EU Transport GHG: Routes to 2050?

Alternative Energy Carriers and Powertrains to Reduce GHG from Transport (Paper 2)

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21 December 2009

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Executive Summary

In recent years GHG emissions from the transport sector in Europe have continued to rise whilst the GHG emissions from other sectors have stabilised or begun to fall. Unless action is taken, transport GHG emissions alone will exceed an 80% reduction target for all sectors or make up the vast majority of a 60% reduction target. This illustrates the scale of the challenge facing the transport sector given that it is unlikely that GHG emissions from other sectors will be eliminated entirely. In this context the overarching aim of the project is to provide guidance and evidence on the broader policy framework for controlling greenhouse gas (GHG) emissions from the transport sector.

The main objective of Paper 2 is to review the potential of alternative energy carriers and powertrains to reduce GHG emissions from all motorised transport modes in the short-term (to 2020) and long-term (to 2050). This review excludes powertrain improvements for fossil fuel-based engines in road transport (which are addressed in Paper 1) and other technical options for non-road transport modes (which are addressed in Paper 3). It forms part of a suite of papers covering the full range of technical and non-technical options for reducing GHG from transport.

Paper 2 covers the road, rail, inland / maritime shipping and aviation sectors. It utilises data and analysis from existing studies rather than undertaking new research. As well as considering the magnitude of the GHG emissions savings that could be achieved by each option the paper also reviews the evidence on costs, timescales for implementation, barriers and secondary benefits. A draft version of paper was presented to stakeholders during a technical focus group in July 2009. Stakeholders' comments have been taken account in this revised version.

In general it should be noted that future CO_2 reduction depends not only on technology options but also on market acceptance, market demands and cost-effectiveness. At the moment there are significant uncertainties and barriers in all of the technology areas reviewed, suggesting an integrated approach is necessary to mitigate the risk from focussing too much on a particular solution. It should also be noted that, whilst the focus of this paper has been on the potential for GHG emissions savings, other impacts also need to be factored into a balanced assessment, i.e. wider impacts on the environment, economy, society and industry. Finally, all the alternative fuel/technology areas discussed are (to varying degree) reliant on the development of sound infrastructure policy (e.g. particularly for refuelling) to allow significant uptake of the new technologies. An active role for Member States is therefore critical in this area.

Liquid Biofuels and Biogas

- Biofuels can theoretically save significant levels of greenhouse gas emissions. However, this is very sensitive to the feedstock and production pathway used, as well as fundamental assumptions in the calculation of savings.
- There are a number of issues which need to be resolved and questions which need to be answered before these savings can be confidently quantified and agreed upon. These issues include the potential for both Direct and Indirect Land Use change (LUC).
- In the short-term, current biofuels are likely to offer only a small/limited potential with greater savings possible in the medium term as advanced feedstocks (e.g. algae) and production processes are developed/mature.
- In the longer term their potential may be constrained by competition for land use (and water) to feed an increasing global population and replace petrochemical derived products (e.g. textiles, plastics and chemicals) with those produced from biomass.
- Application in other than the road transport sector is generally immature and still under development. In the longer term biofuel use may need to be focused in aviation and shipping (and potentially long-range road freight transport) due to potentially limited biomass resource availability and fewer alternatives for abatement in these transport sectors.

CNG, LNG and LPG

- LPG is generally not considered to be a long-term option for GHG reduction. There are some more limited possibilities for further improvements in the shorter- (and possibly medium-) term, including 'bio-LPG' (a blend of 70% LPG and 30% bio-DME).
- In road transport natural gas vehicles (NGVs) using either CNG or LNG are generally a short-term option. In the long-term they may also provide some limited potential when powered by biomethane. However, the uncertainty of whether there will be enough sustainable feedstock to produce biomethane in significant quantities (together with competition with uses in other sectors) may hamper significant uptake of such vehicles. There has also been some consideration of using existing NG distribution systems to act as a bridging technology for H_2.
- In aviation neither LPG nor natural gas is a suitable alternative fuel, primarily because of the need for fuels with much greater energy density.
- In shipping liquefied natural gas is a promising future fuel for ships delivering significant reduction potential in NO_x and SO_x and PM emissions as well as GHG emissions;
- In rail there is some limited experience in using natural gas, usually driven by reductions in air quality emissions unless biogas/biomethane are utilised. Only niche applications seem likely in the future.

Pure Electric and Plug-in Hybrids

- Pure electric powered transport holds the greatest potential for GHG emissions reductions, since it can be produced from essentially carbon-neutral sources and utilized directly at higher net efficiency compared to hydrogen fuel (except perhaps for biological H_2 pathways).
- Significant challenges remain principally in the area of electricity storage – in terms of cost, weight, volume, efficiency and power delivery. These limitations also impact on the useful range of electric vehicles compared to conventional equivalents. These and other barriers mean the mainstream utilization of electric vehicles is still seen as being in the long-term, although smaller scale penetration is already progressing in the short-term.
- Plug-in hybrid electric vehicles are seen as an intermediate (short- to medium-term) technology on the pathway to electric vehicles in the road transport sector, enabling performance characteristics and range similar to conventional equivalents at lower capital costs. They also may have an important role to play in the long-term where range is critical.
- Electric trolley busses are an existing technology that potentially in the long-term might be extended further to trolley systems for trucks or even passenger cars on highways.
- There appears to be no significant interest on research into pure electric aircraft or ships applicable for passenger or freight operations.
- Electric rail is a mature technology that already accounts for over 80% of rail propulsion across Europe. It is uncertain to what degree this proportion could be increased in the future.

Hydrogen and Fuel Cells

- Hydrogen fuel cells offer significant potential to reduce GHGs from road transport in the long-term (depending on the hydrogen production pathway). Their contribution to GHG emissions reductions in the medium term is not anticipated to be high.
- The contribution of FCVs (fuel cell vehicles) will depend on developments in hydrogen / fuel cell technologies as well as in electrical energy storage for competing pure electric vehicles (EVs). FCVs currently have an advantage in range over EVs due to greater energy storage densities for hydrogen relative to electrical energy storage.
- The cost of developing new hydrogen refueling infrastructure is significant (much higher in comparison to developing a recharging infrastructure for pure EVs). The possibility to use the existing natural gas infrastructure as a bridge for hydrogen distribution is being considered.
- Hydrogen powered aircraft or ships appear to be unlikely propositions even by 2050.
- Hydrogen fuel cell powered rail vehicles may have the potential to replace diesel rail in the long term in areas where further line electrification is not economic.

1 Introduction

1.1 Topic of this paper

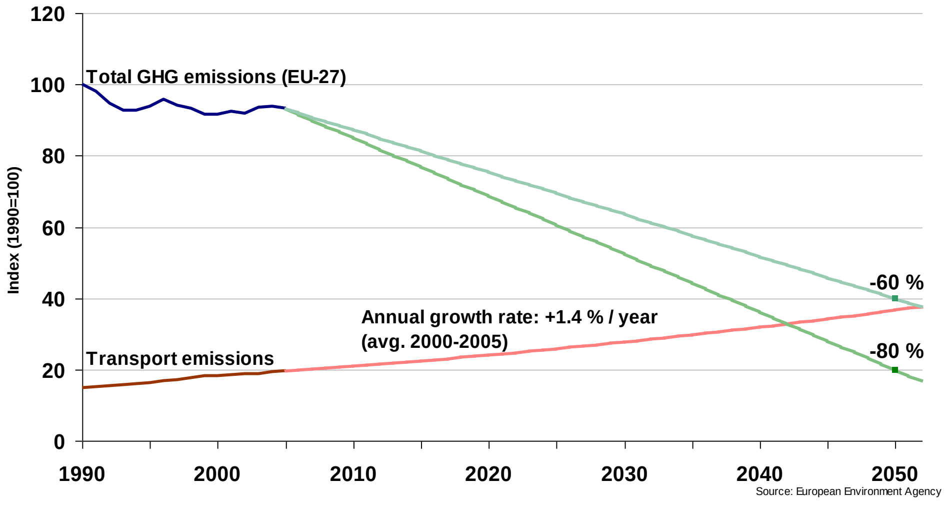
This paper is one of five papers on GHG reduction options for transport drafted under the *EU Transport GHG: Routes to 2050?* Project. These papers review the options – technical and non-technical – that could contribute to reducing transport's GHG emissions, both up to 2020 and in the period from 2020 to 2050. This paper focuses on the potential of alternative energy carriers and powertrains to reduce GHG emissions from all motorised transport modes. The papers aim to provide a high-level summary of the evidence based on existing studies and excludes powertrain improvements for fossil-fuel based engines in road transport (addressed in Paper 1) and other technical options for non-road transport modes (addressed in Paper 3).

This paper was presented in draft form to a Technical Focus Group meeting (at which stakeholders were present) in July 2009 after which it has been updated on the basis of the discussion at the meeting and the comments and further evidence that were received.

1.2 The contribution of transport to GHG emissions

The EU-27's greenhouse gas (GHG) emissions from transport have been increasing and are projected to continue to do so. The rate of growth of transport's GHG emissions has the potential to undermine the EU's efforts to meet potential, long-term GHG emission reduction targets if no action is taken to reduce these emissions. This is illustrated in Figure 1 (provided by the EEA), which shows the potential reductions that would be required by the EU if economy-wide emissions reductions targets for 2050 of either 60% or 80% (compared to 1990 levels) were agreed and if GHG emissions from transport continued to increase at their recent rate of growth. The figure is simplistic in that it assumes linear reductions and increases. However it shows that unless action is taken, by 2050 transport GHG emissions alone would exceed an 80% reduction target for all sectors or make up the vast majority of a 60% reduction target. This illustrates the scale of the challenge facing the transport sector given that it is unlikely that GHG emissions from other sectors will be eliminated entirely.

Figure 1: EU overall emissions trajectories against transport emissions (indexed)[1]



Source: European Environment Agency

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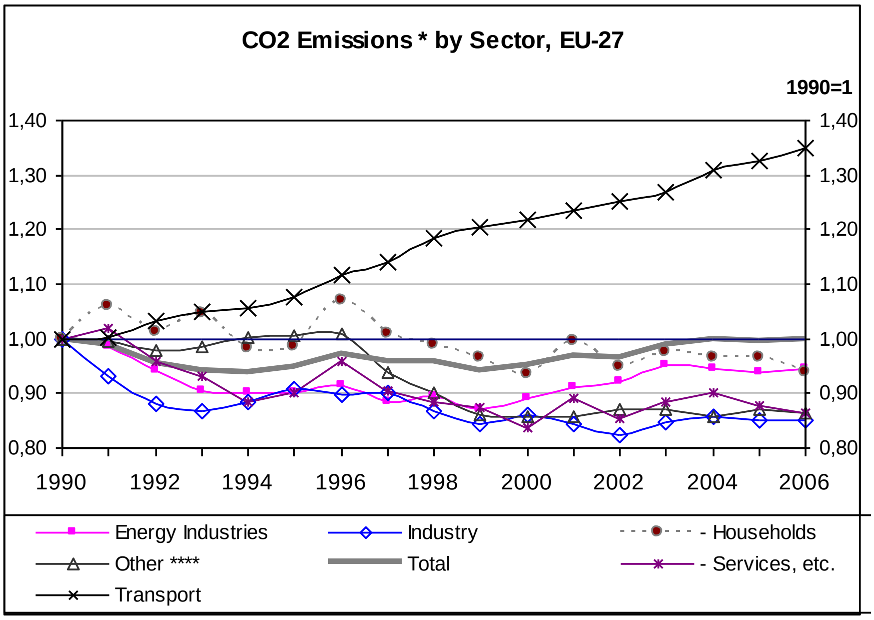
[1] Graph supplied by Peder Jensen, EEA

The extent of the recent growth in transport emissions is reinforced by Figure 2, which presents a sectoral split of trends in CO_2 emissions over recent years. Whilst the CO_2 emissions from other sectors have levelled out or have begun to decrease, transport's CO_2 emissions have risen steadily since 1990. It should be noted that whilst Figure 2 is presented in terms of CO_2 emissions, very similar trends are evident for GHG emissions (in terms of CO_2 equivalent) since CO_2 emissions represent 98% of transport's GHG emissions.

Figure 2: **Carbon dioxide emissions by sector EU-27 (indexed)**[2]



Notes:

i) *The figures include international bunker fuels (where relevant), but exclude land use, land use change and forestry*

ii) *The figures for transport include bunker fuels (international traffic departing from the EU), pipeline activities and ground activities in airports and ports*

iii) *"Other" emissions include solvent use, fugitive emissions, waste and agriculture*

The vast majority of European transport's GHG emissions are produced by road transport, as illustrated in Figure 3, while international shipping and international aviation are other significant contributors.

Recent trends in CO_2 emissions from transport are also expected to continue, as can be seen from Table 1 below. Between 2000 and 2050, the JRC (2008) estimates that GHG emissions from domestic transport in the EU-27 will increase by 24%, during which time emissions from road transport are projected to increase by 19% and those from domestic aviation by 45%. It is important to note that these projections do not include emissions from international aviation and maritime transport, which are also expected to increase due to the growth in world trade and tourism.

