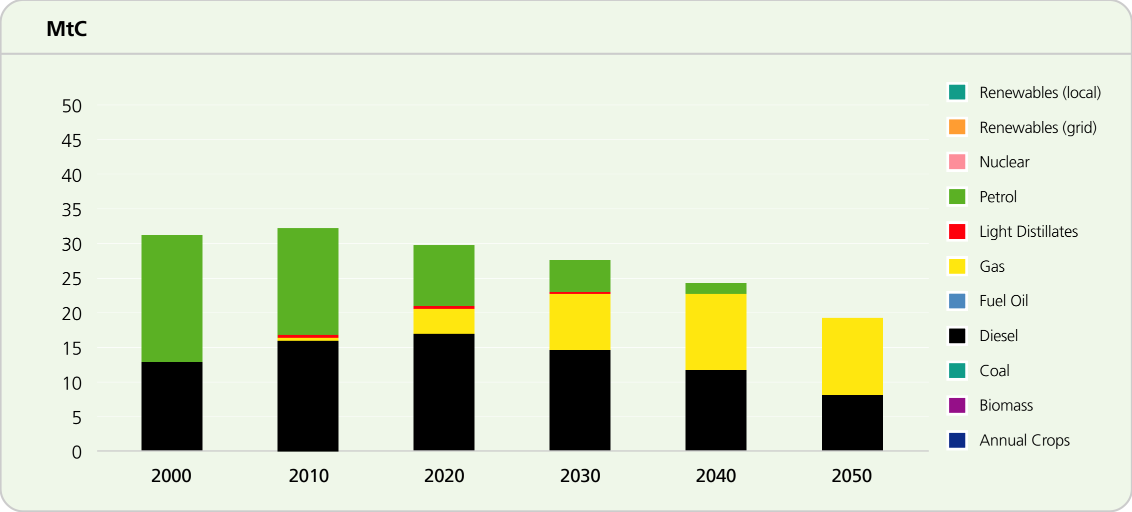
5.1.7 Vehicle Innovation with Renewables

Vehicle Innovation with Renewables

- as previous, a radical shift away from petrol, and subsequently also diesel;
- substituted partly by gas, but then mainly hydrogen;
- gas matches petroleum as feedstock by 2040;
- growing and almost comparable contributions from renewables and biomass by 2050;
- much greater diversity of primary supply sources;
- primary energy demand in steady decline by 2020/2030, but less so than previous cases owing to high renewable and biomass inputs;
- however CO_2 falls even more rapidly owing to shift away from fossil sources – reduced to under half of 2000 level by 2050; and
- much less progress in goods than personal travel: goods over 50% transport carbon by 2050.

5.1.8 Vehicle Innovation with Electrolytic Hydrogen

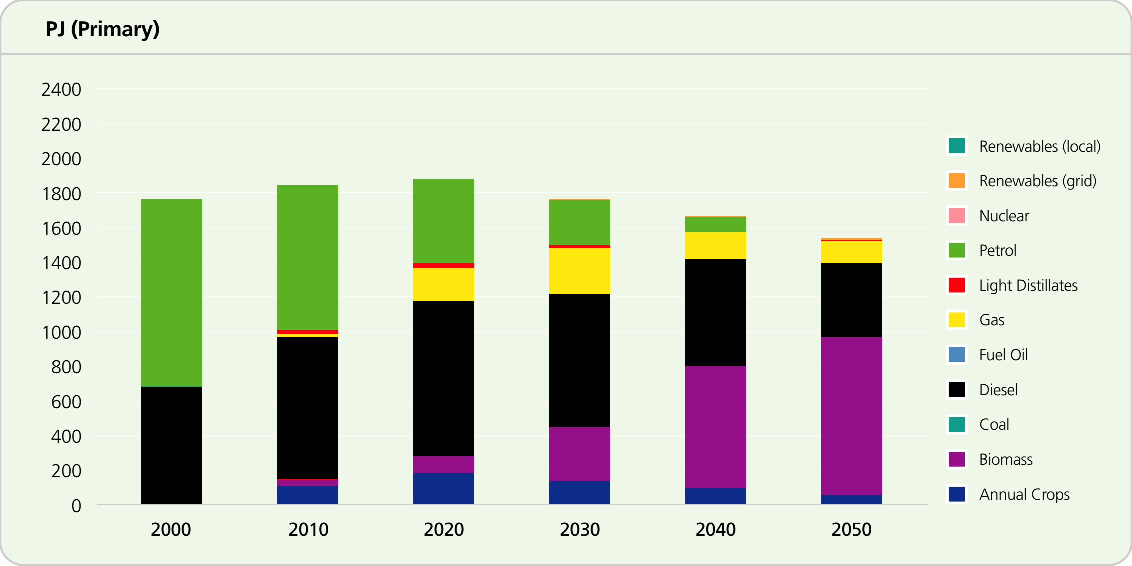


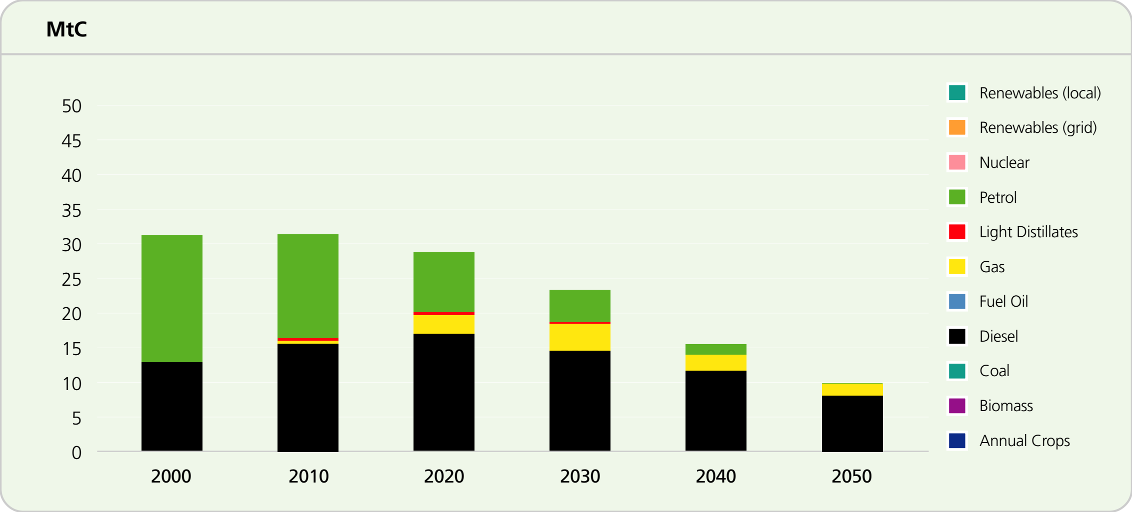


Vehicle Innovation with Electrolytic Hydrogen

- as previous, a radical shift away from petrol, and subsequently also diesel;
- substituted by gas and then mainly hydrogen as road fuels;
- gas demand for electricity generation grows, but also renewables and some biomass;
- diversity of primary supply sources, but gas becomes dominant;
- primary energy demand continues to grow until 2040s, owing to high generation;
- transmission and transformation losses in the electricity to hydrogen pathway;
- CO_2 falls owing to shift away from fossil sources – but less so than in previous case; and
- CO_2 reduced to below 60% of 2000 level by 2050.

5.1.9 Vehicle Innovation with Biomass Hydrogen

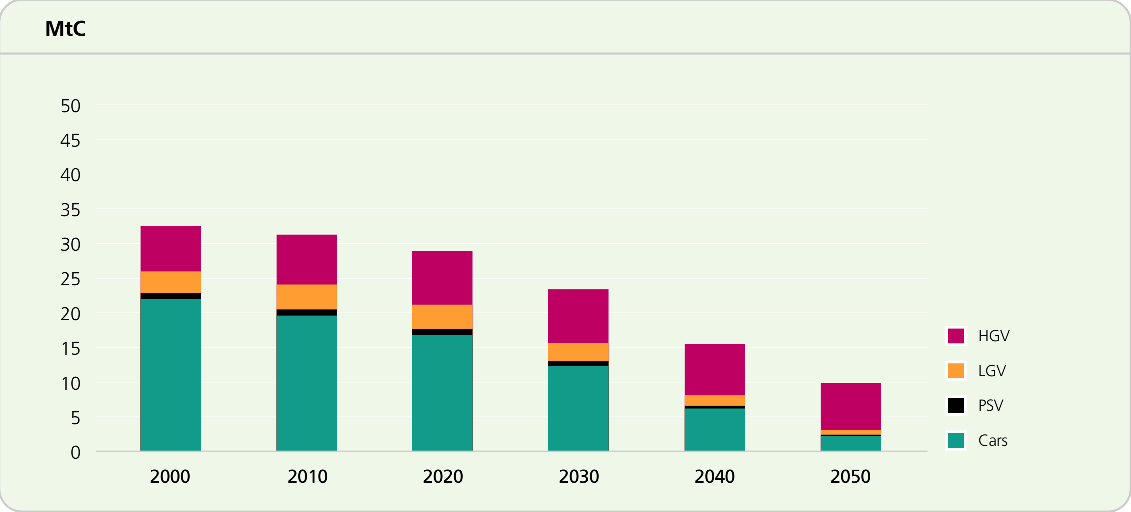




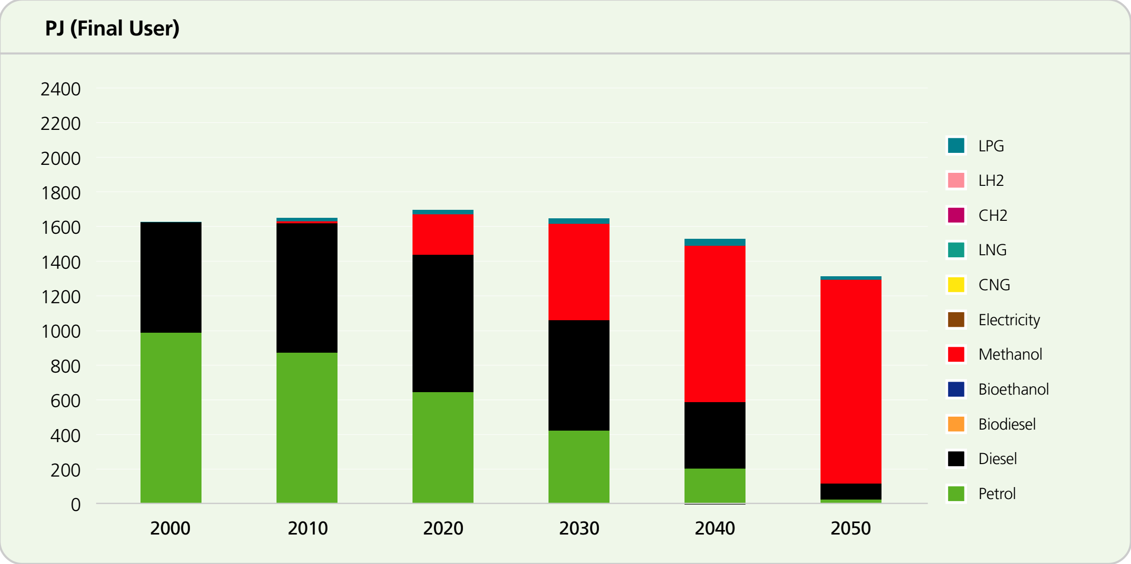
Vehicle Innovation with Biomass Hydrogen