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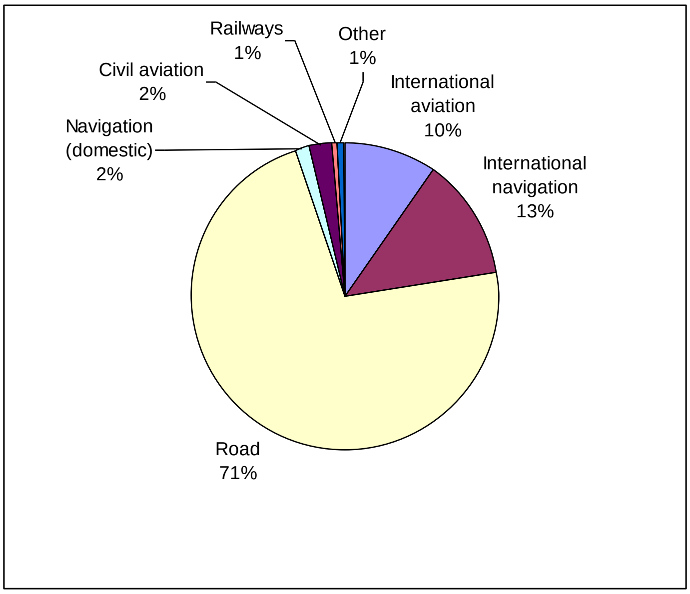
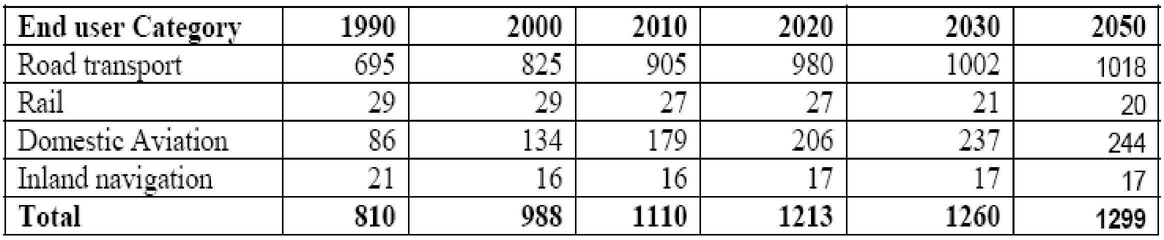
[2] Graph based on figures in DG TREN (2008) *EU energy and transport in figures 2007-2008: Statistical Pocketbook* Luxembourg, Office for Official Publications of the European Communities.

Figure 3: Greenhouse gases emissions by transport mode (EU-27; 2005)[3]



Note: The figures include international bunker fuels for aviation and navigation (domestic and international)

Table 1: CO_2 emissions projection for 2050 by end-users in the EU-27, in Millions tonnes of Carbon[4]



End user Category	1990	2000	2010	2020	2030	2050
Road transport	695	825	905	980	1002	1018
Rail	29	29	27	27	21	20
Domestic Aviation	86	134	179	206	237	244
Inland navigation	21	16	16	17	17	17
Total	**810**	**988**	**1110**	**1213**	**1260**	**1299**

Figures from the EEA (2008), illustrate the recent growth in GHG emissions from international aviation, as they estimate that these increased in the EU by 90% (60 Mt CO_2e) between 1990 and 2005; international aviation emissions will thus become an ever more significant contributor to transport's GHG emissions if current trends continue. Furthermore, the IPCC has estimated that the total impact of aviation on climate change is currently at least twice as high as that from CO_2 emissions alone, notably due to aircrafts' emissions of nitrogen oxides (NO_x) and water vapour in their condensation trails. However, it should be noted that there is significant scientific uncertainty with regard to these estimates, and research is ongoing in this area.

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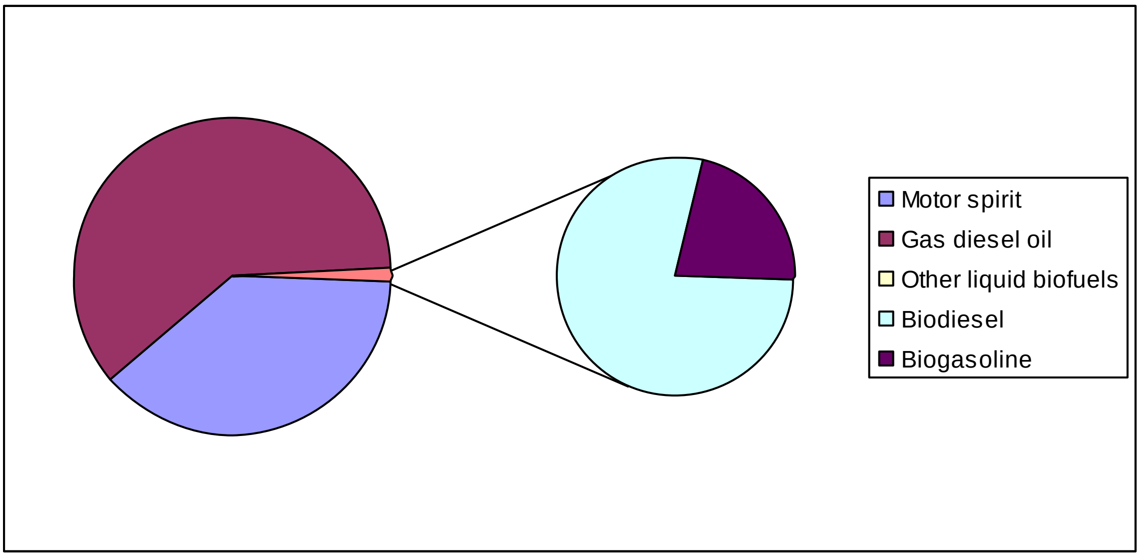
[3] Graph based on figures in EEA (2008) *Climate for a transport change – TERM 2007: Indicators tracking transport and environment in the European Union* EEA Report 1/2008, Luxembourg, Office for Official Publications of the European Communities.

[4] Taken from JRC (2008) *Backcasting approach for sustainable mobility* Luxembourg, EUR 23387/ISSN 1018-5593, Office for Official Publications of the European Communities.

Figure 4: Final transport energy consumption by liquid fuels in EU-27 (2005), ktoe[5]



The principal source of transport's GHG emissions is the combustion of fossil fuels. Currently, petrol (motor spirit), which is mainly used in road transport (e.g. in passenger cars and some light commercial vehicles in some countries), and diesel, which is used by other modes (e.g. heavy duty road vehicles, some railways, inland waterways and maritime vessels) in various forms, are the most common fuels in the transport sector (see Figure 4). Additionally, liquid petroleum gas (LPG) supplies around 2% of the fuels for the European passenger car fuel market (AEGPL, 2009[6]), while the main source of energy for railways in Europe is electricity, neither of which are included in Figure 4. While, alternative fuels are anticipated to play a larger role in providing the transport sector's energy in the future, currently they only contribute 1.1% of the sector's liquid fuel use.

1.3 Background to project and its objectives

The context of the *EU Transport GHG: Routes to 2050* is the Commission's long-term objective for tackling climate change, which entails limiting global warming to 2°C and includes the definition of a strategic target for 2050. The Commission's President Barosso recently underlined the importance of the transport sector in this respect be noting that the next Commission "needs to maintain the momentum towards a low carbon economy, and in particular towards decarbonising our electricity supply and the transport sector"[7]. There are various recent policy measures that are aimed at controlling emissions from the transport sector, but these measures are not part of a broad strategy or overarching goal. Hence, the key objective of this project is to provide guidance and evidence on the broader policy framework for controlling GHG emissions from the transport sector. Hence, the project's objectives are defined as to:

- Begin to consider the long-term transport policy framework in context of need to reduce greenhouse gas (GHG) emissions economy-wide.
- Deal with medium- to longer-term (post 2020; to 2050), i.e. moving beyond recent focus on short-term policy measures.
- Identify what we know about reducing transport's GHG emissions; and what we do not.
- Identify by when we need to take action and what this action should be.

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[5] Graph based on figures in DG TREN (2008), page 206

[6] European LPG Association (2009) *Autogas in Europe, The Sustainable Alternative: An LPG Industry Roadmap,* AEGPL, Brussels. See http://www.aegpl.eu/content/default.asp?PageID=78&DocID=994

[7] http://ec.europa.eu/commission_barroso/president/pdf/press_20090903_EN.pdf

Given the timescales being considered, the project will take a qualitative and, where possible, a quantitative approach. The project has three Parts, as follows:

- Part I ('Review of the available information') has collated the relevant evidence for options to reduce transport's GHG emissions, which was presented in a series of Papers (1 to 5), and is in the process of developing four policy papers (Papers 6 to 9) that outline the evidence for these instruments to stimulate the application and up take of the options.
- Part II ('In depth assessment and creation of framework for policy making') involves bringing the work of Part I together to develop a long-term policy framework for reducing transport's GHG emissions.
- Part III ('Ongoing tasks') covers the stakeholder engagement and the development of additional papers on subjects not covered elsewhere in the project.

As noted under Part III, stakeholder engagement is an important element of the project. The following meetings were held:

- A large stakeholder meeting was held in March 2009 at which the project was introduced to stakeholders.
- A series of stakeholder meetings (or Technical Focus Groups) on the technical and non-technical options for reducing transport's GHG emissions. These were held in July 2009.
- A series of Technical Focus Groups on the policy instruments that could be used to stimulate the application of the options for reducing transport's GHG emissions. These were held in September/October 2009.
- Two additional large stakeholder meetings at which the findings of the project were discussed.

As part of the project a number of papers have been produced, all of which can be found on the project's website, as can all of the presentations from the project's meetings.

1.4 Background and purpose of the paper

This paper is one of five "options" papers (Papers 1 to 5) that were developed under the *EU Transport GHG: Routes to 2050* project. The aim of these papers was to review the technical and non-technical options that could contribute to reducing transport's GHG emissions, both up to 2020 and in the period from 2020 to 2050. A series of papers (Papers 1 to 6) on "policy instruments" that could be used to stimulate the application and take up of these options was also developed. For the purpose of the project, we used the following definitions:

- **Options** deliver GHG emissions reductions in transport – these can be technical, operational or modal shift.
- **Policy instruments** may be implemented to promote the application of these options.

The options were reviewed in the following papers:

1. Technical options for fossil fuel based road transport.
2. Alternative energy carriers and powertrains.
3. Technical options for non-road transport modes.
4. Operational options for all modes.
5. Modal split and decoupling.

This paper is the second in this series of papers, all of which use evidence from existing studies to assess each of the options. It was presented in draft form to a Technical Focus Group meeting (at which stakeholders were present) in July 2009 after which it has been updated on the basis of the discussion at the meeting and any comments and further evidence received. This revised version of the paper can be found on to the project's website.

Alternative fuels and powertrains offer the potential for the most significant long-term GHG emissions reductions from transport technological measures and will be critical to achieve the long term targets for emission reduction set out in Section 1.2.

1.5 Structure of the paper

Following this introduction this paper is structured according to the following further 6 chapters:

2. General Background for Different Transport Modes
3. Liquid Biofuels and Biogas
4. CNG, LNG and LPG
5. Pure Electric and Plug-in Hybrids
6. Hydrogen and Fuel Cell
7. Summary of Key Findings and Conclusions

Each of the chapters from 3 to 6 begins with an introduction to the specific area, which includes an overview of the options for different transport modes. The options are then analysed in turn to assess a range of factors. Where data was available the following factors were included:

- GHG reduction at vehicle level (short-term and long-term);
- Long term overall reduction potential;
- Indication of cost at vehicle level and total cost;
- Timeframe for application;
- Co-benefits;
- Infrastructural requirements;
- Stakeholder vision;
- Barriers;
- Policy instruments;
- Interaction with other GHG reduction options;
- Uncertainties and main open issues.

Each chapter concludes with a comprehensive list of references.

2 General Background for Different Transport Modes

2.1 Road Transport

The road transport sector accounts for about one fifth of the EU's CO_2 emissions, with passenger cars responsible for over half of this. As by far the largest transport source of greenhouse gas (GHG) emissions (and with much faster fleet turnover compared to air, ship and rail transport) road transport has been the primary focus of most of the R&D into alternative fuels and powertrains. Although policy, legislation and R&D have focused on road transport initially, this has began to widen to other transport modes in recent years. Even so, it is anticipated that the greatest potential for long-term GHG reductions lies in road transport with the potential to virtually eliminate CO_2 emissions in the very long term with a switch to renewable hydrogen-fuelled and/or electric vehicles. In the interim there are a number of other measures that are may provide important bridges to eventual independence from fossil derived energy sources, such as biofuels and plug-in hybrid vehicles. However, there are a technical and non-technical challenges and uncertainties for all these options that need to be overcome in order to achieve significant savings in both the short-term (to 2020) and long-term (to 2050 and beyond). Whilst the technical challenges are broadly similar between different road transport modes, it should be noted that the level of applicability of different options is strongly influenced by different usage patterns.

2.2 Aviation

The Advisory Council for Aeronautical Research in Europe (ACARE) targets for aerospace manufacturers include a 50% reduction in CO_2 emissions relative to their year 2000 counterparts. Manufacturers have also committed to delivering 20-25% of the target through airframe improvements (discussed separately in Paper 3). Improvements in engine development are also factored into the overall target, however for commercial aircraft there are no viable short-medium term powertrain alternatives. Since the life time of aircraft is relatively high (about 30 years), measures that can be used in the existing fleet, or retrofitted, are important to realize CO_2 reductions in the short- and medium-term. Potential options for entirely new propulsion systems and fuels (e.g. hydrogen) are generally viewed as possible for introduction only in the long-term (i.e. 2050 onwards). The focus for aviation relevant to this paper has therefore mainly been on developing biofuels suitable for aviation application.

For the aviation sector, significant development in aviation biofuels is only relatively recent. The formation of cross-industry initiatives in the last year has led to demonstration flights and a number of US and European research projects on sustainable biofuels have also only recently started. Aviation biofuels need to be drop-in biofuels that essentially require no aircraft modifications due to their international operation (hence need to be able to use fuel from anywhere in the world) and long lifetimes. Aviation biofuel produced from hydrotreated vegetable oil (HVO) and synthetic kerosene from BtL type processes are the primary viable short-medium term alternatives to conventional jet fuel. Their potential in the long term is uncertain and will depend on competition for biomass from other sources, as well as the potential development of new feedstocks, such as algae.

2.3 Shipping

On a maritime ship fossil fuel is employed to generate on the one hand propulsion and on the other electric power. Electric power is needed for different purposes, e.g. to run the control and navigation systems, to provide crew and/or passengers with lighting, ventilation, fresh water, air conditioning etc. In considering alternative energy carriers and powertrains to reduce GHG emissions, such options may be targeted at both propulsion and other electric power, or simply the provision of other electric power.

The options can either be compatible with existing powertrains (e.g. biofuels) or retrofit or non-retrofit measures with the latter only being applicable to newly built ships. Since the life time of vessels is relatively high (about 30 years), retrofit measures are important to realize CO_2 reductions in the short- and medium-term. Thus only in the long-run design optimization will be effective and it has to be born in mind that to realize a high reduction level in 2050 measures have to be taken far earlier.

For most measures there is still uncertainty as to the costs and the reduction potentials, which can vary significantly with the ship types and whether they are retrofitted or applied to a new ship. Cost and abatement potential data is often not available at all or limited to certain types of ship. Long-term field tests on a large scale are actually needed in many cases. Tests in towing tanks deliver data for still-water conditions mainly.

Inland shipping in many cases is the most energy-efficient way of long distance inland transport of economic goods [1],[2]. However many additional options of reduction of fossil energy demand and GHG reductions still are not or partly unexploited. Although no systematic studies on GHG-reduction of inland navigation are found some references of special interest are available. However explicit evaluation in terms of GHG-reduction potential is lacking or very difficult to extract sometimes from such highly specialized studies. Much of the information that could be traced about inland shipping has its origin in Germany or the Netherlands, who together have the largest share in inland waterway transport in Europe (more than 80% of total tonne.km).

2.4 Rail

The rail sector has many unusual facets compared to the other main modes of transport. For instance, there are hundreds of ‘classes’ of rail vehicle (which include passenger and freight locomotives, diesel multiple units, electric multiple units and shunting vehicles) in service across Europe. They have wide range of specifications and operate across a patchwork of networks (AC electric, DC electric, diesel only, light rail, high speed rail etc), many of which are incompatible and have been upgraded with new infrastructure (e.g. signalling equipment) to varying degrees.

Furthermore, rail vehicles typically have a lifetime of 30-35 [3] years so there are limited opportunities to improve emissions performance. The rail sectors are structured very different across Europe – many are nationalised where as others are partly or fully privatised. As a result of the highly complex nature of the rail sector it is very challenging to make accurate estimates of the carbon savings or costs associated with any technical options related to alternative energy carriers. To establish accurate costs most options would require a detailed local feasibility study to fully understand the issues associated with the specific infrastructure and rolling stock in question.

Before considering the main technical options in more detail it is worth bearing in mind that there are some generic barriers to introducing new technologies in the rail sector. For instance, the complex interactions between the rail vehicles and the infrastructure on which they operate can create difficulties. Any new technology must be shown to be compatible with existing and future rails and signalling infrastructure. In addition, safety requirements cannot be compromised by any new technology. Furthermore, depending on the structure of the rail industry in each country, any change on the railways, particularly to rolling stock, can involve liaising with a multitude of stakeholders. As a result, it seems likely that introducing new technologies will take longer than in some of the other sub-sectors (mainly road transport) particularly given this need for a range of partners (sometimes with conflicting perspectives) to work closely together.

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3 Liquid Biofuels and Biogas

3.1 Introduction

Biofuel is a term for a range of fuels for the transport sector, including vegetable oil, biogas/biomethane, bioethanol, biomass-to-liquid (BtL) biodiesel, hydroprocessed vegetable oil (HVO), biodiesel and conventional biodiesel (also referred to as Fatty Acid methyl Ester, FAME; RME is a FAME produced from rapeseed). Biogas can be used in natural gas powered engines (typically spark ignition), whilst bioethanol is used in petrol spark ignition engines.

Conventional biofuel processes (often referred to as ‘first-generation’) are generally defined as those that convert food crops in liquid fuels. The processes are esterification of vegetable oils to produce biodiesel and fermentation of sugar-rich and cereal crops to produce bioethanol. Advanced biofuel technologies are sometimes viewed as offering a more sustainable alternative to first generation biofuels. Advanced biofuel processes (often referred to as second generation) are typically defined as those that convert ligno-cellulosic materials (e.g. woody or grassy biomass). There are two principle technology routes for producing these advanced fuels – biological and thermochemical. More recently there has also been significant interest in biodiesel produced from hydrotreating vegetable oils and in non-food oil producing crops such as Jatropha that can be grown on land not suitable for food production. Such HVO biodiesel fuels are sometimes considered to fall in between biofuel production that is generally thought of as first or second generation.

Work on thermochemical conversion process is concentrated on demonstrating gasification technology (e.g. for BtL biofuels) and proving pyrolysis technologies. For biological processes the focus is decreasing costs to an acceptable level and improving efficiency, largely through improvements to the hydrolysis stage. Anaerobic digestion (to produce biogas/biomethane) is largely proven, although not necessarily economic for some feedstocks. Work on ligno-cellulosic feedstocks shows steady progress towards decreasing cost and improving yield suitability and pre-treatment. There is also a renewed interest in aquatic species such as algae, with algal-based biofuels sometimes referred to as third generation biofuels.

Because biofuels can be produced from a wide variety of different feedstocks and production pathways, there is a wide range in their cost and in net GHG benefits compared to conventional fossil fuel equivalents. There are also significant complicating issues and uncertainty, such as sustainable biomass resource availability, biofuels interactions with land use, indirect land use change, food, water availability, etc.

3.2 Overview of options

General

Biofuels can theoretically save significant levels of greenhouse gas emissions. However, this is very sensitive to the feedstock and production pathway used, as well as fundamental assumptions in the calculation of savings. In the short-term, current biofuels are likely to offer only a small/limited potential with greater savings possible in the medium term as advanced feedstocks and production processes are developed/mature. In the long term their potential may be constrained by competition for land use to feed an increasing global population and replace petrochemical derived products (e.g. textiles, plastics and chemicals) with those produced from biomass. Much here will depend on the development of promising advanced biofuel technologies and feedstocks (e.g. algae). Given the likely constraints on biofuel production, some future energy scenarios assume their use will be reserved for aviation, shipping and long-distance road freight transport, where alternative low-carbon options are more limited.

Road transport

Current biofuels for road transport include bioethanol, biodiesel and biomethane. Bioethanol is commonly used in blends with petrol in existing road vehicles worldwide, - for example as a 5% blend in Germany, as well as in other EU countries. In the Fuel Quality Directive (FQD, 98/70/EC) as amended by Directive 2009/30/EC, an increased allowance for blends of up to 10% ethanol with petrol has been provided (and E10 blends are already present on the EU market), complementing the Renewable Energy Directive (RED), 2009/28/EC. It can also be used at higher levels up to 85% bioethanol (E85) in specific flexi-fuel vehicles or even higher in dedicated vehicles. In Brazil the fuel is used at various blends all the way from E0 to E95/E100. Biodiesel is currently used in blends of up to 5% (for conventional) biofuels (i.e. B5), with recent amendments to the FQD allowing up to 7% (i.e. B7) and potentially greater blends for advanced biofuels where compatibility is not an issue. Biomethane is the term often used for biogas that has been upgraded to a quality suitable for transport applications (i.e. removing CO_2 and other impurities to achieve 95-98% methane). Bio-DME (dimethyl ether) is another alternative biofuel being considered that can be used in converted diesel engines and may also be used in a 30% blend with LPG in suitable engines.

Bioethanol is manufactured using hydrolysis to produce simple sugars, which are then fermented to produce ethanol. In Europe key biofuel stocks are sugar beet and wheat compared with corn in the US and sugar cane in Brazil. In the future, alternative hydrolysis methods could be used to derive ethanol from ligno-cellulosic materials. FAME biodiesel is produced using an esterification process based on feedstocks of either recovered waste vegetable oils and animal fats or oil extracted from seeds or oil-rich nuts. In the future, gasification may be used to convert a much wider range of feedstocks into biodiesel (e.g. woody or grassy feedstocks) and also reduce competition for land with food production. Similarly, new feedstocks for biodiesel production, including jatropha and algae, may also become significant in the future, as they do not require the use of fertile agricultural land. Also hydro treating offers the potential to produce much higher quality biodiesel from vegetable oils than current esterification processes. Biogas is produced from anaerobic digestion of wet organic waste or other biomass and can be upgraded to biomethane, by removing carbon dioxide, water, and impurities[8].

Aviation

The biofuels that are currently commercially available are not suitable for large-scale use in aviation. This is because aviation fuels must stay liquid at low temperatures and have a high energy content by volume. There are, however, several options under development. The most attractive appears to be synthetic kerosene from BtL (biomass-to-liquids) type processes and from hydrotreated vegetable oil (HVO). The former is potentially similar in performance to the petrochemical derived kerosene which is currently used to power aircraft and has achieved quality certification at 50% and 100% blends. The latter is an area where there is increasing interest from industry and HVO type aviation biofuels have been used successfully in recent demonstration flights.

Shipping

The focus on the use of biofuels in shipping has been on vessels running on diesel, and a number of trials are currently taking place. Ships that run using fuel oil have received limited consideration, although there has been some work considering possibilities like pyrolysis oil and biocrude.

Rail

Currently available biodiesel can feasibly be used in railway traction unit engines in lower percentage blends. However, it is in limited use reflecting that cost is one of the most significant barriers.

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[8] http://www.environmental-protection.org.uk/transport/biomethane-transport-forum/

3.3 General

Biofuels can theoretically save significant levels of greenhouse gas emissions. Analysis based on a number of studies [1] suggesting that bioethanol from sugar beet could offer emission savings (mid range) of between 26% to 51% and biodiesel from oilseed rape offering savings (mid range) of between 38% to 64%. However, according to recent work by by JEC (2008)[12], values calculated with the substitution method show bioethanol from sugar beet could offer typical emission savings of 56% and biodiesel from oilseed rape could offer typical savings of 50%. Ethanol produced from sugar cane in Brazil or Africa performs much better, achieving typically from 70% - 90% GHG savings. GHG emission savings from future advanced biofuels have been reported to be potentially significantly higher at 73%-95% [7]. However, Sensitivity analyses carried out as part of a project for EC DG Environment by AEA and North Energy [12] have highlighted the significant impacts different assumptions and conditions can have on the results of LCA of bioenergy pathways. These include elements such as:

- Country-specific influences (variations in yield, fertiliser application rates and national average electricity generation mixes);
- Source of process heat or electricity;
- Transport distances (e.g. for feedstock);
- Allocation methods (i.e. by price, substitution, energy content or mass)
- N_2O soil emissions assumptions;
- Reference systems (i.e. definition, inclusion/exclusion – particularly important for waste feedstocks); and
- Land use change.

There are also a number of issues which need to be resolved and questions which need to be answered before these savings can be confidently quantified and agreed upon. These issues include the potential for Indirect Land Use Change (ILUC). ILUC can happen when land use changes occur not just where the biofuels crop is planted, but as a result of displacement of the previous land use elsewhere (including in other countries, which may be some distance from the original crop). The main concern is that this may ultimately lead to pressure for deforestation or conversion of grasslands or peatlands to agriculture. Such habitats represent considerable carbon stocks in and above ground, resulting in an immediate increase in greenhouse gas emissions. This increase may outweigh the greenhouse gas benefit from the use of some biofuels leading in extreme cases (e.g. from deforestation) to net emissions potentially several times those of the fossil fuels they are replacing.

Generally due to the indirect land use change (ILUC) issues and food competition, it seems likely that current generation food-crop based biofuels will only be a temporary or at least very limited option, although further detailed analysis is needed to confirm this. (The EC is presently carrying on studies on ILUC effects, and will present a report in 2010 on this specific matter). Other types of advanced feedstocks and biofuels therefore need to be developed in order for greater reductions to be achieved in the longer term [18], [19], [20]. Some studies even suggest that the role of bioenergy is only likely to be significant in the medium-term. This being primarily due to increasing demands on global land use for feeding a growing world population and a growing tendency for petrochemical products (e.g. textiles, plastics, chemical products) to be produced from biomass [21]. Energy yield per hector also needs including in any assessment comparing biofuels to alternatives, for example the energy yield per hectare for solar electricity (photovoltaics) is potentially better than biofuels.

3.4 Road transport

The potential emissions savings in the short- and long-term has been discussed in Section 3.3.

In terms of financial costs research suggests that the costs per litre and competitiveness with petrol and diesel vary depending on the biofuel, feedstock and the country of origin. For example, ethanol from sugar cane in Brazil and Corn from the US are competitive with petrol. In the longer term, the use of cellulosic crops with advanced technologies may reduce costs, although they are currently more costly than biofuels produced using existing fermentation and esterification processes.

There are potential 'benefits' associated with the biofuels which can help reduce costs and greenhouse gas and energy use impacts. When biofuels are produced there are often co-products, such as straw, rape meal and glycerol from oilseed rape for biodiesel which can be used in alternative ways. For example, straw can be used as a heating fuel, rape meal as animal feed and glycerol for use in the chemical industry. Further research in this area is currently taking place.