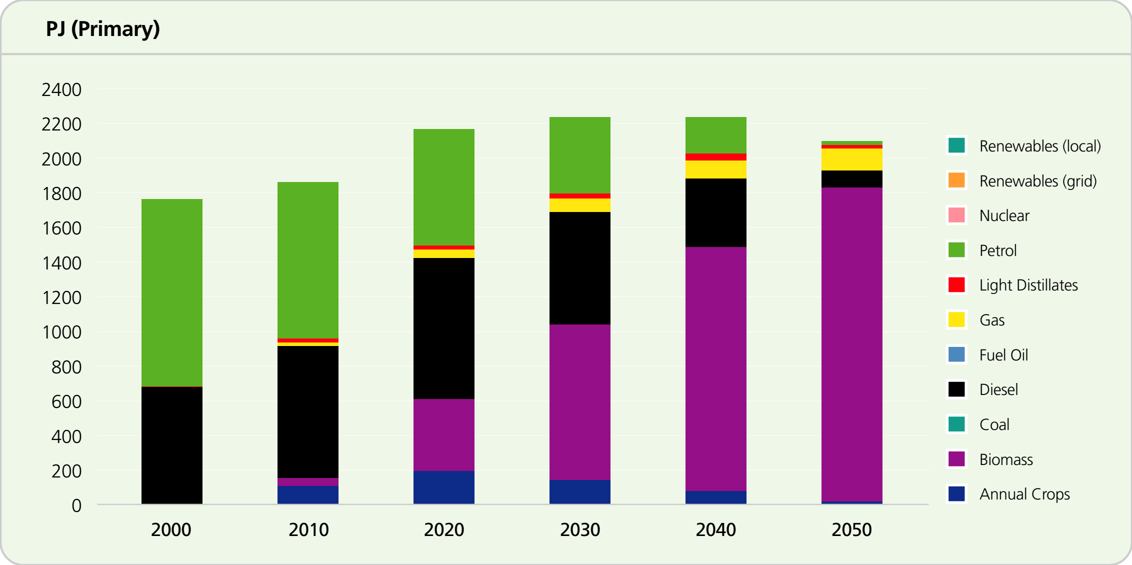
- as previous, a radical shift away from petrol, and subsequently also diesel;
- diesel continues as significant source of fuel, mainly for HGVs, but biomass becomes predominant;
- primary energy demand grows modestly until 2020s, then falls;
- CO_2 falls dramatically owing to shift away from fossil sources for most vehicle types (see below);
- CO_2 reduced to 30% of 2000 level by 2050; and
- goods traffic accounts for nearly three-quarters of transport carbon by 2050.

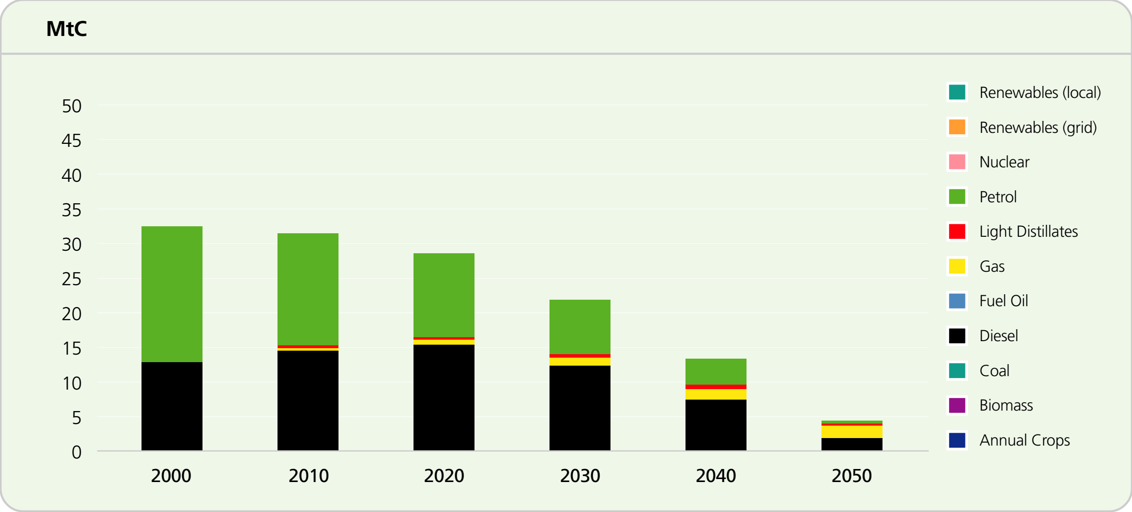
The additional chart included below presents the same carbon emissions results, but disaggregated by vehicle type rather than fuel. This illustrates clearly the potential consequences of technical progress in light vehicles and buses not being matched by improvements in HGVs. In this scenario, HGVs show very little change in total fuel use and CO_2 emissions, and as a result account for half of all road transport carbon emissions by 2040, and more thereafter.



5.1.10 High Biomass Case



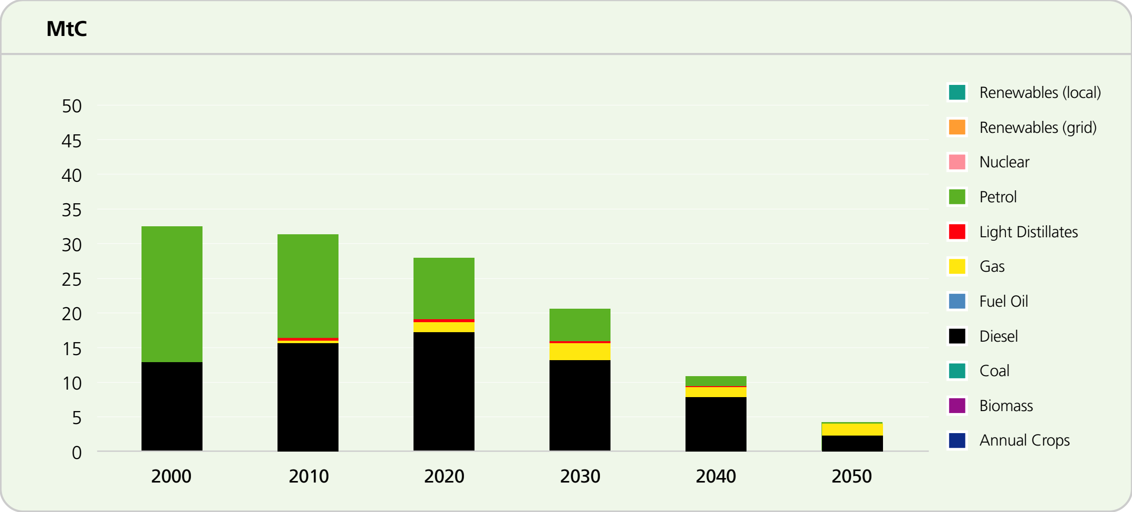




High Biomass Case

- a radical shift away from petrol, and subsequently also diesel;
- substituted predominantly by blended fuels and then methanol;
- feedstock is biomass, initially annual crops but thereafter mostly woody;
- primary energy demand rises to at least 2020 owing to high biomass demands;
- declines thereafter as technical progress supplements shift to biomass;
- however CO_2 falls more rapidly than in all previous cases owing to radical shift away from fossil sources across all vehicle types; and
- CO_2 reduced to under 20% of 2000 level by 2050.

5.1.11 Biomass Combination



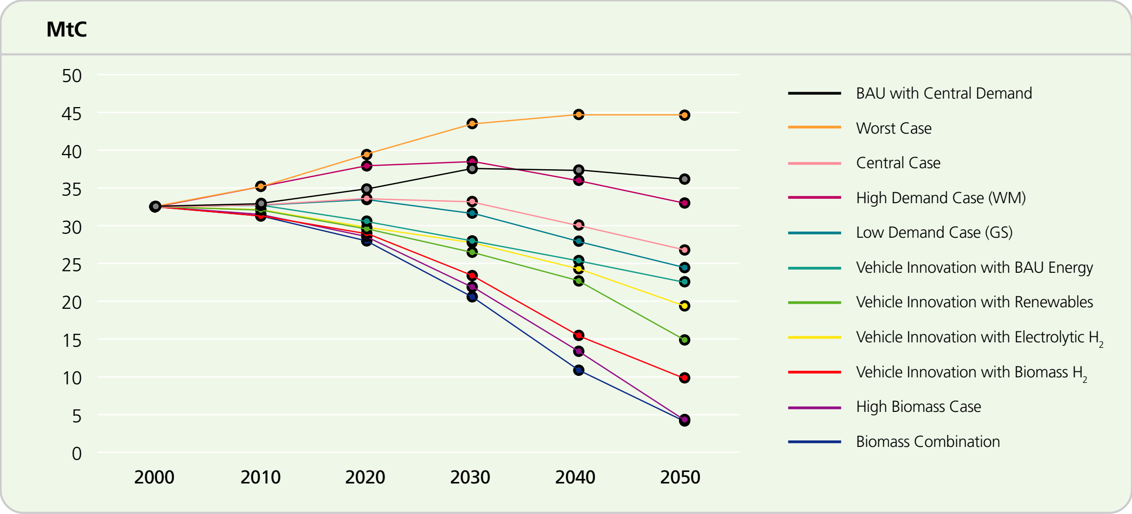
Biomass Combination

- combines key features of previous two scenarios – use of biomass hydrogen plus methanol;
- biomass becomes predominant fuel source in medium to long term; and
- most rapid and deepest reductions in CO_2 emissions in medium term owing to early innovation across all vehicle types.

5.2 Overview of the Scenarios

5.2.1 Carbon Emissions Profiles

The figure below summarises the range of road transport carbon emission scenarios outlined in the previous sections. Clearly these illustrate a huge range of different outcomes, according to the various permutations of transport demand, vehicle technology and energy supply system applied.