In terms of implementation - blends of up to 5% do not require modification to vehicles. Ethanol blends of up to 85% can be used in Flexi-fuel Vehicles, which require relatively little modification and extra cost compared to regular car models. In addition, at lower percentage blends, current biofuels can be relatively easily blended into existing transport fuel infrastructure. Although flex-fuel vehicle (FFV) technology and E85 is already in the marketplace, it does not have significant widespread availability/introduction except in a few European countries (e.g. Sweden). In the future, however, there may be the need to invest more widely in facilities and in the infrastructure to meet the requirements of higher blends at least for petrol-ethanol blends. It is anticipated that future BtL and HVO biodiesel fuels will be of equivalent or higher quality than conventional diesel and will be compatible with existing diesel technologies all the way to 100%. If these fuels were used for blends with conventional fuel greater than the current 5% then there would likely be little need for new diesel fuel infrastructure.

The key policy instrument in place, at the European level, is the Renewable Energy Directive, which requires a mandatory 10% minimum target for the share of renewable energy in transport energy consumption to be achieved by all Member States by 2020. It is currently anticipated most of this will be achieved using biofuels. Member states are introducing measures to move towards this, and previous Biofuel Directive targets. For example, in the UK the RTFO requires transport fuel suppliers to ensure that a percentage of their sales in the UK are from renewable sources and there are similar schemes in the Netherlands and Germany.

Key issues include the competing uses of biofuels and related feedstocks and consideration needs to be given to the extent to which wider uptake of biofuels which could divert resources from other applications for example heating, that may have greater life-cycle greenhouse gas benefits. Further concerns over land availability and ownership, land use change and the effect on food and feedstock commodity prices are other key potential barriers. Evaluation of biofuels also needs to include an assessment of the impact of lost tax revenues from fossil fuel (and the degree to which this is offset through direct or indirect benefits of biofuels).

3.5 Aviation

As with road transport, the use of biofuels can theoretically save significant levels of greenhouse gas emissions in the aviation sector. However, steps will need to be taken to ensure that the biofuels produced are truly sustainable and offer greenhouse gas savings when the whole life cycle (including indirect effects) is taken into consideration.

A stimulus for research and development of aviation fuels is the need for aviation to meet future emission targets. Recent work conducted by AEA [2] suggested stakeholders in the aviation industry believe a take up of 30% of all commercial aviation jet fuel by 2030 (which is equivalent to around 60% of current demand) may be needed in order for the industry to achieve its mid to long term CO_2 reduction targets.

In terms of stakeholder engagement in this area a number of cross-industry initiatives were formed in the last few years, such as the Commercial Aviation Alternative Fuels Initiative (CAAFI, a US air transport industry coalition) and the more recent Sustainable Aviation Fuels User Group

(SAFUG), formed to accelerate the development and commercialisation of sustainable new aviation fuels.

The barriers which need to be addressed depend on the fuel used. When considering BtL, the barriers include:

- The need to identify and develop and cost-effective and sustainable biomass supply chains for large and capital intensive BtL process plants;
- BtL plants may be limited in scale by the practicality of supplying large volumes of biomass feedstock;
- The higher capital costs for BTL plans compared with CtL (Coal-to-Liquid) and GtL (Gas-to-Liquid) plants are likely to provide a significant barrier to commercialisation.

For these reasons Hydrotreated Vegetable Oil is viewed [2] as having the potential to becoming commercially available in shorter timeframe than BtL biodiesel. However, this fuel currently uses predominantly oils from or competing with food crops as a feedstock, leading to conflicts here and potentially high ILUC emissions.

In terms of wider sustainability concerns a key issue is the potential that any fuel produced for aviation would displace production capacity for road fuels. In addition, is suggested [3] that biokerosene production using available advanced technologies requires further processing steps compared with road fuel production and therefore produces smaller emissions savings at greater cost.

More widely than road transport is the competing uses of biofuels and related feedstocks with other applications, that may have greater life-cycle GHG benefits. As with road transport concerns over land availability and ownership, land use change and the effect on food and feedstock commodity prices are other key potential barriers.

3.6 Shipping

Maritime research on biofuels to date has concentrated on those vessels that currently run on diesel [4]. At present little biofuel research has been undertaken on powering large ships that currently use fuel oil, although there has been some consideration of alternatives such as PPO (pure plant oil), pyrolysis oil and biocrude. The greenhouse gas savings achieved by running marine vessels on biofuels does have the potential to be significant, however issues, particularly around production, will be similar to those highlighted in road and aviation transport. Though its use of diesel may be less of a concern.

The cost to the sector will depend to a certain extent on the subsidies provided to the shipping industry. For example in the UK red diesel is used which is much cheaper than the biodiesel equivalent.

However, work is currently being undertaken to research and develop cost effective ways of producing biodiesel that does not compete directly with the road market. For example, the Biox process [5] claims to reduce biodiesel production costs so that it is competitive with petroleum diesel. The plant only started operating in summer 2006, so more time is required to fully assess the outcome. Pure plant oil (PPO) currently costs around 30 pence per litre [6] (35 Eurocents) in the UK, so is similarly priced to red diesel, however in order for a vessel to run on PPO fuel, engine modifications would be required incurring an inevitable financial cost

Biodiesel has been shown to reduce the wear and tear of an engine due to its increased lubricity. This will lead to operational cost savings, however clear financial savings are difficult to estimate.

In terms of stakeholder engagement a number of trials (of ships run on biofuels) have recently been conducted such as the UK Seafish project, the Canadian BioMer and Bioship projects and the US Indiana River Marina project.

While the use of biofuels on land is far more advanced, using biofuels at sea has several advantages, which include:

- Marine diesel contains higher sulphur content than land based diesel which translates into substantial sulphur dioxide emissions at sea. With biofuels these emissions would be reduced by over 99% [7];
- Marine engines are lower revving and more tolerant of different types of fuels than land based engines. This tolerance should allow marine engines to run on a lower grade of fuel and ultimately cheaper biofuels like PPO, pyrolysis oil and biocrude.
- The BioMer [4] study found that biodiesel in a blend with petroleum diesel enables it to burn better reducing carbon monoxide (CO) emissions substantially - there was found to be a 35% reduction with B100 against conventional biodiesel. Emissions of fine particulate matter (PM) and unburned hydrocarbons were also shown to be reduced (tests showed that when using B100, PM emissions were reduced by 82%). However, nitrogen oxide (NOx) emissions were found to increase slightly in the BioMer project by 10% with B100 but less than 5% with B20.
- Biodiesel is non-toxic and biodegradable and so it offers an environmentally friendly alternative to diesel in terms of spillages at sea. For example, B20 has been shown to biodegrade twice as fast as 100% petroleum diesel and pure biodiesel has been shown to degrade by 85-88% in water within 28 days [8]. However, this may cause problems in long-term storage of the fuel.
- Some studies have shown that the increased lubricity (reducing friction) of biodiesel reduces the wear and tear of the engine and ultimately the cost of maintaining vehicle fleets.

A number of economic, technical and social barriers [4] have been identified:

Economic barriers include:

- The barriers to the uptake of biodiesel in the marine sector are primarily economic rather than technological [9]. Cost reductions are needed to make biodiesel more competitive with red diesel.
- Pure plant oil is more competitively priced with red-diesel but as yet the technology has still to be proved.

Technical barriers include:

- Biodiesel has a 15% lower specific energy content than conventional gas oil [10]. Therefore for a given power output, the fuel consumption will be higher. This would require vessels to have larger fuel tanks or operate at a reduced range.
- Other possible technical issues are that biodiesel may be more corrosive and more abrasive than standard fuels. Biodiesel may also cause problems with fuel injector coking, leaving higher levels of engine deposits and therefore the filters may need to be changed more often.
- Some biofuels also lead to higher levels of NO_x emissions.
- Availability of supply could also be an issue if large volumes of biodiesel were required.
- Although the major element of the feedstock is vegetable or animal oil, the process also uses alcohol. The industry currently uses methanol manufactured from crude oil as it is the cheapest option but it would be technically feasible to use bio-ethanol to increase the "bio" proportion of the feedstock.

Social barriers include:

- A low level of awareness by shipping companies over the viability of biodiesel.
- Infrastructural requirements (e.g. tracking, separation of fuels to avoid contamination).

Policy measures [11] to take forward the use of biofuels in ships include ‘market based’ instruments such as a differentiated fuel levy and ‘command and control instruments’ such as a fuel life-cycle carbon emissions standard. Wider measures such as the inclusion of shipping in EUETS could also help bring forward the use of biofuels.

As with road and aviation transport there is the need to consider how the use of biofuel and related feedstocks relate to the use and greenhouse gas savings in other applications. This is true for both biofuels based on current feedstocks, but also advanced biofuels. For current biofuels, competition is mainly with land for food production /other food crops. For advanced biofuels, competition for grassy/woody biomass feedstocks is particularly significant with the heat and electricity sectors which use similar feedstocks. However, with the future decarbonisation of the electricity sector bioenergy will become less attractive in this area.

3.7 Rail

The greenhouse gas savings achieved by running rail on biofuels could theoretically be significant and the potential for savings in the short- and long-term has been discussed in Section 3.3. As with other modes wider impacts of the production of the biofuels need to be taken into consideration before agreement on savings can be reached. In terms of long term overall reduction potential it should be noted that diesel traction (rather than electric) accounts for only 20% of European railway operations. There is also significant variation in the use of diesel versus electric rail between countries (for example in Switzerland), which is fully electrified and diesel traction is rarely used. Therefore the overall potential savings from biofuel use on European railways is relatively small.

The current use of biodiesel is limited because conventional diesel is often significantly cheaper than biodiesel [13]. This is particularly the cases where duty reductions are in place for rail compared to fuels for road transport application. The cost of oil seed feedstock is a significant component here. In the future, advanced BtL diesel fuels, which are currently being developed, could be less expensive, although currently they are significantly more costly.

There are additional benefits with the use of biodiesel in rail. Research [14] suggests that biodiesel can reduce gaseous and particulate emissions, has a higher cetane number and flashpoint and improved lubricity. While the negative impacts include a reduced energy content, and incompatibility with certain elastomers.

Biodiesel is technically feasible for use in railway traction unit engines in lower percentage blends, but there are still disadvantages such as increased fuel consumption and decreased power. Blends in excess of B30 may increase life cycle costs. Advanced biofuels can meet a higher specification and in fact may prove to be better than fossil fuels

While costs are limiting current use, stakeholders in certain countries are taking biodiesel in rail forward. In India, a National Biodiesel Mission engaging all stakeholders aims to increase production of biodiesel to levels that will enable blends of 20% biodiesel to be sold in the county by 2012. While in the UK, in 2007, Virgin Trains were the first company to run a train on biofuels (in the UK) on a 20% biodiesel blend. By converting their Voyager fleet to run on B20 biodiesel, Virgin Trains could cut their CO_2 emissions by up to 14% [15].

In terms of policy the Renewable Energy Directive which requires a mandatory 10% minimum target for the share of biofuels in transport petrol and diesel consumption to be achieved by all Member States by 2020 may have an impact in terms of taking use forward.

In terms of alternative price based policy measures there is currently little scope to introduce a duty differential to encourage the increased use of biodiesel without first increasing duty on conventional diesel, which would, at least in the short-term increase the cost of fuel used by the railways. Similarly, obligations on suppliers of fuel to railways to use a certain proportion of biodiesel in their fuel would also increase the costs of the fuel, as long as the costs of biodiesel remain higher than conventional diesel. Where railways do pay fuel duty, it is possible to reduce the duty on Biofuels, for example, in proportion to the percentage blend used. However, whether it is possible to introduce a sufficiently large differential that would encourage the use of Biofuels will depend on the various costs and tax levels in any particular country.

As with road and aviation transport there is the need to consider how the use of biofuel and related feedstocks relate to the availability, use and greenhouse gas savings in other applications.

3.8 Gaps in Identified Information

- *General:*
  - The key overarching gap is, in relation to all modes, a more detailed understanding of the sustainable development impacts of the use of biofuels. This includes the potential for indirect land use change and if it is significant how this could be mitigated[9] and a better understanding of the socio-economic impacts. Increased understanding on advanced biofuels is required.
  - An understanding of the impact of current policy measures e.g. RED and future policies in encouraging take up of more sustainable biofuels is a gap.
- *Road Transport:*
  - Research [2] is required to understand the future fleet capability for use of biofuels and for higher blends. Further research into higher blends to address any issues over quality is necessary. This includes research into quality standards. An appreciation of the availability of more sustainable biofuels could impact on vehicle and engine design would be useful.
- *Aviation:*
  - The demand for aviation biofuels and a better understanding of how it will impact on and interact with demand in other sectors is required [2].
  - An understanding of the potential for biofuels use in new planes (engine) configurations is necessary.
- *Shipping:*
  - An increased understanding of the longer term potential for the use of biofuels in shipping building on the IMO (2009) [11] work is necessary including, as with aviation, an understanding of demand and interaction with different sectors.
- *Rail:*
  - An increased understanding of how the cost barrier can be overcome is required.