Arguably they fall into four groups, as follows:

- the Worst Case scenario (although it is not in fact the worst conceivable case) stands out as leading to dramatic further increases in carbon emissions;
- the Business as Usual and the World Markets demand scenarios both result in continuing growth in carbon emissions in the short to medium term, but a decline thereafter. However, in neither case do carbon emissions return to 2000 levels even by 2050;
- a further group of five scenarios are characterised by modest changes in emissions levels in the short to medium term, followed by significant reductions in the longer term. These are characterised by modest to rapid technical progress; low or central traffic growth projections; and a range of energy system configurations encompassing both Business as Usual and High Renewables cases; and
- the most dramatic reductions in the medium and long term are achieved where fuels are made increasingly from woody biomass. This assumes fairly rapid changes also in the fuel and vehicle configurations, but several different pathways appear technically possible.

It should be borne in mind that these are the carbon emissions from the transport system alone. As explained above, there are opportunity costs for carbon emissions reductions associated with the use of both renewable electricity and biomass. These issues are addressed in Sections 6 and 7.

5.2.2 Comparisons of Different Scenarios from the Perspective of Energy Security

Risks Associated with Gas

None of the scenarios carries significant risks associated with gas. Gas use for transport is only significant in the 'rapid technical progress' scenarios, where it is used initially directly and then to generate hydrogen (either directly by reformation or via power generation). Even in these cases the resulting gas demand is not large when compared with what is likely to be demanded from other demand sectors – domestic, services and industry. Gas vehicles could well be bi-fuelled. Furthermore, any hydrogen production could be designed to draw on a range of different fuels quite quickly in the advent of external disruption to gas supplies.

Nevertheless, there are obvious concerns about heat, power and transport demands for energy all being increasingly dependent on imported gas. These would tend to indicate that hydrogen is not unambiguously good from an energy security viewpoint whilst hydrogen production is primarily gas-dependent (either directly or via electricity).

Long Term Risks to Oil Supply

Scenarios with only limited or modest rates of progress in transport technology offer little insurance against the concentration of power in the hands of a few oil exporters. Continuing improvements in energy efficiency assist in all scenarios, and scenarios with lower demand for transport services reduce demand further. But without more fundamental technical change demand for oil remains above 1000 PJ in 2050. A combination of rapid demand growth in the transport sector and limited technical progress would lead to ever increasing demand for oil to 2050, an outcome which would be accompanied by very high risks.

In scenarios with rapid technical progress to fuel cells or biofuels, demand for oil could fall to 25% of current levels or less by 2050. In these cases, cartel power and oil risks would presumably be negligible. The impacts of these changes on oil demand are most marked after 2020, but significant reductions in demand for oil, principally through use of more efficient vehicles, are possible before then.

Risks of Sudden Oil Disruption

In contrast, none of the scenarios provides much insurance against sudden disruption of oil supplies in the short term, beyond the possibilities of bi-fuelling, etc discussed above. Oil remains the dominant fuel in the transport sector out to 2020 or beyond in all scenarios; in no cases are there readily available options for a rapid shifting away from oil based fuels. More radical scenarios could be devised, but do not currently appear very plausible; this reflects the considerable degree of inertia in the system and the lack of an alternative, as yet, which could quickly and easily be introduced on a large scale. In these circumstances, policy responses will therefore need to focus on the security of infrastructure, diversity of commercial arrangements and international co-operation.

In the second quarter of the century, the technological options that assist in reducing long term oil demand also provide some greater security against short term threats. Use of hydrogen would allow flexibility to use a range of primary energy sources – principally gas, indigenous or imported biomass and primary electricity. In this sense, the option of electrolytic hydrogen from an expanded electricity sector provides additional security. Indigenous biomass and primary electricity provide the only options secure against simultaneous oil and gas threats. Therefore the high biomass scenarios give the best results from the point of view of transport sector carbon emissions and transport fuel security.

Overall Conclusions on Oil Security

There is an obvious link between transport fuel demand and security of energy supply. In broad terms, options which improve the environmental performance of the road transport sector tend also to be helpful in terms of energy security (although the converse is not necessarily true).

Beyond this, however, we did not feel able to come to any clear estimate of the extent to which considerations of fuel security will reinforce the drivers for technical change in the sector. Such an estimate is beyond our remit and our expertise; but in exploring this issue we have concluded that a precise delineation of the nature, extent and timing of the risks associated with oil supply is lacking, as was an adequate framework for risk management within which to draw clear policy conclusions. This is arguably an area that would merit further consideration.

6. Hydrogen from Renewable Electricity

6.1 'Well-to-wheel' Emissions and the Optimum Use of Renewable Electricity for Carbon Reduction

Initial uses of gaseous hydrogen as an energy carrier are likely to be in road transport. This is the market where liquid (or other high energy density) fuels have a significant advantage. Whilst fuel cells in stationary applications can use natural gas, those most suitable for automotive use require hydrogen.

However, under current circumstances in the UK, there are no carbon benefits in producing hydrogen for use in transport from renewable electricity. Each kilo watt hour (kWh) of renewable electricity produced saves approximately 100 grams of carbon (gC) when used to avoid the use of gas in power generation[13]. If the electricity is used instead to manufacture hydrogen for transport use in a fuel cell vehicle, we estimate the carbon saved will be only 60 gC/kWh[14]. There are carbon benefits because fuel cell vehicles are more efficient than their petrol equivalents and because the carbon content of oil is higher than that of gas. But the benefits of using renewable electricity to displace demands for fossil electricity are larger, mainly because of the relatively low efficiency of fossil fuelled power generation. Thus, for as long as fossil fuels remain the marginal fuels for power generation used at current efficiencies, it is not advantageous in environmental terms to use renewable electricity for hydrogen production.

The problem can be addressed from the other direction by posing the question '*For there to be carbon benefits in using electricity to produce hydrogen for vehicle use, what needs to be the nature of the marginal power generation?*'.

Making the same assumptions as above, the use of electrolytic hydrogen for vehicles has carbon benefits when the electricity is from sources that generate with carbon emissions of 60 gC/kWh or less.

There are only four types of generation that have the prospect of achieving this:

- renewable sources;
- nuclear power;
- fossil fuel sources with high levels of carbon sequestration and disposal; and
- gas generation at efficiencies exceeding 80%, which means in conjunction with CHP.

From the point of view of this analysis, renewable, nuclear and fossil plus carbon sequestration are broadly equivalent 'carbon free options'[15]. In the following analysis, we consider primarily renewable sources for three reasons:

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[13] This is a conservative assumption based on modern combined cycle gas turbine (CCGT) as the long run power generation option of choice – a higher carbon-reduction figure applies, if some coal-fired generation is avoided. Low carbon technologies (renewables and nuclear) tend to have lower operating costs, and therefore are currently used for baseload. Whilst it is possible to conceive of zero carbon options operating off baseload, this is unlikely in the short and medium term.

[14] This is on the basis of comparing fuel cycle emissions of a hydrogen fuel cell and a diesel hybrid, at efficiencies expected to be achievable in the next decade. See Annex 1 for the assumptions and details of these calculations.

[15] In a full fuel cycle 'well-to-wheel' analysis there may be some carbon emissions from fuel processing activities, but these are generally small compared to fossil fuel generating options.

- renewables are generally considered to be more likely to prove cost-effective as sources of power generation in the medium and long term[16];
- many of the environmental issues and financial costs associated with nuclear power and carbon dioxide disposal are unresolved and highly controversial; and
- some renewables may offer additional options for economic hydrogen production associated with their intermittency and remote location (see Section 6.2).

However, for much of what follows, discussions about the use of renewables for hydrogen production apply equally to all zero carbon sources.

Therefore we conclude that there will only be carbon savings from using electricity for hydrogen vehicles when the dominant technology is renewables or if the dominant gas technologies are CHP.

6.2 The Conditions under which Carbon Reduction is achieved by Using Renewables for Hydrogen

In light of the discussion in the previous section, it follows that for there to be a net carbon benefit from using renewable hydrogen in transport, hydrogen made from renewable electricity needs to be available without it being at the expense of other energy uses of renewable electricity. This might be the case in the following circumstances:

- **excess renewables capacity** – where the production of low carbon electricity (for example from renewables and gas CHP) is so large that it exceeds the non-hydrogen electricity demand sufficiently often to be able to produce significant quantities of hydrogen from the excess power. This makes low carbon power the short-run marginal source of supply for electricity and therefore for electrolytic hydrogen;
- **additional effective market demand for renewable hydrogen** – where the transport use of hydrogen gives rise to additional demand for renewables (or other low carbon) hydrogen, supporting additional investment in renewables. Under these conditions new grid connected renewable electricity sources are developed and utilised specifically as a result of an additional market in transport. This effectively makes renewables the long-run source of hydrogen supply; and
- **renewable hydrogen off-grid** – where there is potential for the economic production of hydrogen from renewable electricity sources off-grid (and this is more economic than grid connection). In this case new renewable capacity off-grid is stimulated by the existence of the transport demand for hydrogen.

Initial thoughts on the conditions for, and prospects and timing of, each of these situations to apply are examined below.

6.2.1 Hydrogen from Excess Renewables Capacity

At some point in the future expansion of renewable electricity, the output of intermittent renewables is likely to exceed grid demand at certain times. This will initially be the case when the renewables supply is

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[16] See e.g. PIU Energy Review, table 6.1.

high at times of low grid demand (for example windy summer nights). Under these conditions, the 'excess' renewable energy would be available much more cheaply than usual, and so production of hydrogen would be potentially useful as a cost-effective energy system storage technology. The generation of electrolytic hydrogen would in these circumstances be 'zero carbon' because it would not be at the expense of displacement of fossil electricity.

However the energy supply position is crucial in establishing when, and to what extent, this situation is likely to arise in practice. The Great Britain electricity system minimum demand is about 20 GW and typical summer night demand is 25 GW. Intermittent renewable supply would therefore have to rise to a higher figure than this for hydrogen production from 'excess renewable electricity' to occur at any time[17].

Wind power (including offshore) seems the most likely renewable source to supply large amounts from intermittent supply in the medium term. Assuming a typical load factor of 40% (3.5 TWh/year/GW), 25 GW of wind power would generate about 90 TWh/year, i.e. about 25% of GB electricity demand. Even in optimistic scenarios for renewable energy, this would only be achieved sometime after 2020[18].

However, even at this penetration of wind power, the amount of 'excess renewable electricity' would be very modest, in the context of the amount of transport hydrogen which would be needed. In the scenarios described above for rapid change including the rapid expansion of renewables, we project a possible use of 600 PJ/year of hydrogen by 2050. This would require 230 TWh/year of electricity, equivalent to approximately 70 GW of wind capacity, i.e. more than a doubling of the existing system capacity. Whilst this is not impossible, it clearly presents a large investment challenge.

The above calculations also assume that hydrogen is used in high-efficiency fuel cell vehicles. If fuel cell technology were not available at an affordable price for vehicle users, and if hydrogen were instead being used in internal combustion engines, the incremental electricity requirement for hydrogen production would be 430 TWh/year, i.e. more than the whole of current electricity demand.

The long term potential of intermittent renewables (in particular wind and solar) is very large – sufficient to supply the whole of UK energy demand. Even though these sources are intermittent, that may not prevent them taking a very large market share. A number of strategies may be adopted to address intermittency including:

- geographical dispersal so that supply sources have uncorrelated intermittency;
- better control systems to switch the timing of interruptible demands;
- maintaining non-renewable supplies for emergency use;
- international interconnection to allow greater trading; and
- use of more energy storage.

Hydrogen may have a key role to play in the last of these, as a fuel that can be used in either transport or power generation, thereby allowing the electricity sector to benefit from the large and widely-

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[17] Low carbon marginal electricity might occur with a smaller intermittent renewable component if there are significant other low-carbon (non-intermittent) generation sources, e.g. biomass, fossil fuels with carbon sequestration and nuclear. This would allow 'zero carbon marginal electricity' onto the system somewhat earlier. However, these options are likely to be in competition for investment with intermittent renewables.

[18] In none of the scenarios considered by the PIU Energy Review is such a position reached by 2020.

dispersed energy stores associated with the transport sector (at depots, filling stations and in vehicle fuel tanks). Some other options, by smoothing the demand for power, would militate *against* the availability of hydrogen from 'excess renewables'.

The penetration required for surplus renewable supplies (i.e. over and above baseload power demand) to make any significant contribution to transport fuels seems from this analysis unlikely to occur before 2020. It will take longer still for the contribution to be substantial. And the carbon benefit of any contribution would be reduced if the hydrogen generated were not to be used in efficient fuel cells.

However, the timescales within which the growth of renewables would be available to support renewable hydrogen for transport would be improved if the gas-CHP share of the energy mix were also to increase – bearing in mind that, in principle, it would be possible for renewables and gas-CHP to provide all new electricity generating capacity over the next 20 years[19]. And in the medium term (20–30 years) there is very considerable scope for additional CHP, especially if stationary fuel cell technology becomes available.

However, the task for renewables and CHP to supply not only existing demands (buildings and industry), but also new transport demands is far more challenging. CHP capacity is constrained by the availability of suitable heat loads, and these are expected to diminish in the long term as buildings and industrial processes become more efficient. Large new demands for electrolytic hydrogen for vehicles would probably require gas fired power from non-CHP technologies[20]. In this case, the use of electrolytic hydrogen still produces a carbon penalty.

We conclude that:

- niche transport markets for hydrogen could in principle be met from low-carbon electricity with carbon benefits in the short and medium term, provided that the future development of the electricity generation system focuses on renewables and CHP; but
- the supply of electrolytic hydrogen to mass-market vehicle applications is likely to require more electricity than can be supplied from renewables and CHP alone for at least the next 30 years.

6.2.2 Additional Effective Demand for Renewable Hydrogen

It has been argued that the use of hydrogen in transport could produce a new, and high value, market demand for renewable electricity, and that this might itself stimulate additional investment in renewable electricity capacity.

Both the acceptable price for hydrogen and the premium that motorists might pay for hydrogen from renewable sources are inevitably speculative. Environmental aspects aside, the main factors that would affect whether hydrogen could compete with existing fuels would include the costs of vehicles, relative fuel efficiency, and relative fuel costs. This discussion puts on one side the question of the cost of a future fuel cell car, compared to a future ICE car, and focuses on fuel cost, price and taxation issues. This is on the expectation that as fuel cell vehicles are deployed in significant numbers in the market, their capital cost is likely to converge with that of more conventional technologies.

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[19] This was the case in two of the four scenarios investigated by the PIU Energy Review.

[20] The only PIU scenario involving electrolytic hydrogen has substantial non-CHP gas generation in place in 2050 to meet the demand for 1500 PJ/year of hydrogen.

Reasonably favourable long term assumptions for fuel cell hydrogen are that:

- fuel cell vehicles have comparable long term costs with ICE (and hybrid) vehicles that provide the main alternatives to reducing carbon emissions; and
- fuel efficiencies of fuel cells are 30% higher than a diesel hybrid taking into account energy losses in hydrogen storage.

These assumptions can be regarded as fairly realistic in the short term, but more speculative for the longer term, in that efficiencies of both technologies can be expected to improve to one degree or another.

Clearly the most favourable regime for renewable hydrogen would be for it to be untaxed and compete with petroleum fuels (and fossil hydrogen) that are fully taxed. With these assumptions, renewable hydrogen could be marketed competitively at 30% above post-tax (i.e. pump) prices of diesel. The latter are currently approximately 75p/litre (i.e. £20/GJ or 7p/kWh) of which 75% is fuel excise duty and VAT.

The expected future costs of cheaper sources of renewable energy delivered to an electrolyser might be approximately 3.5 p/kWh (£10/GJ). The costs of hydrogen produced by electrolysis from these sources would then be a little less than £20/GJ[21], or broadly equivalent to the pump price of diesel. Thus, hydrogen from renewable electricity will be taken up by motorists to the extent that fuel cells retain their energy efficiency advantage over diesel, and while hydrogen commands a very low (or zero) rate of fuel duty.

Maintaining a very favourable tax regime for renewable hydrogen in the transport sector could therefore provide some modest stimulus to renewable generation over and above current support systems (Renewables Obligation, etc).

This kind of taxation regime would certainly be required to encourage an innovative option such as hydrogen, at least in the short term. However, if taxes were driven by low-carbon goals, it would be irrational for Government to maintain such a regime for a large market penetration of hydrogen, unless producing and using hydrogen in that way secured particular carbon reduction benefits.

And it is necessary to ask why Government would choose to support renewables in this way for the production of hydrogen, rather than supporting renewable generation directly. The fact that incentives to renewable hydrogen could be implemented through a differential excise duty rather than a direct subsidy does not alter the fundamental economics – it is equally a subsidy.

The principle underlying fuel taxation in the UK is that all fuels are treated equally, except to the extent that there are external costs or benefits that justify differential treatment. The existing zero rate of duty for hydrogen is the same irrespective of the source of hydrogen and, we assume, justified as support for a potentially important and innovative technology. Hydrogen would provide some noise and air quality benefits, but (as argued in Section 9) the relative advantages of the technology will be eroded over time as the performance of other vehicle types improves. We therefore expect that the long term fiscal treatment of hydrogen will be based primarily on any carbon benefits.

[21] Assuming a conversion efficiency of 73% and an electrolyser costs of $8/GJ based on Ogden, J.M. and Nitsch, J. Solar Hydrogen, in Johannsen T.B. et el 'Renewable Energy'. Island Press, 1995.

However, as shown in Section 6.1 above, there are no additional carbon reduction benefits, under current conditions, from using renewable electricity for new hydrogen demands rather than using the same electricity to displace existing fossil fuel generation. The carbon benefits of renewable electricity derive largely from the renewable nature of the electricity, not from the fact of its being used for hydrogen powered cars[22]. For the foreseeable future, it is therefore logical to subsidise the production and use of renewable energy by the most cost effective route.

Renewable electricity sources are currently effectively subsidised by 3 p/kWh through the Renewables Obligation. A zero fuel excise duty on hydrogen represents a subsidy of about £15/GJ of hydrogen, and if the hydrogen is produced by electrolysis, this is equivalent to a subsidy of 4 p/kWh on the electricity. We conclude that each unit of renewable electricity supported through a zero fuel excise duty for hydrogen production would require a bigger subsidy level and achieve a lower carbon saving than supporting renewables more strongly through a broader mechanism such as the Renewables Obligation.

6.2.3 Hydrogen from Off-Grid Renewables

Whilst renewable electricity generation connected to the grid seems most likely to be best used for carbon reduction by replacing fossil fuel electricity generation, this argument does not necessarily apply to prospective renewable electricity sources which are not grid connected.

Of course, most generation is grid connected for good reasons:

- grids allow generation sources to be connected to remote power demands with low losses due to the use of high voltage transmission; and
- grid connected systems have large economic benefits in minimising excess power generation capacity and/or energy storage requirements.

It is therefore economic to connect all significant power generation that is within easy access of the existing grid. As all filling stations are likely to be connected to the grid, non-grid produced electricity for local use is implausible.

An exception might be where the costs of electricity transportation are unusually high, and hydrogen might offer an alternative. This would be because bulk transportation of energy over long distances (under sea or on land) is generally more economic by pipeline than by wire. In the UK, this is only likely for remote but substantial sources of power generation, such as offshore or island-based renewables, where there are significant additional costs in connecting the generator via undersea cable to shore.

Provisional estimates of connecting an offshore wind farm on the edge of the UK Continental Shelf to the UK grid indicate that it might add 1–2 p/kWh to the costs of electricity, i.e. an additional 25–50% to the costs of delivery to a large commercial user such as a filling station.

The best-case scenario for hydrogen transportation might be for hydrogen produced in very large amounts from renewable electricity at very large distances from UK consumers, e.g. from solar power in the Sahara Desert or Australia. The costs of shipping hydrogen from solar production facilities in North Africa to central Europe have been estimated to be approximately £5–£6/GJ[23]. This is broadly similar to

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[22] There are carbon benefits from the greater efficiency achievable with hydrogen fuel cells than other technologies, but these are largely offset by the losses in making hydrogen from electricity.

[23] $7–$9/GJ, see Ogden, J.M. and Nitsch, J. Solar Hydrogen, in Johannsen T.B. et el 'Renewable Energy'. Island Press, 1995.

the cost of transmitting high voltage electricity a similar distance, but the economies of scale of hydrogen transportation are likely to be better. Therefore any future large intercontinental trade in solar hydrogen may well rely on transportation of hydrogen not electricity.

We conclude that more analysis is needed in this area. However, the scope for large off-grid production of hydrogen in the UK does not appear to be sufficient to revise our broad conclusions on the carbon benefits of hydrogen from renewable electricity in the medium term.

6.3 An Electrolytic Hydrogen Infrastructure

Renewable electricity could be used for hydrogen production at or close to the point hydrogen is required (for example vehicle refuelling points). The alternative would be to generate the hydrogen from electricity remotely and then to transport it to the vehicle refuelling point. There is, however, a range of uncertainties about the production of this hydrogen, its transportation, and its destinations.

The development of fuel distribution and refuelling infrastructure poses a substantial challenge to the uptake of any alternative transport fuel, especially gaseous ones. Aside from the technical difficulties with refuelling and on-board vehicle fuel storage, most alternative fuels are caught in a classic 'chicken and egg' dilemma. This is where, on the one hand vehicle manufacturers will not deploy new technologies if there is inadequate refuelling infrastructure, whilst on the other hand energy suppliers will be reluctant to invest in new infrastructure while there is no significant demand. This problem is much reduced where the fuels are either confined to captive fleets (i.e. those refuelling at depots) or used in bi-fuel vehicles which can also use a conventional fuel alternative. However, this section specifically considers the strategic and large scale deployment of the fuel into vehicle fleets at large, and the associated infrastructure requirements.