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4 CNG, LNG and LPG

4.1 Introduction

Natural gas (consisting mainly of methane) is a clean-burning fuel with current low-level application mainly in the road-transport sector. Its use in natural gas vehicles (NGVs) offers significant Well-to Wheels (WTW) CO_2 reduction potential over petrol-engined vehicles (comparable to diesel) and also reductions in air quality emissions. Natural gas is carried either compressed (in CNG vehicles) or liquefied (in LNG vehicles) in heavily insulated tanks [15]. NGVs are generally seen as a short-medium term technology to reduce greenhouse gas emissions on the way to the eventual use of hydrogen fuel cell and/or electric vehicles. There is particular interest in NGVs for application with biogas/biomethane rather than natural gas, discussed further in section 3. There has also been some suggestion that mixtures of hydrogen and natural gas used in NGVs (and compatible with existing gaseous distribution technology) may act as a bridging technology for more widespread use of hydrogen as a road transport fuel.

Liquefied petroleum gas (LPG) is a mixture of mainly propane and butane gases, pressurised to form a liquid. These gases can occur either individually or in combination. LPG can occur naturally with other hydrocarbons such as wet natural gas in oil and gas fields, or it can be extracted at oil refineries during the production of other petroleum products. LPG road vehicles have been in use for many years in low quantities, mainly driven by reduction in air quality pollutants, although net GHG emissions reductions compared to petrol in modern dedicated vehicles are similar to diesel.

4.2 Overview of options

Road Transport:

NGVs using CNG or LNG are already in-use in relatively low numbers and niche applications, mainly in the form of bi-fuel vehicle for light-duty vehicles and dedicated NGVs for heavy-duty applications. In general natural gas vehicles (NGVs) have spark ignition engines, although many standard road vehicle diesel engines can be converted to run on a mixture of diesel and up to 90% natural gas. Such duel-fuel engines are just starting to be introduced for heavy-duty vehicles. In addition there is the possibility for using existing NG distribution systems to deliver a mixture of hydrogen and natural gas to end use applications (including NGVs) as a bridging step to a hydrogen economy.

Aviation:

Natural gas and LPG are not suitable alternative fuels for aviation, primarily because of the need for fuels with much greater energy density.

Shipping:

Natural gas, when stored in a liquid state as liquefied natural gas (LNG), is a promising future fuel for ships: LNG delivers very significant reduction of NOx and SOx and PM emissions and at the same time also a reduction in CO_2 equivalents. LPG is not being considered as a viable alternative fuel for shipping.

Rail:

There is some limited experience in using natural gas in rail applications, usually driven by reductions in air quality emissions unless biogas/biomethane are utilised (e.g. a biogas powered railcar is in operation in Sweden). There is no experience in using LPG currently. As for aviation (and to an extent shipping), the high volume and weight requirements of natural gas and LPG storage systems is a significant impediment for rail applications.

4.3 Road Transport

4.3.1 CNG and LNG

Emissions

Natural gas has a high octane number (approximately 120) allowing a higher compression ratio than is possible using petrol, which can increase engine efficiency. However, achieving the maximum benefit requires that the vehicle (engine and fuel system) is dedicated to CNG or LNG. Many current vehicles using CNG are converted from petrol vehicles or manufactured as bi-fuel vehicles, with two fuel tanks, which cannot take full advantage of CNG's high-octane ratio [1]. Compared with the life-cycle GHG emissions of a petrol-fueled vehicle, a CNG bi-fuel vehicle has roughly 25% less total CO_2-equivalent emissions (on a WTW basis) [2], roughly equivalent to diesel engined vehicles. NGVs (i.e. natural gas vehicles running on either CNG or LNG), have a number of other advantages over petrol equivalents. For cars, advantages include the following:

- Reduced carbon dioxide emissions (25%);
- Reduced nitrogen oxide emissions (35%-60%);
- Potentially reduced non-methane hydrocarbon emissions (50%-75%;
- Fewer toxic and carcinogenic pollutants;
- Little or no particulate matter and eliminated evaporative emissions (for dedicated vehicles).

However, air quality benefits will diminish in the short-term due to tightening in the relevant type-approval Euro standards, although this tightening may come at a higher fuel penalty cost for petrol and diesel compared to CNG vehicles. Any evaluation of future impacts has to therefore include in the base assumption the impact of vehicles in compliance with EURO 6/EURO VI emission requirements. In the long-term local emissions would be higher than hydrogen-fuelled or electric alternatives

Transit buses equipped with model year 2004 CNG engines produce 49% lower NOx emissions and 84% lower particulate matter emissions versus transit buses equipped with model year 2004 diesel engines. Significant air quality benefits have also been recorded for other heavy-duty vehicles. For example, in a recent study of CNG and diesel United Parcel Service (UPS) delivery trucks, CNG trucks produced 75% lower carbon monoxide emissions, 49% lower nitrogen oxides emissions, and 95% lower particulate matter emissions than diesel trucks of similar age [3,4,5].

In general natural gas vehicles (NGVs) have spark ignition engines, although many standard road vehicle diesel engines can be converted to run on a mixture of diesel and up to 90% natural gas. For example, Dual Fuel Euro 5 Technology is currently being applied to Volvo Trucks [16]. This technology gives significant reductions in GHG emissions and fuel cost savings compared with standard diesel engines and are expected to be around 20% more efficient than equivalent spark-ignited natural gas engines.

There is some potential to optimise NGV technology to further improve the performance of dedicated CNG or LNG vehicles compared to conventional petrol and diesel equivalents. However, the principal benefit for NGVs in the future is from the use of biogas/biomethane, where very significant emissions reductions are possible, depending on the source of the fuel. This is also discussed in section 3.

In terms of the net life-cycle (so called 'well-to-wheel' GHG emissions impacts, these are significantly affected by the source of the natural gas. For the current EU mix the indirect/fuel cycle GHG component accounts for around 13% of the overall total, however for natural gas sourced from Russia via a 7000km pipeline, this rises to 28% [16]. This has important implications for the medium-longer term as the mix of sources of EU natural gas changes and the proportion of gas sourced from Russia is likely to increase significantly - eroding the benefits of NGVs over conventional petrol fuelled vehicles. Ultimately the short and long-term reduction potential offered by NGVs is linked to the availability of sustainably sourced biogas/biomethane. Here there is still significant uncertainty due to complicated issues around land use change (for biogas produced from energy crops) and competition for biomass with other sectors, such as heat (discussed separately in Section 3).

Biomethane produced from anaerobic digestion of grassy biomass (e.g. from specifically grown switchgrass) or organic waste has lifecycle CO_2 emissions between 60% and 200% lower than petrol and diesel. The higher emission reduction potentials are due to the fact that organic waste left untreated would otherwise decompose to release methane into the atmosphere (a greenhouse gas over 20 times more powerful than CO_2). If the methane was not being released into the atmosphere, biomethane is almost carbon neutral over the life cycle as it is made from organic waste.

There are a few policies supporting the use of biomethane already, e.g. in Lille, France, where the local authority collects organic waste, produces biomethane and uses it to power local buses. Despite its advantages the uncertainty of whether there will be enough feedstock could considerably endanger the large-scale uptake of biomethane run vehicles [21].

There has also been some consideration of using existing NG distribution systems to deliver a mixture of hydrogen and natural gas to end use applications as a bridging step to a hydrogen economy. The EC's NATURALHY project has considered this in detail[10]. Information is also presented in section 6.

Costs

Typically, for cars and car-derived vans run on natural gas, the additional capital or aftermarket conversion costs are in the range €4,380-€4,480 in the UK [5] and up to €4,500 in Germany [6]. The cost differential for heavy-duty vehicles is also significantly higher than diesel equivalents due to low volume production and high costs of on-board storage. A new compressed natural gas mid-large sized bus can cost US$30,000 more than a new diesel equivalent bus [18], with at least US$12,000 due the fuel system [19]. Equivalent costs for the fuel systems of refuse vehicles and heavy-goods vehicles are around US$9000 [19]. Since natural gas is a gaseous fuel, it must be stored and handled differently than more traditional liquid fuels like diesel or petrol. Therefore, CNG HDVs require special refuelling facilities as well as special maintenance facilities which add to costs.

Technical and Market Projections for NGVs

The utilisation of Natural Gas as an automotive fuel varies widely within as well as from one country to another, depending on the cost and availability of the fuel in relation to alternative fuels, notably petrol and diesel. As of November 2008 there were 957,316 NGVs on European roads - with Italy being the leader (580,000 NGVs), followed by Ukraine (120,000 NGVs) and Russia (95,000 NGVs) – with 3,000 refueling stations across the continent [1].

NGVs could play a significant role in the medium term. While the transportation sector may rely primarily on radical changes in motive power such as fuel cells, advanced batteries, and cellulosic biofuels, developmental risks and uncertainties are likely to delay widespread use of such options for decades. NGV technology is considered by some to be among the most appropriate interim solutions for use during that crucial transitional period to reduce petroleum dependence and its environmental effects [6,7].

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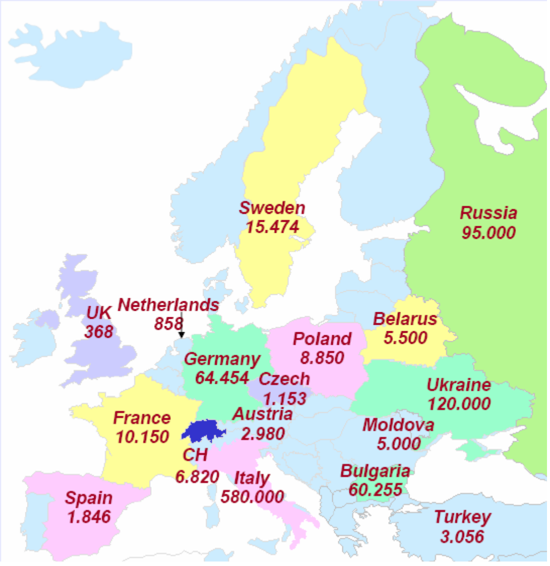
[10] More information on the NATURALHY project is available at: http://www.naturalhy.net/

Figure 4.1 – NGVs in Europe



Source: International Association for NGVs (IANGV), European Association for LPG (AEGPL), 2009, Road Signage for Natural Gas and LPG Fuelling Stations - Requesting to Amend the Convention on Road Signs and Signals, http://www.unece.org/trans/doc/2009/wp1/WP1-57-Pres2e.pdf

Light-Duty Vehicles

Light-duty NGVs as well as petrol-to-natural gas conversions are already produced and sold in large volumes. Current and projected petrol use in LDVs dominates the vehicle world, and projected diesel LDV use will only marginally moderate overall petroleum consumption and emissions. In addition, light-duty NGVs will also play a key role in acquainting the now-unfamiliar public with the gaseous fueling that is likely to be required for initial hydrogen fuel cell vehicles.

Natural gas is normally stored on board the vehicle in high-pressure tanks at about 200-250 bar (CNG) with the weight of fuel and tank typically about four times heavier than the equivalent full diesel storage tank in automotive applications. LNG tanks are lighter and the fuel has a higher energy density, so the vehicle range can be around three times that of CNG for the same volume of tank (but still significantly less than a diesel vehicle). Also, liquefaction removes many of the impurities present in natural gas, allowing better fuel combustion. However, LNG can be lost from LNG vehicles through boil-off if stored for more than a few days, and there are other handling problems [15]. This loss combined with the energy required for liquefaction of the natural gas can lead to significantly higher net GHG emissions from LNG fuelled vehicles.

Medium- and Heavy-Duty Vehicles

In the next 5-10 years medium-duty vehicles (MDVs) and HDVs - primarily HDV refuse trucks and buses, with some port drayage trucks and other goods movement vehicles – may continue to be the dominant classes for NGV applications. Line-haul trucks (typically the largest and heaviest class of HDVs) are considered to be a longer-term NGV application while return-to-base truck and bus operations are more practical near-term applications due to their use of centralized refueling infrastructure.

Non-Road Heavy-Duty Vehicles

In addition to potential on-road diesel truck and bus replacement, the heavy-duty NGV market also has the potential to expand further into non-road vehicle markets. Heavy-duty off-road, rail, and maritime diesel uses today account for a substantial share of total fuel consumption and emissions. These non-road market sectors have not yet been required to meet on-road near-zero emission regulations, leading to opportunities for significant emission benefits remain large.

These markets represent a significant broadening of applications for the improved heavy-duty natural gas engines anticipated through current and proposed research and development. Initial applications could occur within this decade and expand substantially over the next. Target markets may include utility vessels such as tugs, tows, ferries, tour boats, and small coastal freighters. Off-road construction and mining vehicles - from haulers to excavators - can also benefit from these improvements and further expand the market, particularly as emission regulations broaden to include them.

Infrastructure

NGV fuelling infrastructure includes onsite compression (or insulated storage, in the case of LNG), storage facilities, containments, and vending equipment including status monitoring, measurement, controls, and connections. Refuelling infrastructure is currently very expensive, typically costing €375,000 to €750,000 for a fast-fill CNG refuelling station for road vehicles (refuelling time comparable to diesel), and €150,000 to €450,000 for LNG [15]. The cost of LNG, CNG, and liquefied to compressed natural gas (LCNG) infrastructure can be gradually reduced over the next decade, notably through manufacturing refinements and increasing scale-economies. In the coming decade, possible breakthroughs in practical adsorbent natural gas storage systems may occur, including storage on vehicles. This technology may or may not prove to be dominant over compression for NGVs in later years.

The durability and reliability of CNG and LNG infrastructure can also be improved significantly within the decade, primarily through research and development of improved materials and manufacturing processes.