For conventional fuels, a distribution system and a network of refuelling stations has been built up, with substantial investment, over many decades. For alternative fuels, and especially hydrogen, significant elements of this infrastructure would need to be replicated from scratch. These can be considered under two main headings; filling stations and distribution networks.

Filling Stations

With road transport being in its nature a dispersed activity, refuelling the transport fleet as a whole requires a large and quite dense network of refuelling points, currently totalling around 13,000 across the UK. However, a sparser network than this would be sufficient; perhaps 2,000 to 3,000 stations for a fleet of dedicated alternative fuelled vehicles (AFVs), or fewer still for bi-fuel vehicles.

It is quite possible that hydrogen (or indeed most other alternatives) could be dispensed from some of the same filling stations as are in use today. However, hydrogen in either compressed or liquefied forms requires quite different storage and pump arrangements (including either cryogenic tanks or pressurised cylinders), so would not be easily incorporated in all cases. Thus a substantial amount of new equipment, and possibly some new sites, would be needed. Even so, this 'adding an extra pump' approach would still be less costly than building an entire parallel network from scratch.

Fuel Distribution

A fuel distribution system for hydrogen would probably have a substantially different structure from the present system.

One important difference is that large-scale manufacture of hydrogen from biomass or other renewable sources is likely to be more widely dispersed and decentralised than that of petroleum fuels, making bulk distribution through pipelines less straightforward, but perhaps also less necessary. Hydrogen could be distributed by pipeline, but as yet the likely nature and costs of a hydrogen pipeline distribution network remain far from clear.

Coupled with this, the much lower energy density of hydrogen makes distribution by tankers much less efficient, as it would take a number of tanker trips for hydrogen to move as much energy as from a single trip for petrol or diesel. Technologies are improving, but currently, transporting liquefied hydrogen imposes other demands over and above this, while transportation of compressed hydrogen in cylinders is quite impractical on a large scale. This suggests that, if tankers were to be used to deliver hydrogen fuel to filling stations, then shorter trips from a denser network of manufacturing sites and/or distribution depots would be needed. Even then, this could well cause a significant additional traffic problem in major urban areas, and a pipeline delivery network would increasingly be needed as demand developed.

Hydrogen could also be derived from biomass on a relatively small scale, although the economies of scale are not well-established. For this reason the prospect of local generation of hydrogen, either reformed from natural gas or produced from water through electrolysis (with either gas or electricity supplied through their existing distribution networks) is particularly attractive in logistical terms for transport fuels. In either case this does not present serious technical obstacles, as the technology to generate the hydrogen can be scaled down to suitable sizes if needed; but as argued elsewhere in this report, both of these pathways have drawbacks on energy supply or carbon emissions grounds.

6.4 Conclusions on Renewable Electricity and Hydrogen

The conditions under which hydrogen from renewable electricity will be genuinely carbon-neutral have been examined, and all appear unlikely to arise in the short term. In particular, it is concluded that:

- owing to the expected level of penetration of renewables into the UK electricity system, production of electrolytic hydrogen for transport is not likely to be an effective way of using renewables to save carbon, until at least 2030;
- the combined penetration of renewables and gas fired CHP into the UK electricity grid system could more easily allow the production of hydrogen with some carbon reduction benefits in the short and medium term, but only for niche markets. Supply of low carbon electricity for mass market hydrogen is unlikely until at least 2030;
- the use of differentiated fuel excise duty for renewable hydrogen could incentivise a market for renewable electricity as a premium fuel, but there seems to be no reason (at least for carbon emissions reduction) to subsidise renewables in this way rather than more generally; and
- the economics of using electricity for hydrogen production that is sourced from UK off-grid supplies (including offshore) is uncertain and complex.

For the period to 2030, there are potential carbon benefits from using renewable electricity for supplying hydrogen for niche vehicle markets, provided that renewables and gas-CHP generation options are deployed at rapid (but feasible) rates. However, constraints on the rate of development of these power generation sources mean that renewable electricity will have more carbon benefits in substituting for fossil fuelled electricity, than in supplying hydrogen for mass road transport market applications until at least 2030.

7. Biofuels for Road Transport

7.1 The Biomass Options

We have concluded that there is little prospect in the short and medium term of renewable electricity supplying low-carbon electricity in the volumes needed for mass market transport demand. However, it is important to recognise that renewables do not have to be used for power generation. The most abundant sources available to the UK (solar, wind and wave) are generally best used for power generation, as argued above, but biomass fuels can be used for heat, power or transport fuels. The issue of using biomass for transport (via hydrogen production or otherwise) therefore needs to be addressed separately.

The term ‘biomass’ covers a wide range of fuel sources, including, for example, human and animal wastes; but for current purposes, we focus on the two main energy crop options, as follows:

- certain annual food crops can be used to make liquid fuels (e.g. oil seed rape for oils that can be esterified as a diesel substitute, and cereal and sugar crops from which ethanol can be derived by fermentation). These are established technologies; and
- woody or lignocellulosic crops can potentially be converted through a range of technologies. The potential resources include fast growing trees, such as willow, from which wood can be harvested, usually by short-rotation coppicing. Alternatives include some large and highly productive species of grasses, of which *miscanthus* (or elephant grass) appears to be the most promising for the UK.

Woody biomass can also be derived from various waste streams, including sawdust, agricultural residues and industrial and commercial waste. The total amount available from this source is smaller than could be produced from purpose-grown crops and may fall in future if waste reduction policies are successful. However, these waste streams might provide low cost resources from which woody biomass might be derived for early niche market applications, whilst the technology, economics and infrastructure of woody energy crops are established. They are also attractive because they contribute actively to other sustainability goals (i.e. waste management), and have very low carbon overheads because they would otherwise not have been utilised.

As noted above, the annual crop options can be used in more or less unmodified conventional vehicles, either as alternative fuels or, with even fewer problems, as low-percentage blends into existing petrol or diesel fuels. The woody crops offer a range of possibilities for fuels, including conversion into hydrogen or alcohols, either methanol or ethanol. Alcohols from these sources too can be blended into existing fuels at low levels, or they can be used as full alternatives or high percentage blends. For methanol in particular, however, significant engine modification is needed for the latter. Also, each engine type needs to be tested and homologated for each new fuel if it is to be used in any quantity, and manufacturers may be unwilling to go to this trouble and expense for a wide range of engines unless a major new market is assured.

Alternatively, if hydrogen fuel cells become a viable option, these bioalcohols could be used as feedstocks for renewable hydrogen production – and might at the same time solve the problem of hydrogen transportation, as alcohols could easily be distributed by tanker, and then reformed into hydrogen for dispensing. Methanol might also be used directly in some types of fuel cell in the future.

As the conversion efficiencies of these various fuel options from woody crops are quite similar, it is not particularly material to the line of argument in this report which of the various final fuels (methanol, ethanol or hydrogen) becomes the preferred option; all are quite similar in terms of primary energy demands and carbon emissions. The importance of the alcohol options, though, is that they offer a clear and technically feasible alternative path to a renewable transport fuel system even if hydrogen fuel cells prove not to be viable. They could also be used in a range of different technical configurations according to what proved to be most advantageous; directly in an advanced (probably hybrid) internal combustion engine; reformed into hydrogen on- or off-board the vehicle for use with fuel cells; or (in the case of methanol) directly in fuel cells.

Like other renewable sources of energy, however, the rate at which biomass energy might be developed is limited by a range of technical, practical and economic considerations. Biomass sources from the UK are inevitably constrained by the land area available; this point is discussed below. Biomass might also be imported to supply UK transport energy needs, but it is important to consider how far this is likely. Vehicle and vehicle fuelling technology is increasingly international in character. It therefore seems unlikely that the UK would become heavily dependent on biomass-derived transport fuels without at least the whole European market taking roughly the same direction. This assumption of parallel development is underpinned by the existence of a powerful overall policy framework at EU level, in the form of the Common Agricultural Policy and other relevant drivers.

On the other hand, the UK agricultural sector cannot be seen in isolation. Agricultural and market conditions already lead to significant specialisation within and between the Member States, and on a timescale out to 2050 it is likely that this process will continue in the event of a substantial development of biofuel crops. Depending on the precise feedstock in question, therefore, it is not impossible to imagine a substantial scale of imports from other EU Member States (e.g. Sweden), from EU candidate countries (e.g. Poland) or from farther afield (e.g. Brazil).

Ultimately production patterns would be determined by the economics of the industry, including the relative profitability of food and non-food crops. Nonetheless, it is useful to envisage a situation where biomass-derived fuels on a large scale would largely be met from UK-based resources as a ‘reality check’ on such scenarios. The box below therefore addresses this point by way of illustration.

UK Biomass and the Potential for Use in Transport

Fuel demand from the UK road transport sector is currently 1600 PJ/year and we expect this to change to somewhere in the range 1000–2250 PJ/year by 2050 depending on the demand for transport and the technologies used. How demand actually moves in this range will be important in determining what proportion biomass-derived fuels could contribute. In addition, the form of the fuel will influence the type of engine that can be used and therefore the energy efficiency of the transport system.

The scope for biomass to contribute to energy supply will depend on land availability. In the long term this is inevitably speculative, but for the purposes of this illustration we assume that up to 25% of UK agricultural land might in time become available. This amounts to approximately 4 million hectares (Mha).

The potential energy supply available then depends on the productivity of the energy crop and the conversion process that is used, as follows:

- yields of transport fuel from annual crops are typically 50 GJ/ha for rape methyl ester (RME) and 50–120 GJ/ha for ethanol[24]; and
- yields of wood are currently about 300 GJ/ha, but expected to rise to 400 GJ/ha. Conversion efficiencies into methanol or hydrogen are typically 65%, so that the effective yield of transport fuel is 200–250 GJ/ha.

Combining the simple land use and yield assumptions, annual crops from 4 Mha could supply 200–500 PJ/year of transport fuel, i.e. 12%–30% of current demand. Woody fuels, on the other hand, might supply 800–1000 PJ/year, i.e. 50% of current demand and potentially the whole of demand in 2050 in a low-growth, high-efficiency scenario. Thus the latter appears the more attractive long term option, as the former could only supply a relatively small share of total fuel from a very large land area.

Furthermore, a simple comparison on this basis may be misleading anyway. The chosen figure of 4 Mha would represent about two-thirds of all UK arable land, and annual biofuel crops would by-and-large require land of this quality. Obviously this would be an extremely high proportion of the UK resource to take out of food production, and would be concentrated in the eastern side of England. Furthermore, yields would vary substantially according to conditions. Some relevant crops (e.g. sugar beet) can only be productively grown on the best quality arable soils, so it would not be practicable to increase their production to the sort of scale implied here anyway. In contrast, woody biomass would be much more flexible and could be grown more widely, e.g. on poorer soils and in wetter and cooler conditions. A switch of land use of this magnitude would of course still be very substantial and have major implications, but it appears more plausible as well as more productive to achieve a substantial switch to biofuels with woody crops than with annual ones.

We conclude that:

- food crops converted to RME and ethanol might play a niche role in the short to medium term, but are never likely to satisfy a large proportion of transport fuel demands; and
- on the other hand, although they cannot yet be used within existing transport fuel markets, indigenous wood or other lignocellulosic crops could in the long term satisfy most, or even all, UK road transport fuel demand through the production of methanol, ethanol or hydrogen.

The latter conclusion is perhaps surprising and needs some caveats. The whole of UK road transport demand could only be met by *indigenous* biomass-derived fuels if all the following were true:

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[24] Based on CONCAWE report 2/02. The UK would be likely to fall towards the top end of the range for most crops, owing to high quality land and reliable level of rainfall. There are additional energy products associated with the straw of rape and cereal crops, which might give carbon benefits, but are unlikely to be used for transport fuels.

- woody fuels are able to take up around 25% of UK agricultural land;
- road transport technology shifts to high efficiency vehicles based on hybrid and fuel cell technology; and
- transport demand is towards the low end of plausible growth projections.

Nonetheless, this is not an 'all or nothing' scenario, and a lesser share of road fuel could be manufactured from this route. One of the attractions of the 'energy carrier' scenarios using hydrogen or an alcohol is that the fuel can be sourced from a combination of sources, both indigenous and imported.

7.2 Carbon Benefits of Biomass-Derived Fuels

As explained above, the carbon benefits of using renewable electricity for vehicle hydrogen are poor because there are greater benefits in substituting it for electricity from fossil fuels in the coming years. As biomass too can be used for a number of alternative purposes, we have undertaken a similar assessment for biomass-derived fuels.

For biodiesel and bioethanol, the fuels are designed for use in the existing transport system. There is no plausible case for using them as heat or power generation fuels. Even taking into account the energy inputs to fuel production, there are carbon benefits from using biodiesel and bioethanol to substitute for (or extend) oil-derived fuels. However, the carbon benefits of biodiesel and bioethanol are much less than from using a similar area of land for woody biomass for energy. Furthermore, there are also significant additional disbenefits from nitrous oxide emissions from soils which adversely affect the greenhouse gas balance of annual crops, but which have not been quantified here. We therefore focus in what follows on woody biomass.

Woody biomass can be used for transport or other energy uses. The best use for carbon reduction outside the transport sector is in CHP systems, as this allows maximum efficiency. If biomass CHP substitutes for gas-fired power generation and gas heating, the carbon benefits are approximately 60 gC/kWh of biomass used. Biomass power generation without energy recovery might save 40 gC/kWh, and biomass heating would have benefits of about 50 gC/kWh.

The benefits in transport depend on the transport fuel into which it is converted and the vehicle technology displaced. Making the conservative assumption that the alternative vehicle is an efficient diesel hybrid and taking account of losses in reformation and hydrogen compression, using biofuel-derived hydrogen in a fuel cell vehicle in 2010 will have a benefit of approximately 55 gC/kWh of biomass used. And using a methanol fuel cell vehicle will have benefits of approximately 50 gC/kWh.

There is some level of uncertainty around all of these numbers, so that drawing a precise conclusion from broadly comparable numbers would be unwise. However a defensible conclusion seems to be that using woody biomass to manufacture hydrogen (or alcohol) for use in an efficient fuel cell vehicle has comparable carbon saving benefits to using biomass for CHP, and probably larger benefits than using biomass for either heat or power generation alone.

Although this study has not undertaken detailed economic analyses of different options for the manufacture of hydrogen, it is worth noting that there seems no doubt that hydrogen from biomass will be cheaper than hydrogen from electricity. Using reasonable assumptions about the costs of different energy inputs, hydrogen from biomass is expected to be slightly more expensive than from gas, but approximately half of the costs of hydrogen from electricity[25]. Bearing in mind the discussion of relative prices in Section 7.2.2, biomass as a hydrogen feedstock is therefore likely to have economic as well as environmental benefits compared to renewable electricity.

The conclusions for hydrogen from biomass are therefore significantly different from those for hydrogen from renewable electricity. Using hydrogen as a transport fuel, as opposed to elsewhere in the economy, has potential economic and environmental benefits, because of the efficiency of fuel cells compared to other vehicle prime movers. But with renewable electricity these benefits are offset by the costs and inefficiency of converting electricity to fuel. Conversion of biomass to hydrogen appears to be a preferable option.

7.3 Infrastructure for Alcohols or Other Liquid Fuels

Filling Stations

For liquid fuels (e.g. methanol or ethanol) the technical challenges of new fuel pumps are not too great; being liquids, they can be handled in much the same way as petrol or diesel. With methanol, its toxicity raises particular concerns in terms of fuel handling by the general public, and safer nozzles would be needed. Its corrosive properties require some materials which can be used in petrol or diesel pumps to be avoided, but this is not a serious problem as alternatives are readily available.

In most cases, therefore, methanol or ethanol could be added relatively easily to existing installations, provided there were not too much competition for space from a wide range of other fuels or grades. A recent US study estimated the cost of adding methanol capacity to a typical existing refuelling site would be in the region of $60,000 to $70,000 per site. In the context of a shift to fuel cells, however, this lower cost would have to be offset against the technical difficulties and much higher costs of on-board reformation of alcohols to hydrogen, or the technical barriers to their direct use in fuel cells.

Fuel Distribution

As liquid fuels, it seems likely that alcohols would be distributed by tanker, much as conventional fuels are now. Alcohols have a significantly lower energy density than petrol or diesel, so it would take more tanker movements to transport the same energy content of fuel. This might however be offset to one extent or another by greater energy efficiency of future vehicles.

Furthermore, methanol might in the medium term be manufactured at refuelling stations from natural gas, and in the longer term, sourcing such fuels from biomass would probably result in its manufacture being more widely dispersed than the refining of petroleum. The first of these arrangements would obviate the need for tankering, while the second could reduce the average distances over which fuels would need to be transported by road.

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[25] For example, Ogden, J.M. and Nitsch, J. Solar Hydrogen, in Johannsen T.B. et el 'Renewable Energy' (Island Press, 1995) give costs of $7–$9/GJ from biomass, compared to $16/GJ from wind at high wind speed sites and $5–7 from natural gas.

A further point is that an alcohol fuel might in the long run be used as the feedstock for off-board reformation of hydrogen, which in turn would be used as the final fuel. If so, then distributing the alcohol as an intermediate feedstock would help to solve some of the more problematic aspects of hydrogen distribution.

7.4 Conclusions on Biofuels

The currently available biofuels – biodiesel and bioethanol – could play an expanded role in the short and medium term, probably as conventional fuel extenders. But they do not provide a major element of the pathway to a longer term strategic biofuel contribution, which is dependent on high-yield crops and fuel-efficient vehicle technology.

Combining the conclusions on the potential resource and on carbon benefits, we conclude that under favourable circumstances of land use and technological development, hydrogen (or methanol or ethanol) derived from woody biofuels could play a very significant role in UK road transport energy supply, and that this might be the best way to use biomass to reduce carbon emissions. However, we would also stress that deployment of energy crops on a large-scale basis has potentially important environmental impacts (e.g. on landscape and biodiversity) which would need to be carefully considered.

The timescale of a substantial biomass-derived hydrogen or alcohol contribution is potentially important in considering the pathway to a zero carbon vehicle future. Our transport technology scenarios indicate that 250 PJ of hydrogen might be needed in a rapidly advancing vehicle sector by 2030. This might be supplied by gas, but then the carbon benefits would be small compared to good diesel hybrids. As we have shown elsewhere, the electricity system is unlikely to be able to supply such a large new demand from additional low carbon sources, as on these timescales low carbon electricity is better used to substitute existing electricity demands. There is therefore the possibility of real conflicts emerging between the development of potentially zero carbon (fuel cell) vehicles and the ability of the energy system to deliver them with low-carbon fuels.

Biomass may be able to fill this gap, producing renewable hydrogen (or alcohols) for vehicles, without prejudicing the best role of the electric renewables (wind, wave and solar) in securing the biggest carbon reductions. In addition, alcohol fuels might provide an 'insurance policy' as an alternative route to very low carbon road fuels, in the event that the fuel cell/hydrogen route proved impractical for some or all classes of vehicle. Note, however, that it is quite unlikely that both of these pathways would be pursued in parallel for any length of time, as this would incur two sets of development costs, two largely parallel sets of infrastructure, etc.

8. Intermediate Technologies

8.1 Pathway Technologies

There are a number of technologies already on the market that offer significant benefits in terms of carbon emissions, and local air quality. These include electric vehicles, although their battery range is currently too limited to be of interest to more than niche markets. But much more promising is the hybrid vehicle which offers the same level of performance as existing vehicles and has no new infrastructure demands. Hybrid cars currently on the market, such as the Toyota Prius, cut carbon emissions by around 30%.

Hybrids use a combination of a small conventional engine and an electric motor. Battery power is used at lower speeds and for stop-start driving in urban areas. The engine drives the vehicle at higher speeds and coasting, and the braking system recharges the battery while it is running. With no need for recharging facilities, and running off petrol (and potentially diesel), these are essentially conventionally fuelled, but highly efficient, vehicles. It can be expected that the current hybrids will evolve as they gain a market share, and it is believed they have the potential to double the fuel economy and halve the carbon emissions of an average sized petrol or diesel engined vehicle.

The development of the hybrid vehicle can also be seen as a contribution to the progressive 'electrification' of vehicles. Improvements in electronic control systems and electric drive trains, for example, are all vital elements of developments that are essential to the commercialisation of fuel cell vehicles. Indeed, the first hydrogen fuel cell vehicles being demonstrated are in fact hybrids themselves combining a battery with a fuel cell.

Electric vehicles have virtually no emissions at the point of use, and are comparatively clean from a fuel cycle perspective but, as mentioned already, seem unlikely to secure major market penetration due to the limited range and performance of their batteries. In addition, although tailpipe emissions are zero, the energy source for the electricity (the majority of which is fossil fuel) has to be taken into account in any assessment of the environmental impacts of these vehicles. A 'well-to-wheel' assessment is necessary to give a fair comparison with all other available options. We anticipate that electric vehicles will probably remain confined to niche markets, and in time may be partly or completely superseded by fuel cell equivalents.