Barriers

The following bottlenecks are slowing down the growth in the sector [7]:

- *Technical* bottlenecks that have been observed during tests of Natural Gas vehicles (in particular heavy goods vehicles, HGVs) include difficulties due to the durability of some components (particularly natural gas regulators and on-board LNG tanks), problems with engine failures and a large variation in economic returns due to variations in operational performance.
- *Infrastructure for CNG run vehicles:* According to Shell an estimated 20,000 sites (at a cost of US$350,000 each) in the European Union need to be converted to meet the potential demand for NGVs. This would mean a total investment of US$7 billion – plus the vehicle conversion cost, which appears to be high, especially when compared to competitors like the clean diesel technologies industry, where these investments are not necessary.
- *Storage:* Most of today's CNG vehicles are bi-fuelled. The CNG fuelling and storage equipment is added to the petrol fuel system. While in buses and some commercial vehicles, the loss of storage volume is acceptable many consumers might not be prepared to accept this for their cars. Vehicle fleets are typically served from corporate-based filling stations, whereas consumers require CNG to be available at a large number of service stations.
- *Awareness:* People are generally often are confused about the difference between the LPG and CNG/LNG. This unawareness poses a safety risk to the user when using the wrong fuel, although the filler neck is designed in a way that should prevent misuse unless the filler neck is significantly manipulated by the user.

4.3.2 LPG

Emissions

Although LPG (also known as Autogas) has a relatively high energy content per unit mass, its energy content per unit volume is low. Thus LPG tanks take significantly more space and weigh more than petrol or diesel fuel tanks. Information from the European Autogas industry (AEGPL 2009[22]), based on JEC Well-To-Wheel (WTW) analysis[23] demonstrates that an Autogas-fuelled vehicle generates 14% and 10% fewer CO_2 emissions than its petrol and diesel run equivalents respectively. Compared to petrol the best quality LPG bi-fuel engines produce fewer NOx emissions and virtually eliminate emissions of particulates [11]. Table 1 illustrates the difference of the Energy Content to LNG/CNG. With the significant improvements made in emissions reductions from conventional petrol and diesel vehicles, the largely air quality related benefits of LPG have been eroded over the years. This, coupled to the fact that the fuel is derived from oil refining, means that it is therefore often not seen as a fuel that could significantly contribute to reducing carbon emissions in the future. However, recently there has been increasing interest in bio-DME produced for use in converted diesel engines, which may also be used in a 30% blend with LPG in suitable engines – often referred to as "bio-LPG".

Table 4.1 – Fuel Energy Content

Fuel	CNG	LNG	LPG
Energy Content (Gross heating value)	37-40 MJ/m^3		
	46-49 MJ/kg	45,5MJ/kg	46,23 MJ/kg
Octane Number	120	120	92

Source: International Association for Natural Gas Vehicles (IANGV), 2009 http://www.iangv.org/natural-gas-vehicles/natural-gas.html

Costs

For new LPG cars additional costs vary between €1,130 to €2,740 in the UK [10], and €1,500 to €2,500 in Germany. [6] Table 2 illustrates the difference in the associated costs compared to Natural Gas LDVs.

Table 4.2 – Costs associated

Costs	Nat. Gas LDV (CNG or LNG)	LPG LDV
Additional purchase price/conversion cost vs. similar conventional vehicles	€4,380-€4,500	€1,310-€2,500

Source: What Green Car, 2009, http://www.whatgreencar.com/cng.php, Auto News (2009), http://www.auto-news.de/ratgeber/tipps_tests/anzeige_Nie-ohne-Gutachten-Vorsicht-bei-Gasanlagen-Nachruestung_id_24189

Technical and Market Potentials for LPG

LPG is already an established alternative energy for passenger cars in Europe. Particularly in contrast to LNG/CNG many of the European countries already have an appropriate infrastructure (i.e. a sufficient number of tank stations), although there is significant variation across Europe. Currently there are there are more than 33,000 LPG tank stations in Europe, with Turkey and Poland being the leaders [8].

With appropriate leadership from public authorities, LPG could make a substantial breakthrough by partially replacing traditional fuels [9], with up to 10% of the European market according to AEGPL (2009)[22]. However, the growth projections in the public domain suggest that LPG will probably play a less significant role than CNG/LNG in the medium term [12]. In addition for LPG, as already mentioned, there is much weaker driver in terms of reducing greenhouse gas emissions in the long- term compared to alternative technologies and fuels.

4.4 Aviation

Natural gas and LPG are not suitable alternative fuels for aviation, primarily because of the need for fuels with much greater energy density.

4.5 Shipping

Natural gas, when stored in a liquid state as liquefied natural gas (LNG), is a promising future fuel for ships on fixed lines (i.e. where refueling infrastructure is guaranteed): LNG delivers very significant reductions of NOx and SOx and PM emissions and at the same time also a reduction in CO_2 equivalents. Where available, LNG is expected to remain a less expensive fuel than distillate fuels. This combination makes it particularly interesting for use, in particular for ships in regional trades (where less LNG needs to be stored on-board) where LNG is available.

Emissions

The fuel has a higher hydrogen-to-carbon ratio compared with oil-based fuels, which results in lower specific CO_2 emissions (kg of CO_2/MJ of fuel). In addition, LNG is a clean fuel, containing no sulphur; this eliminates the SOx emissions and almost eliminates the emissions of particulate matter. Additionally LNG operation can bring about large reductions in NOx emissions (~90%) in four-stroke engines (the potential for reduction of NOx emissions for large two-stroke engines has not yet been demonstrated). The use of LNG in ships results in some emissions of methane (CH_4) primarily due to leakage, hence reducing the net GHG emissions benefit from 25% to about 15% over conventional oil-based fuels [20]. Liquid biomethane has the potential to deliver essentially zero emissions.

Costs

Currently, the cost of bulk LNG is similar to residual (heavy) fuel oil, and significantly cheaper than distillate (fossil) fuels. Natural gas can also be processed to produce Fischer–Tropsch diesel, for use in diesel engines. However, in this case, the NOx benefit that is associated with LNG operation would be lost and there would also be a potential cost, energy and CO_2 penalty. Also, natural gas can be reformed on site and used as fuel for fuel cells; however, this is currently not considered to be an interesting option in the short-term due to the principal fuel-cell challenges (including cost, durability and power density). Presently, only four-stroke medium-speed engines for direct-drive LNG propulsion are already on the market.

Barriers

One of the main challenges for the use of LNG as a fuel for ships is to find sufficient space for the onboard storage of the fuel. At the same energy content, LNG has a volume 1.8-times larger than diesel oil. However, as the bulky pressure storage tank also requires a large space, the actual volume requirement is in the range of three times that of diesel oil.

In addition, the availability of LNG fuels in bunkering ports is a challenge, which would need to be solved before LNG becomes a practical alternative. Conversion from diesel propulsion to LNG propulsion is possible, but the LNG is mainly relevant for new ships since substantial modification of engines and allocation of extra storage capacity is required.

At present, the LNG technology is only available for four-stroke engines. For two-stroke engines, a different gas-engine concept, based on direct injection, may be more attractive. The NOx benefit of this technology is less than the premixed lean-burn concept that is used in four-stroke engines. [14]

4.6 Rail

4.6.1 CNG and LNG

There is some limited experience in using natural gas in rail applications, usually driven by reductions in air quality emissions unless biogas/biomethane are utilised. A recent example of a natural gas powered rail vehicle is the Swedish biogas powered railcar [15].

Connection to infrastructure is possible, but expensive (as discussed earlier in section 4.3). Availability of suitable engines is uncertain for rail applications. In contrast to the diesel engine sector, the supply of gas-powered engines for non-stationary operation is very limited. Gas-powered engines with ratings <200kW are predominantly used as stationary motors in block-type thermal power stations at present. In the UK, CNG and LNG are generally used for heavy vehicles – trucks, buses and waste collection vehicles. Cummins also offer CNG conversions for HGVs. CNG buses have been demonstrated widely in other countries in Europe, although there are still concerns over their reliability and high capital costs. Available natural gas engines can also only cover the lower end of power classes needed for railway applications. More powerful engines (500-2000 kW) mainly exist for stationary applications.

It should also be noted that shifting to alternative fuels such as CNG or LNG might lead to some conflicts with the likely long-term shift to hydrogen-based road transport. If operators make large investments in natural gas vehicles and refuelling infrastructure, it may not be economically viable to shift to hydrogen in the medium-term. A further factor with a particular bearing on the issue of running locomotives on natural gas is the fuel's comparatively low energy density compared with diesel fuel (1:5 at 200 bar).

For NGVs it is necessary to carry out comprehensive modifications to the engine's carburetion in order to harness its potential in respect of pollutant emissions. A further disadvantage for LNG concerns the high input that liquefaction entails and the elaborate infrastructure required to supply the fuel. Its storage at fuelling points requires it to be cooled using liquid nitrogen. Vehicle tanks have to be vacuum-insulated so as to keep waste steam losses due to heat entry down to acceptable levels [15].

Most of the rail infrastructure in Europe is electrified, with the potential for much greater long-term emissions reductions as the electricity system is decarbonised. In the long-term hydrogen fuel cell powered vehicles seem the most likely alternative to diesel alternatives where electrification is not cost-effective. It therefore seems highly unlikely that natural gas powered rail vehicles will significantly contribute to GHG emissions reductions in the long-term.

4.6.2 LPG

No information has been identified on rail applications. Whilst petrol engines can be converted to run on LPG fairly easily, for diesel engines conversion is more complex as it involves changing the compression ignition system of the diesel engine into a spark ignition system. Better emissions savings and performance are obtainable for dedicated LPG engines; however availability of suitable engines is uncertain. CO_2 emissions are very similar to diesel engine vehicles and the principal driver is reductions in emissions of NO_x and PM (up to 90% lower than equivalent diesel powered vehicles).

Similarly to natural gas, barriers include reduced range and increased volume and weight required for fuel storage. Also shifting to LPG could lead to some conflicts with the likely long-term shift to hydrogen-based road transport. If operators make large investments in LPG vehicles and refuelling infrastructure, it may not be economically viable to shift to hydrogen in the medium-term.

LPG is therefore not an attractive prospect in terms of GHG emissions reduction.

4.7 Gaps in Identified Information

- *General:*
  - There is only little information on projections for CNG and LNG up to 2050. For example, additional data are needed for GHG emissions, energy consumption and costs. The gap in identified information is partly due to the fact that CNG/LNG is not considered to be a long-term option;

  - Further research needs to be put into the availability of feedstock of biomethane, which is considered to be the only option with radical emission reductions.
- *Road Transport:*
  - While data are present for short-term developments further research needs to be put into long-term applications, e.g. by using biomethane;
  - Projected long-term data on capital cost, emissions and energy consumption for different types of automotive vehicles need to be investigated.
- *Aviation:*
  - As natural gas is not suitable alternative fuels for aviation, there are no further information gaps in this area;
- *Shipping:*
  - Projected long-term data on capital cost, emissions and energy consumption for different types of ships need to be investigated;
- *Rail:*
  - As to only limited experience in using natural gas in rail applications there is not much information in the public domain;

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5 Pure Electric and Plug-in Hybrids

5.1 Introduction

Pure electric powered transport is often seen as the ultimate prize, since it can be produced from essentially carbon-neutral sources and utilized directly at higher net efficiency compared to hydrogen fuel. However, significant challenges remain for road transport principally in the area of electricity storage – in terms of cost, weight, volume, efficiency and power delivery. These limitations also impact on the useful range of electric vehicles compared to conventional equivalents. These and other barriers mean the mainstream utilization of electric vehicles is still seen as being in the long-term.

Plug-in hybrid electric vehicles are seen as an intermediate (short- to medium-term) technology on the pathway to electric vehicles in the road transport sector, enabling performance characteristics and range similar to conventional equivalents at lower capital costs.

5.2 Overview of options

Road Transport:

Electric vehicles have only been used in niche applications historically due to high capital cost and poor range and performance. Recent developments in battery technology and increasing concerns over climate change have renewed interest in EV technology across passenger and freight transport modes. Plug-in Hybrid EVs (PHEVs) are seen as a bridging technology between hybrid electric vehicles (HEVs) and pure EVs.

Aviation:

No material /significant interest has been identified on research into pure electric aircraft applicable for passenger or freight operations.

Shipping:

Although many types of ship have made the transition to integrated electric propulsion systems, these are powered mostly by diesel or fuel oil generators, and in some cases gas turbines. Electric storage itself is not seen as a viable storage medium for ship powertrains, although there may be some opportunities in the future to supplement the auxiliary electric requirements using electricity generated using solar photovoltaic (PV) panels.

Rail:

Electric rail is a mature technology and accounts for the majority of rail propulsion across Europe. Electrification usually entails the addition of overhead power lines to an existing rail route that was previously worked by diesel rolling stock. There is also mounting interest in bi-modal diesel-electric rolling stock that can be run on both electrified track (powered via catenary) and unelectrified track (powered via diesel engine).

5.3 Road Transport

Electric vehicles are not a new technology; they have been around in various guises since the early 1900's and are the technology of choice for niche markets such as golf carts, milk floats and mobility scooters. However, the last concerted efforts to launch the technology for mainstream road vehicles (such as General Motors' EV1) failed due to a lack of consumer appetite for the technology and a lack of progress on new battery technology [8]. The lead acid batteries available at the time were very expensive (the battery pack for the EV1 cost $25,000) and suffered from a poor energy density, meaning the EV1's battery pack weighed a staggering 1,175 lbs and only delivered a range of 50-70 miles [8].