8.2 Natural Gas Vehicles

Natural gas (usually in compressed form) offers a direct alternative to diesel ICE engines. It is particularly attractive as a short to medium term option for heavy duty diesel vehicles, as it burns more cleanly and is quieter, and the heavy and bulky fuel tanks needed are less of a problem with larger vehicles. Fleet applications are particularly attractive, as vehicles can be refuelled overnight through depot-based compressors. However the market for dedicated gas powered vehicles has been very weak in the UK, owing in part to the high cost of compressors.

However, the anticipated availability of natural gas/diesel dual-fuel vehicles could improve the situation. These dual-fuel engines can run on up to 90% natural gas with 10% diesel, or can run on 100% diesel. This gives them an obvious advantage in terms of flexibility for refuelling, and demonstrations suggest that the emissions benefits can be high – i.e. offering the CO_2 advantage of diesel combined with the NO_X and noise advantage of natural gas. The possibility of short term threats to fuel supply disruption make natural gas vehicles attractive to major delivery companies; but they do not, of course, represent a shift away from fossil fuel dependency.

8.3 Liquefied Petroleum Gas (LPG)

LPG comprises primarily propane and butane (largely propane in the UK). These are two of the lightest components of crude oil and are often contained in natural gas. They can be compressed to a liquid at very low pressures, and in this form can be used in a standard spark-ignition engine with very minor adjustments. The main modification required is the provision of an alternative fuel tank and supply to the engine. Most current LPG vehicles are bi-fuelled (i.e. they retain a petrol tank and fuel supply as well) in order to be able to use petrol in areas where LPG is not readily available.

In the UK there are around 55,000 LPG vehicles on the roads, of which about 10,000 were supported by PowerShift grants from the EST. There are approximately 1,400 filling stations offering LPG, with around one refuelling pump opening every week. Given current reduced levels of fuel duty on LPG, the UK market now appears to be well on the way to being self-supporting with an increasing number of LPG vehicles being purchased without any form of PowerShift subsidy.

LPG vehicles have lower tailpipe CO_2 emissions than petrol equivalents, primarily because of the lower carbon content of the fuel. In addition, the 'well-to-tank' energy and emissions are very much lower. So the 'well-to-wheel' CO_2 benefits of LPG over petrol are significant. In addition, dedicated mono-fuelled LPG vehicles could be more efficient than current bi-fuelled vehicles as LPG has a higher octane rating. LPG use in vehicles therefore represents a good option in terms of broader energy efficiency policy whilst petrol use is significant. But LPG will remain unlikely to offer carbon benefits when compared to diesel. In addition, good quality LPG conversions offer some air quality benefits, although these are being eroded over time by the improved performance of other vehicles.

Currently LPG is exported and therefore increasing its use in the UK vehicle fleet is a sensible option for reducing carbon emissions. However, its feasible penetration of the total vehicle fleet is probably only around 10%. Even at its maximum level of penetration, LPG will therefore have a rather marginal impact on either total road fuel energy demand or CO_2 emissions, and does not provide a pathway to non-fossil fuel transport.

8.4 Hydrogen from Fossil Fuels

The major focus of this study has been the use of hydrogen from renewables. With the exception of hydrogen from woody biomass, the medium term environmental benefits have been found to be unpromising. Even the development of a large woody biomass hydrogen sector may well take time. The short and medium term development of any hydrogen fuelled transport sector is therefore likely to depend on gas reformation – the cheapest route to hydrogen.

The environmental benefits of fuel cell vehicles using hydrogen from gas are not large. We estimate that the ‘well-to-wheel’ carbon emissions of a fuel cell vehicle using locally reformed hydrogen in 2010 might be approximately 80–85 g/km. In contrast, the figure for a diesel hybrid will be approximately 100 g/km (see Annex 1). The ‘hydrogen from gas’ option therefore appears to have some CO_2 benefits. These might also be offset by methane leakage from the natural gas system – this is unlikely to be a significant factor for North Sea gas, but might well be for gas imported in the longer term from Asia. The scale of any overall environmental benefit is therefore not very clear.

So, whilst the largest gains in carbon reduction from hydrogen will have to await renewables (perhaps initially biomass), there may be modest benefits (and at least no significant losses) in using hydrogen from gas before any renewables markets are sufficiently developed, provided that the hydrogen is used efficiently. This may be important in establishing early niche markets for hydrogen, at least without environmental losses.

The transition to mass market hydrogen vehicles will only be possible with a fully developed hydrogen infrastructure. The nature of such a major infrastructure change is that it will be exceedingly costly if it is done rapidly, replacing assets before the end of their natural lifetimes. Hydrogen from gas therefore also seems likely to provide a step on the route to a slower and more economically acceptable transition to hydrogen vehicles.

The level to which gas use for transportation hydrogen is acceptable may depend on other factors than environmental issues. Given that the greenhouse gas emissions of fuel cell vehicles using hydrogen from gas are broadly similar to those of diesel hybrids, costs will be an important factor. Hybrids will be cheaper initially, but the inherent simplicity of the fuel cell traction option may outweigh this ultimately.

Fuel security will also be an issue. Currently oil security is generally seen as more problematic and oil is certainly scarcer globally. Moving to a gas powered transport system might therefore be advantageous. On the other hand, the rest of the energy system (heat and electricity) is increasingly dependent on gas, and there are some doubts about the reliability of some gas exporting countries and the extensive pipeline infrastructure needed to bring gas to western Europe. A fully gas powered road transport system would therefore bring new energy security risks. However, the development of a small hydrogen sector based on gas reformation will not significantly increase any gas security threats over and above those created by much larger demand in other sectors.

9. Local Impacts: Air Quality and Noise

UK and EU legislation currently sets health-based objectives for air quality for 2005 and 2010. Motor vehicles are a major contributor to emissions of the two most problematic local pollutants; nitrogen dioxide (NO_2), and fine particles (PM_{10}). NO_2 is also implicated in generating ozone, another intractable regional-scale pollutant. Although new technologies will continue to cut emissions of pollutants for some years, business as usual scenarios suggest that increasing traffic will overtake the improvements in technology by around 2020. New vehicles coming onto the market today meet EURO 3 standards and by 2006 will meet even tighter EURO 4 standards. There is now only marginal scope for further reductions in emissions; the most significant impact on air quality would be made by increasing the retirement rate of older, substantially more polluting vehicles.

Some of the future vehicle technologies under discussion have the potential for lower tailpipe emissions of NO_X and/or PM_{10} than conventional petrol and diesel engines. Different fuels have different environmental advantages. ***Diesel*** vehicles have significantly lower CO_2 emissions compared to ***petrol***, because of the higher efficiency of diesel engines. However some new petrol technologies – particularly gasoline direct injection (GDI) will offer significant improvements in fuel efficiency. Diesel engines emit higher levels of NO_X and particles than new petrol vehicles, so they are generally better for global warming, but worse for local pollutants.

Hydrogen powered vehicles offer very low tailpipe emissions; some NO_X if used in an internal combustion engine, or zero emissions using fuel cell technology. This is true whatever the source of the hydrogen. However the additional impact of low, or even zero emission vehicles on air quality is only likely to be marginal when measured against the relatively clean EURO 4 standard vehicles. The primary focus of local authorities who are considering low emission zones as part of their air quality management plans, is to speed up the introduction of EURO 3 and 4 vehicles, and restrict access to the older, much more polluting vehicles which are the main culprits in emission terms. Modelling suggests that, even if all vehicles in major hotspots were upgraded rapidly to modern EURO standards, the impact on air quality would still be relatively limited because of regional and transboundary air pollution effects[26]. The supplementary contribution of some alternatively fuelled vehicles in these circumstances would probably be vanishingly small.

From an environmental perspective, therefore, any technologies or fuels offering improvements in tailpipe emissions of local pollutants beyond EURO 4 standards are worth having, but not at excessive cost (other mitigation measures may be more cost-effective), and not at the expense of increased emissions (including, crucially, greenhouse gases) elsewhere in the fuel cycle.

Increasing importance is attached to noise exposure. The European Union's 2002 Directive on the assessment and management of noise requires Member States to carry out noise mapping. Ultimately, Member States will be required to put in place action plans to reduce noise levels. However, noise is a complex environmental issue. General levels of ambient noise may be less troublesome than individual

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[26] London LEZ Joint Feasibility Study: Conclusions and Interim Recommendations. AEA Technology, 2002.

noise events, which are as dependent upon time as decibel level. It may be worse to be woken in the middle of the night by a single noisy HGV, than to be exposed to high levels of traffic roar during the day.

EU legislation also sets standards for vehicle noise, particularly engine noise. Above certain speeds, tyre noise is the predominant source of noise output from vehicles, but this is an intractable problem and is independent of vehicle engine technology. At lower speeds – and thus in most urban areas – engine noise predominates, alongside noise from body and chassis rattle. As with air quality, tightening EU standards will ensure that conventional engines continue to improve their noise performance, but alternative technologies such as CNG, hybrids and electric/fuel cell power offer the promise of quieter (or in the latter case, silent) running. Again, as with air quality, the actual contribution which even a significant proportion of quieter vehicles would make to the overall ambient noise climate would be difficult to detect, but in sensitive areas – for instance night-time deliveries of goods to urban locations – they may make a worthwhile contribution.

Overall, the local impacts of future vehicle technology choices offer some improvements over current conventional technologies, but whether these are worth having is dependent upon the technology and the location and timing of deployment. Given the expected improvements which conventional technologies are already expected to deliver, the primary environmental criterion for alternative technologies remains the further reduction of greenhouse gas emissions. However, complementary improvements in local impacts are worthwhile, especially if they contribute towards air quality objectives within the timescale of the current Air Quality Strategy.

10. Conclusions

This review assesses the optimal role for transport fuels in the future energy mix, primarily with regard to environmental considerations. The focus is specifically on the development of hydrogen in terms of its carbon impacts as against those of the range of alternative energy sources. Our main conclusions are as follows.