However, significant improvements in battery technology and increasing concerns over climate change have meant they have risen back up the political agenda as an option for reducing emissions from the road transport sector. A new generation of electric vehicles (EVs) and the relatively new concept of a 'plug-in hybrid electric' vehicle (PHEV) will be launched over the next couple of years, with the first volume manufactured EVs (The Mitsubishi I-MiEV and Citroen C1 ev'ie) available later this year. Whilst the Norwegian company 'Th!nk' launched the 'City' EV in 2008, financial problems at Th!nk meant production was halted in December [9]. However, interim financing has been arranged and new order from the Netherlands and Spain should see production restart [9]. Most recently Chinese car maker BYD has announced it is about to release its new E6 electric car due out before the end of the year will do 250 miles (400km) on a single charge and can be fast charged fully in as little as 1 hour (with half-charge in 10 minutes). BYD is the world's number two in rechargeable batteries, and for the E6 it is using a ferrous battery it has developed itself, lending some weight to the claims [21].

An electric vehicle is powered solely by electricity stored in on-board batteries. An EV does not feature an on-board engine and is charged by plugging into the National Grid. In the future some models, such as those being develop by Renault-Nissan may allow the ability to swap their batteries with fully recharged ones, rather than the user having to wait with their vehicle for them to recharge. This allows the battery charging step to be moved out of synch with vehicle usage.

A Plug-in hybrid electric vehicle (PHEV) features a larger battery than a conventional hybrid vehicle (e.g. the Toyota Prius) and is therefore able to be recharged via the Grid and operate over a short distance in electric-only mode. However, the battery is smaller than an electric vehicle so a conventional petrol engine and fuel tank is employed to extend the range. PHEVs are also referred to as 'extended-range EVs' (ER-EV) in some instances. This terminology is reserved for series-hybrid based PHEVs, which use an electric motor to power the wheels of the car and uses an ICE as a generator to recharge its battery pack that does not power the wheels directly. Parallel-hybrid configurations (such as the 'Hybrid Synergy Drive' developed by Toyota) utilise both the electric motor and ICE to provide traction at high power requirements (e.g. under hard acceleration and at high speeds).

The new generation of EVs and PHEVs have come about because of significant advances in battery technology. In particular the emergence of lithium-ion (Li-ion) batteries as the battery technology of choice has provided the necessary step change in energy density. In other words, Li-ion batteries allow the same amount of energy to be stored in a much smaller volume than their predecessors such as Nickel Metal Hydride (Ni-MH) or lead acid batteries. This has eliminated many of the 'packaging' issues related to EVs, so providing space to accommodate passengers and baggage is no longer such a significant challenge. The reduced weight of the batteries also means far less of the power they supply is expended moving their own mass.

That said, big improvements in battery technology are still needed before EVs and PHEVs can become a commercial proposition. The barriers will be covered in more detail later in this section but price remains a key issue. However, it is hoped that relatively new variants of the Li-ion battery chemistry such as those featuring an iron-phosphate cathode (as opposed to a cobalt oxide cathode in conventional Li-ion batteries and as developed by BYD mentioned above) or a lithium titanate anode (e.g. NanoSafe batteries developed by Altairnano) will help address some of these issues.

As far as policy makers are concerned perhaps the strongest argument for the widespread deployment of EVs and PHEV is their potential to reduce carbon emissions from the transport sector. Whilst EVs and PHEVs both have significant benefits in this regard EVs are almost certain to achieve higher carbon savings. This is because they can only be powered by electricity from their on-board battery, where as PHEVs can still make use of their range-extending engine. In theory, a PHEV could be driven as a pure-electric vehicle but in practice this is unlikely to happen. Firstly, it would negate a key benefit of a PHEV (not needing to worry about the location of the level of charge remaining in the battery). Secondly, many PHEVs are configured so that the engine cuts in when significant amount of charge (around 40% for the Chevrolet Volt) still remains, although this might change in the future depending on advances in electrical energy storage.

Even with the current energy mix EVs already produce less CO_2 per km than petrol or diesel vehicles [1],[2]. This is because the electric drivetrain is far more energy efficient than the drivetrain for petrol or diesel vehicles – 65% vs 18%-23% respectively. EV's advantage in this regard is sufficient to outweigh the losses that occur during power generation, which achieves between 35% and 42% energy efficiency depending on whether it's coal or gas fuelled power plant[1]. This is partly because refining oil to produce petrol or diesel also incurs losses (around 83% efficiency [1])

In terms of per vehicle CO_2 emissions reductions a WWF study [1] suggests that petrol and diesel vehicles currently produce 1,619g of CO_2 and 1,300g of CO_2 per kWh of motive energy, respectively. This compares to 619g of CO_2 per kWh motive energy for the European average energy mix (around 450gCO_2 / kWh net electricity generation). Interestingly, this rises to 1,037g of CO_2 per kWh for the US energy mix due to the much higher proportion of coal power generation in the US.

A study published on the Institute of Lifecycle Analysis' website [2] shows a range of values for the lifecycle CO_2 emissions from EVs depending on the generation type. The "Usage" phase (i.e. the emissions arising from using the vehicle) ranges from less than 1 MgCO_2 for hydro electricity to around 10 MgCO_2 for liquefied natural gas and 17 MgCO_2 for coal. Similarly to hydro electricity, lifecycle emissions from the "Usage" phase based on other renewable electricity generation or nuclear power could be expected to be extremely small. In contrast, the Usage phase for petrol produces around 21 MgCO_2.

Therefore, these studies suggest that whilst EVs are more energy efficient and hence lower carbon than conventional petrol and gas vehicles, the extent to which this is the case is heavily dependent on the energy mix. Furthermore, as grid electricity is decarbonised (e.g. as the proportion of renewables increases and if and when carbon capture enabled fossil fuel power stations begin to replace existing fossil fuel power stations) the carbon advantage for EVs will increase further. In that sense a significant shift to electric vehicles could be thought of as 'locking in' a lower carbon future for the transport sector. The Renewable Energy Directive (2009/28/EC) sets a target of 20% of energy across the EU to be renewable (with 10% of energy used in transport to be renewable). Eurelectric has also indicated that it is fairly realistic that the electricity generation sector can be almost fully decarbonised by 2050.

As mentioned earlier, PHEVs will also produce lower carbon emissions than conventional vehicles, although not to quite the same extent as EVs. However, the CO_2 emissions associated with PHEVs compared to conventional vehicles is even harder to predict than EVs. This is because the CO_2 emissions from PHEVs will also vary according to the proportion of vehicle km that are electrified (i.e. undertaken in electric-only mode) and the proportion that is undertaken whilst the range-extending engine provides traction power and the vehicle dynamics during these periods. The proportions will be influenced by a variety of factors including:

- The availability of infrastructure;
- The usage profile of the user;
- The ease of re-charging;
- The relative price of electricity and petrol/diesel.

A study by Mobilitaet in Deutschland [22] has reported that that 80% of the Germans drive 50km or less a day (with an average of 40km). Similarly, a study from the UK Department for Transport [23] also show that only 93% of car trips are up to 25 miles (40km), but account for only 62% of total car CO_2 emissions. Work cited by Toyota [24] on tests on PHEVs in France carried out with EDF also found 80% of daily trips being made were less than 25km.

A 2007 study by EPRI [3] states that even when the electricity is generated with current coal technologies (which is the most carbon intensive form of generation), PHEVs result in 28% to

34% lower well-to-wheel GHG emissions than conventional vehicles. A more realistic energy mix would increase this gap significantly. The study also considered a range of potential 2050 energy mix scenarios ranging from 100% advanced supercritical coal (the most carbon intensive scenario even though super-critical coal plant is significantly more energy efficient that current coal plants) to 100% renewables. These 2050 scenarios resulted in 40% to 65% lower well-to-wheel GHG emissions for PHEVs than conventional vehicles.

In terms of overall reductions, an aggressive 'hybrid-and-electric' scenario (8% EV, 24% PHEV, 28% hybrid electric and 40% internal combustion engine) detailed in a 2009 report by McKinsey [4] quotes a 49% reduction in 2030 CO_2 emissions vs a no action baseline and a 22% reduction vs 2006 levels.

The other main benefits of electric vehicles are their positive impact on air quality and noise at low speeds typical in urban areas. Whilst the location of CO_2 emissions sources does not affect their impact on global warming, the location of air quality emissions such as particulate matter (PM) and oxides of nitrogen (NO_x) is critical in terms of determining their impact. This is because air quality emissions are strongly linked to a range of public health issues such as respiratory disease. Electric cars can be virtually silent at low speeds and remain much quieter than conventional cars at higher speeds. On the whole this is perceived as a benefit because traffic noise can be a source of irritation for those living in urban areas or close to major roads. However, there are some genuine safety concerns from organisation representing blind people [21]. As a result the US Federation of the Blind is actually campaigning for minimum noise standards [21].

Burning any kind of fossil fuel produces air quality emissions, whether it's petrol or diesel in vehicles or coal at power stations. However, most power stations are located well away from centres of population. In contrast traffic tends to be worst in urban areas where the concentration of people is greatest. Consequently, EVs and PHEVs, which are powered wholly or partly by electric power from power stations, are effectively displacing the air quality emissions away from these centres of population. As outlined above this will have a clear benefit for public health.

The marginal capital cost of EVs and PHEVs compared to conventional vehicles is relatively high. This is largely due to the high cost of Li-ion batteries, which seem to have become the battery technology of choice for the next generation of EVs.

According to a 2008 study by Cenex/Arup [5] the current cost of Li-ion batteries is between \$1,000/kWh and \$2,000kWh. Given that the Mitsubishi i-MiEV (a small EV to be launched later this year) has a 16kWh battery, the expense of the batteries quickly becomes apparent. That said there seemed to be a consensus amongst the industry sources consulted during the Cenex/Arup study that prices will fall to \$250/kWh to \$300/kWh once manufacture volumes rise to 100,000 battery packs per annum.

The marginal capital cost of small EVs is between £6,500 and £20,000 when the Citroen C1 ev'ie, Th!nk City and Mitsubishi I-MiEV (the first three volume manufactured EVs available in Europe) are compared to equivalent conventional vehicles. This rises to between £30k and £50k when large EVs such as the Tesla Roadster and Land Rover Range Rover Conversion are considered.

For medium PHEVs (no small PHEVs are currently close to market) the marginal capital cost is between £8,500 and £14,000 according to the anticipated prices for the Chevrolet Volt and Toyota Prius Plug-in Conversion.

In the automotive industry there is often a fairly tenuous link between the cost of vehicles and their price. Vehicles are often launched as loss leaders to gain a foothold in the market, with the hope of turning a profit several years down the line [6]. Particular care should be taken when considering the price and cost of EVs and PHEVs since the current cost of batteries is such that it is impossible for them to be competitive with conventional vehicles if 'normal' profit margins were applied.

It is very difficult to estimate the overall cost of introducing EVs and PHEVs on a widespread basis since so much depends on whether battery prices reduce and to what extent car manufacturers and Governments are willing to subsidise them. Even estimating the 'true' cost is very challenging since it necessitates obtaining commercially sensitive information.

That said, it is clear that the rate at which manufacture volumes and hence uptake of EVs and PHEVs will increase will depend on upon a number of factors:

- Improvements in current technological barriers, such as the rate of charge/discharge (affecting charging time, regeneration of braking energy and power delivery), electrical energy density (affecting range), etc;
- The availability of charging infrastructure;
- The rate at which battery costs reduce, which is related to:
    - The price of key materials such as cobalt which has fluctuated significantly over the past couple of years;
    - The demand for Li-ion cells (which are combined to make large EV and PHEV batteries) from other sectors such consumer electronics;
- The level of up front price support available in the short to medium term to offset the marginal capital cost;
- Other availability of other support measures/incentives to encourage consumers to purchase EVs and PHEVs;
    - Preferential parking spaces;
    - Reduced tax;
    - Exemption from congestion / parking charges;
    - Use of bus lanes.
- The willingness on the part of consumers to change their refuelling behaviour and accept a more limited range.

Any of these factors could present significant barriers to widespread uptake of EVs and PHEVs.

The other key barriers relate to the availability and performance of the requisite charging infrastructure both at home and at other key locations. Consumers are likely to demand a widespread charging infrastructure before committing to purchase EVs, and to a lesser extent PHEVs, in any great numbers. Whilst there is already widespread electricity infrastructure across Europe, installing a comprehensive network of charging points will be very costly.

Venture capital backed start-up company 'Project Better Place' are keen to pursue the idea of battery swap stations as a more rapid alternative to their complimentary network of charging points. Their business model will entail providing access to their network of battery swap stations and charging points via a mobile phone-style contract [7]. They have already begun building their first slow-charging network in Israel[7] and have secured 103 million Euros of investment to build a recharging network in Copenhagen, Denmark in partnership with Dong energy.

Slow-charging an EV using single-phase grid electricity will typically take between 6 to 8 hours. Fast charging technology is already available, although current battery technology is not always compatible or optimised for it and it requires a three-phase electricity supply and sufficient space to house the equipment. The higher voltage for fast charging equipment (440V) compared to standard household levels (now 230V ±10% in Europe) also leads to additional safety considerations. These are further potential barriers to the EV uptake but wouldn't necessarily pose a major problem for PHEVs, which could switch to their conventional engine when it isn't convenient to wait for the battery to recharge.

Furthermore, capacity of the low voltage distribution networks will also begin to become an issue once significant number of vehicles are re-charging from the grid. In the UK it is suggested this point could be reached once 15%-20% of vehicles are recharging from the Grid. It has also been suggested that there may be benefits of adding car batteries to the power grid (e.g. storage capability for sustainable energy generated during low power demand periods). Such benefits might strengthen the business case from the point of view of the power industry. However, current battery technology is not suitable for such an application as it would significantly shorten the usable battery life (entailing prohibitively high additional costs for replacement in the vehicles lifetime).