1. Our assessment of the optimum use of renewable electricity for carbon reduction leads us to conclude that whilst fossil fuels remain the marginal fuels for power generation used at current efficiencies, it is not advantageous to use renewable electricity for hydrogen production. However, there will be carbon savings from hydrogen vehicles using electricity from a power system dependent largely on gas and renewables, if the dominant marginal gas technologies are CHP. But the supply of hydrogen to mass market vehicle applications is likely to require more electricity than can be supplied from renewables and CHP alone for at least 30 years.
2. The carbon benefit of using renewable electricity–based hydrogen derives largely from the renewable nature of the electricity, not its use for hydrogen production. Maintaining a favourable tax regime for renewable hydrogen in the transport sector could provide some modest stimulus to renewable generation over and above current support systems (Renewables Obligation Certificates (ROCs) etc). Each unit of renewable electricity supported through a zero fuel excise duty for hydrogen production would require a bigger subsidy level and achieve a lower carbon saving than supporting renewables more generally via a mechanism such as the Renewables Obligation.
3. The potential benefits of hydrogen, from renewable or non renewable sources, need to be seen against the benefits from hybrid vehicles, which are already available (although from a limited number of manufacturers), and are likely to develop technologically. Hybrids have the potential to double vehicle fuel efficiency and halve CO_2 emissions, even using conventional fuels.
4. In addition, hybrid vehicles can offer substantial benefits in the short term for air quality and noise, particularly in urban hot spots. The further reductions in emissions ultimately achievable through hydrogen fuel cells, although significant, will be of relatively less value, in terms of their health and environmental impact. We conclude therefore that, in the absence of any CO_2 reduction benefit, the environmental case for accelerating a wide scale introduction of a hydrogen fuel celled vehicle fleet ahead of the availability of renewable energy sources is not strong.
5. Natural gas offers an alternative to diesel, and is particularly attractive for heavy duty fleet vehicles. In these applications it offers benefits in terms of conventional pollutants, noise and carbon emissions – but does not, of course, represent a pathway out of fossil fuel dependence.
6. Biodiesel and bioethanol are designed for use in the existing transport system, although engine modifications are needed to use biofuels in pure form. Even taking into account the energy inputs to fuel production, there are carbon benefits from using biodiesel and bioethanol to substitute for (or extend) oil-derived fuels. However, the carbon benefits of biodiesel and bioethanol are much less than from using a similar area of land for woody biomass, particularly if these are converted to hydrogen or methanol for use in fuel cells. Furthermore, there are also significant additional disbenefits from nitrous oxide emissions from soils in crop production, and these are typically substantially larger from arable crops than from woody biomass plantations, because of the greater use of inorganic fertilisers. Woody crops offer additional benefits in terms of uptake of carbon by the plants, but in common with all energy crops, there are important potential impacts (e.g. on landscape and biodiversity) to be considered.

7. The scope for biomass to contribute to energy supply will depend on land availability. If up to 25% of UK agricultural land is available (4 Mha) food crops converted to RME and ethanol could play a significant niche role in the short to medium term, but are never likely to satisfy a large proportion of transport fuel demands. On the other hand, although wood crops cannot be used within existing transport fuel markets, indigenous wood crops converted to alcohols or hydrogen could in the long term satisfy most, or even all, UK road transport fuel demand. However this could only be a reality if woody fuels take the equivalent of around 25% of UK agricultural land; if road transport technology shifts to high efficiency vehicles based on hybrid and fuel cell technology; and if transport demand is towards the low end of the growth projections. This is not an all or nothing scenario, however; it would be quite possible for a smaller share of UK road fuels to be supplied from indigenous sources, with additional supplies imported.

8. Reforming natural gas to produce hydrogen for use in fuel cells is a relatively low-carbon option, although the benefits relative to highly efficient diesel hybrids are limited. This is the lowest cost route to hydrogen, and therefore would seem to be an appropriate option for fuelling initial niche markets of fuel cell vehicles. But use of gas reformation for mass market vehicles has energy security implications that might outweigh the small carbon benefits. Mass market fuel cell vehicles may therefore only be appropriate at the point when renewable fuels (possibly biomass and later renewable electricity) become fuelling options.

9. There are substantial uncertainties around the infrastructure issues associated with the introduction of a hydrogen fleet. In particular they depend on whether the hydrogen is produced at local sources, or is distributed through a network. It seems unlikely that these issues can be confidently resolved in the short term. In the meantime, and before a wide-ranging network of hydrogen fuel supply is available, there is the opportunity to proceed incrementally through bi-fuelling, and through dedicated depot based fleets meeting niche markets.

10. To the extent that infrastructure issues can be resolved a case can be argued for accelerating development of a hydrogen fuelled vehicle fleet, even ahead of the widespread availability of renewably sourced energy, on grounds of security of supply reflecting long term geo-political uncertainties. A full assessment goes beyond the scope of this review but certain implications emerge:

    - where a long term risk is seen to arise from the transfer of economic power to potentially unreliable exporting countries, energy efficiency measures and the development and use of new fuels – combined with socio economic measures to reduce dependency on the more energy-intensive transport modes – may be a more appropriate and cost–effective response;

    - addressing risks of short term interruption is more difficult, but could additionally be aided by promoting wider diversity in fuels and suppliers and infrastructure redundancy. In this regard there may be advantage from bi–fuelled vehicles, and secondary fuels, such as hydrogen and ethanol or methanol, that can be derived from a number of primary fuels.

11. Our analysis has illustrated a number of possible pathways to a future low-carbon transport system. In some cases the necessary technologies are already well known and available; in others they are still under development. As well as novel vehicle technologies (notably fuel cells), it is important that certain energy supply options are not neglected. In particular, it appears that more attention should be paid to the possibilities of manufacturing hydrogen and/or liquid fuels from woody biomass crops.

12. Our modelling reflects the widely–held view that technical progress in heavy goods vehicles will be less rapid than elsewhere. However our results illustrate that, as a result, fuel demand and carbon emissions from HGVs may well remain large and growing, and could do much to counteract the improvements which are possible in other vehicle classes. We therefore feel that it is important that research and development efforts in this area should become a more strategic priority.

13. In sum, we conclude that, from the point of view primarily of environmental considerations, the optimal balance of transport fuels, having regard for the likely overall energy mix, will reflect three principal considerations:

    - hydrogen from renewable electricity sources for a mass market vehicle application is likely to be insufficient for at least 30 years, but significant transitional benefits can be secured from bi-fuelling and from dedicated depot based fleets meeting niche markets, including using hydrogen derived from gas;

    - in the short to medium term priority should attach to the substantial and more certain benefits from improving energy efficiency, including development of hybrid vehicles and related technologies;

    - while existing biofuels could make a useful contribution at the margins, more considerable long term benefits may derive from the potential of woody crops converted to methanol, ethanol or hydrogen, which under certain circumstances could satisfy most of the UK's road transport fuel demands.

Annex 1

Carbon Saving Benefits of Different Technical Options

Carbon benefits of renewable electrolytic hydrogen

Carbon benefits of using renewable electricity

Energy content of electricity	1.0kWh
CCGT use displaced	1.0kWh
Carbon saved	100.00gC

Carbon benefits of using renewable electricity for hydrogen

Energy content of electricity	1.0kWh
Efficiency of electrolysis	72%
Energy of hydrogen produced	0.7kWh
Losses	9%
Energy of hydrogen used	0.66kWh
Hydrogen FC vehicle consumption	1.04MJ/km
Hydrogen FC vehicle distance	2.27km
Conventional vehicle dist displaced	2.27km
Conventional vehicle consumption	1.35MJ/km
Energy of diesel displaced	0.85kWh
Upstream losses	6%
Upstream energy losses displaced	0.05kWh
Total oil saved	0.90kWh
Carbon saved	61.61gC

Comparison of the two routes

Net benefit of use in transport	**–38.39gC**

Electricity carbon content required for carbon saving

Diesel vehicle consumption	1.35MJ/km
Diesel vehicle emissions	94.05gCO2/km
upstream	5.55gCO2/km
total	99.60gCO_2/km WTW
equivalent H_2 vehicle	99.60gCO_2/km WTW
Hydrogen FC vehicle consumption	1.04MJ/km
equivalent H_2 emissions	95.768gCO_2/MJ
electrolyser eff	72%
losses in compression	9%
equiv electricity emissions	62.747gCO_2/MJ
equiv electricity emissions	61.606gC/kWh
gas to power efficiency	**81%**

Carbon benefits of biomass hydrogen

Carbon benefits of using biomass for heat and power

Energy content of biomass	1.0kWh
Energy content of CHP electricity	0.3kWh
Energy content of CHP heat	0.5kWh
Carbon saved by CHP	61.25gC
Carbon saved in electricity only	40.00gC
Carbon saved in heat only	50.00gC

Carbon benefits of using biomass for hydrogen

Energy content of biomass	1.0kWh
Efficiency of reformation	65%
Energy of hydrogen produced	0.65kWh
Losses	9%
Energy of hydrogen used	0.59kWh
Hydrogen FC vehicle consumption	1.04MJ/km
Hydrogen FC vehicle distance	2.05km
Conventional vehicle dist displaced	2.05km
Conventional vehicle consumption	1.35MJ/km
Energy of diesel displaced	0.77kWh
Upstream losses	6%
Upstream energy losses displaced	0.05kWh
Total oil saved	0.81kWh
Carbon saved	55.62gC

Comparison of the two routes

Net benefit cf CHP	**–5.63gC**
Net benefit cf electricity	**15.62gC**
Net benefit cf heat	**5.62gC**

Carbon benefits of using biomass for methanol

Carbon benefits of using biomass for heat and power

Energy content of biomass	1.0kWh
Energy content of electricity	0.3kWh
Energy content of heat	0.5kWh
Carbon saved	61.25gC
Carbon saved in electricity only	40.00gC
Carbon saved in heat only	50.00gC

Carbon benefits of biomass for methanol

Energy content of biomass	1.0kWh
Efficiency of reformation	65%
Energy of methanol produced	0.65kWh
Losses	0%
Energy of methanol used	0.65kWh
Methanol FC vehicle consumption	1.24MJ/km
Methanol FC vehicle distance	1.88km
Conventional vehicle dist displaced	1.88km
Conventional vehicle consumption	1.35MJ/km
Energy of diesel displaced	0.71kWh
Upstream losses	6%
Upstream energy losses displaced	0.04kWh
Total oil saved	0.75kWh
Carbon saved	51.11gC

Comparison of the two routes

Net benefit cf CHP	**–10.14gC**
Net benefit cf electricity	**11.11gC**
Net benefit cf heat	**1.11gC**

Carbon benefits of using gas for hydrogen

Emissions from a diesel hybrid

Diesel vehicle consumption	1.35MJ/km
Diesel vehicle emissions	94.05gCO$_2$/km
upstream	5.55gCO$_2$/km
Diesel vehicle emissions WTW	99.60gCO$_2$/km WTW

Emissions from a FC vehicle

Hydrogen FC vehicle consumption	1.04MJ/km
reformer efficiency	70%
Losses	9%
gas consumption	1.63MJ/km
FC vehicle emissions WTW	83.14gCO$_2$/km WTW

Carbon conversion factors

Gas	50.0gC/kWh
CCGT electricity	100.0gC/kWh
Average UK electricity	110.0gC/kWh
Petrol	64.8gC/kWh
Diesel	68.4gC/kWh

Annex 2
Full Modelling Results

The Full Modelling Results are available at:

- **www.est.org.uk;**
- **www. ieep.org.uk;**
- **www.nsca.org.uk**