In terms of timescales, volume manufactured EVs are being launched this year in very small numbers (e.g. the first global production run for the Mitsubishi I-MiEV is just 2,000 vehicles). Other models will launch over the next couple of years. However, manufacture volumes are expected to remain very modest until 2015 at the earliest, especially in light of the global recession. As highlighted above there is also a need to develop a widespread recharging or battery swap infrastructure before significant sales can be achieved.

BYD's PHEV sedan is already available in China, with a few hundred having been sold. GM was due to launch the Chevrolet Volt in 2010 but it remains to be seen how their financial problems will affect the proposed launch. Other models such as a plug-in version of the Toyota Prius will also become available in small numbers over the next couple of years.

Providing consumers show an interest in purchasing EVs and PHEVs, growth returns to the world economy and steps are taken to roll out charging infrastructure, EV manufacture volumes could begin to rise post-2015. However, significant levels of uptake are unlikely to be achieved until the early 2020's [5] at the earliest. PHEVs are less reliant on a widespread charging infrastructure (providing the user has somewhere to charge the vehicle regularly) so they could act as a 'bridging technology' whilst the infrastructure is developed. Their lower battery cost ought to help in this regard.

One key uncertainty relating to EVs and PHEVs is the competition they will face from advanced diesels over the short to medium term, particularly with some demanding emissions targets to meet. Advanced diesel technology that has already began to be introduced feature technologies such as sequential twin-turbocharger systems and improved fuel injection systems.

The European automotive sector is subject to a suite of emissions regulations. One of the most recent additions is an average 130gCO_2/km limit for new cars, to be phased in between 2012 and 2015. In addition, The European Commission has proposed a tougher limit of 95gCO_2/km for 2020. Car manufacturers will be left to meet these targets in whatever way they see fit. In reality the technologies needed to hit 130gCO_2/km are already widely available – for example, hybridisation and engine downsizing will both play a part. It has previously been estimated the cost for meeting the 130gCO_2/km limit by 2012 through engine technology alone would be on average €2,500 per new car [25]; updated average cost figures for the more graduated introduction to 2015 have not been identified.

The 2020 target will prove more challenging but it has been suggested these could still be largely achieved by advanced diesel technology with significant hybridisation, which is significantly cheaper than EVs and PHEVs. Therefore, whilst EVs and PHEVs may still be preferred by policy makers in the long term (since they have the potential to be very low carbon indeed if the grid can be decarbonised to a large extent) they will by no means be the only low-carbon technology employed by manufacturers in the short to medium term. However, meeting the 2020 targets without alternative fuels would only be possible with nearly 100% diesel share and a significant hybridised and downsized vehicle park (i.e. everybody drives only small and mini vehicles). This is not a realistic development, leaving a clear need for alternatives. Recent industry roadmaps for PHEVs and EVs suggest ambition to achieve as many as 4 million vehicles in the EU by 2020 (EPoSS, 2009) [26]. However,

In terms of electrified public transport, trolley buses (electric buses that draw electricity from overhead wires) provide a good example of proven technology in a number of cities (e.g. San Francisco, Vancouver, Athens, Salzberg and Beijing). Trolley bus systems can have significant cost advantages over alternative more expensive tram and light-rail systems. Modern systems also increasingly utilise hybrid technology by including a a small diesel engine or battery to allow for travelling short to considerable distances away from the overhead wires (i.e. for auxiliary or emergency use only, or full dual-mode capability). It may even be conceivable for the long-term to add trolley systems for trucks or even passenger cars on highways.

5.4 Aviation

Whilst there is some interest in the development of enabling technologies for an all-electric aircraft (e.g. high-efficiency electric motors utilising superconducting materials), these are primarily being considered for use in combination with fuel cells with hydrogen fuel. No material /significant interest has been identified on pure electric aircraft applicable for passenger or freight operations.

5.5 Shipping

According to [16], nearly all cruise ships and many other ship types including shuttle tankers, product carriers, ferries, icebreakers, and offshore oil exploration platforms have made the transition to integrated electric propulsion systems, in both in-hull and podded propulsion variants. Modern ships tend to consume more electricity than did their predecessors and integrated electric propulsion systems provide significant operator flexibility to optimise system efficiency. This is because they enable the ability to only use the minimum amount of electricity generation equipment for a given operational scenario. Generators may therefore be operated closer to their optimum outputs, with spare capacity shut down. This improves the overall system efficiency and also reduces maintenance requirements.

However, the primary fuel used to power these electric propulsion systems is currently overwhelmingly diesel or fuel oil powered engines, with COGEN gas turbines [17] with the exception of submarines, where fuel cells or nuclear power can be used instead.

Electric storage itself is not seen as a viable storage medium for ship powertrains, although there may be some opportunities in the future to supplement the auxiliary electric requirements using electricity generated using solar photovoltaic (PV) panels. Current PV cell technology would on average only be sufficient to cover a fraction of the auxiliary power even if the complete deck area was covered by photovoltaic cells [18]. Naturally, at certain times and in certain areas solar radiation will be above average and auxiliary power demand could be met. Also, by using highly efficient (presumably expensive) solar cells (of the type used on spacecraft), it is possible that PV cells could be used to meet 100% of current auxiliary power demand on average, or to provide a small fraction of engine power demand [18]. As solar power is not always available (i.e. during night-time) backup power would be needed and even if the power is available throughout the daytime, this would not help reduce auxiliary power at night unless there is an energy storage system available on board. Solar energy can also be used for heating purposes, e.g. water in port (excess heat is normally available on board ships at sea).

Currently, it would appear that solar cells are not very attractive for covering large maritime power demands. However, in a long term perspective it could very well be interesting as partial power. However, there is also potential for GHG reductions via ship utilization of onshore power supplies while in port, which could provide some benefits.

5.6 Rail

Electric rail is a mature technology. Electrification usually entails the addition of overhead power lines to an existing rail route that was previously worked by diesel rolling stock. This allows electric trains to draw power from the overhead wires and use it drive their electric motors. There is nothing to stop diesel trains continuing to use the tracks and this so called ‘running under wires’ is actually fairly common, particularly where there are gaps in the network that are not electrified.

‘Light’ rail networks such as the Metro/Underground networks across Europe also tend to be powered by electric traction but tend to be designed as electric networks from the outset.

Electric trains use typically 60-70% less energy per seat-km than equivalent diesel trains according to information on similar diesel and electric rolling stock available from a 2007 report for RSSB [19]. However, the performance in terms of CO_2 emissions varies significantly due to the source of the electricity / grid electricity generation mix. In the future the relative GHG emissions performance of electric rail over diesel rail will increase further due to the anticipated rapid decarbonisation of electricity generation.

More recently there is mounting interest in bi-mode diesel-electric rolling stock that can be run on both electrified track (powered via caternary) and unelectrified track (powered via diesel engine). Such bi-modal systems (e.g. as specified in the current Intercity Express Programme in the UK [20]), allow rolling stock to be used on mixed stretches of track. This allows the possibility to circumvent the need to electrify certain stretches of track which are not cost-effective and still provide long-distance electrified through-services. The main GHG reduction options for electric rail include: improved regeneration, weight reduction (usually used to provide more space and better comfort) and aerodynamics.

5.7 Gaps in Identified Information

- *General:*
  - Latest costs of Li-ion battery variants (cobalt oxide cathode, iron-phosphate cathode, manganese oxide cathode, nickel oxide cathode and lithium titanate anode);
- *Road Transport:*
  - Data on the proportion of the fleet that would need to be recharging from distribution network to cause significant capacity issues.
- *Aviation:*
  - N/A
- *Shipping:*
  - N/A
- *Rail:*
  - Total % of European rail kms that could practically be electrified bearing in mind 80% are already electrified.

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6 Hydrogen and Fuel Cells

6.1 Introduction

Whilst hydrogen is the most abundant element on earth is does not occur naturally in a pure form. Therefore, unlike coal, natural gas or oil it is not a 'primary fuel'. However, hydrogen is considered to be an 'energy carrier'. In other words it can be used to move and store energy, which are valuable properties, particularly given the difficulties in storing electricity, which is the other main energy carrier.

To make use of hydrogen as an energy carrier it must first be coaxed away from the elements to which it bonds (for example, carbon in the case of methane, CH_4, and oxygen in the case of water, H_2O). There are currently two main ways in which hydrogen can be produced: reformation of natural gas or the electrolysis of water. Other options are also being explored for the future, such as biological, thermal and thermochemical pathways, and thermally or photolytically (light) assisted electrolysis.

Reformation of natural gas is currently the dominant means of production and is responsible for 96% of the hydrogen produced worldwide [1]. The lifecycle or 'well to wheel' GHG emissions for any application of hydrogen are heavily dependent on the means by which hydrogen is produced. As will be illustrated in the proceeding paragraphs, the electrolysis of water has the potential to be far less carbon intensive if the requisite electricity is supplied from a low carbon source (e.g. renewables or nuclear).

In a transport context the main technology for making use of hydrogen is fuel cells, which exploit an electrochemical reaction between hydrogen and oxygen to generate electricity [13]. Hydrogen, which is typically stored on board the vehicle in pressurised tanks, is fed to the anode whilst oxygen in the form of air is fed to the cathode. With assistance from a catalyst, hydrogen atoms then split into protons and electrons [13]. Next, both the protons and electrons migrate from the anode to the cathode, but crucially they follow different paths. The electrons flow through an external electrical circuit, thus creating an electric current. In contrast, the protons pass through the electrolyte that separates the anode and cathode before the being reunited with the electrons, as well oxygen atoms, at the anode. The products of this reaction are water and heat.

The main types of fuel cell are as follows:

- A proton exchange membrane (PEM)
- Molten carbonate (MC)
- Solid oxide (SO)

The most suitable fuel cell for transport applications is a PEM [1]. This because they have the advantage of relatively low operating temperatures of around 80°C, which allows them to start up quickly [1].

6.2 Overview of options

Road Transport:

Vehicles powered by hydrogen fuel cells are a medium- to long-term option to reduce CO_2 emissions from road transport. R&D into the use of hydrogen and fuel cells for road transport has been mainly focused on passenger cars to date, although there are high-profile European projects demonstrating hydrogen fuel cell busses. There has also been some interest in the automotive sector in using hydrogen in internal combustion engines as a bridging technology to fuel cells.

Aviation:

There is some interest in the development of enabling technologies for an all-electric aircraft (e.g. high-efficiency electric motors utilising superconducting materials) for use in combination with fuel cells and hydrogen fuel. However, potential application is still generally seen as very long term due to the need to overcome significant barriers and the long lifetime of aircraft.

Shipping:

In theory hydrogen fuel cells could be used power ships along with most other modes of transport. However, significant barriers coupled with the long lifetimes of ships that mean it is difficult to envisage hydrogen playing a significant role in shipping even up to 2050.

Rail:

There is some interest in the application of hydrogen fuel cell propulsion technology to rail, including experimental projects in Japan, Denmark and the US. However, the technology is only likely to be a realistic alternative where electrification is not possible /attractive.

6.3 Road Transport

The focus of most current hydrogen and fuel cell development has been on road transport applications – particularly in passenger cars. Some car manufacturers have investigated employing hydrogen internal combustion engines (ICEs) as a bridging technology to make use of hydrogen as a fuel without a full scale switch to fuel cells. However, they have been the target strong criticism for their poor energy efficiency [1] compared to fuel cells, relying on hydrogen produced from renewable sources to offer potential reduction in net emissions compared to conventional petrol or diesel vehicles. In contrast the high efficiency of fuel cell vehicles could offer benefits over conventional ICEs even if the hydrogen were produced from natural gas. Energy efficiency will be covered in more detail later in this section.

It is important to note that a fuel cell vehicle (FCV) will utilise an electric drive train similar to that of a plug-in hybrid electric vehicle. The fuel cell and hydrogen tank would replace the range extending engine and petrol tank. However, the electric motor/s (which drive the wheels), battery pack and control architecture would be similar if not identical. Indeed, several car manufacturers such as General Motors and Ford are choosing to develop low carbon vehicle drive train ‘platforms’. This is where certain basic components are common between a number of different vehicles (e.g. an electric car, a plug-in hybrid electric car and a fuel cell electric vehicle). By designing cars in this manner car manufacturers are able to minimise costs.

Unless the hydrogen is produced on-board the vehicle (this is unlikely to prove cost effective) or at home energy stations, it must then be transported close to the point of use and stored in a pressurised tank. Pipelines are the favoured means of transporting hydrogen due to the high cost and energy losses associated with the main alternative - liquefying hydrogen and transporting it by ship or truck [13]. A fuel cell then uses hydrogen and oxygen to produce electricity via an electrochemical process [13].

All of the steps in the hydrogen supply chain or ‘pathway’ incur an energy penalty. In other words, energy is expended during each step of the process, which has a significant impact on the energy efficiency of a fuel cell vehicle (FCV) or other end uses for hydrogen. Unfortunately, whilst FCVs can reduce GHG emissions compared to conventional vehicles this means they will never achieve the same emissions cuts as pure electric vehicles (EVs) [1]. Their performance compared to plug-in hybrids (PHEVs) will be dependent upon the proportion of the PHEV vehicle km that are undertaken in electric-only mode.

For instance a study by WWF [1] illustrates these points by considering the overall efficiency of:

- A hydrogen fuel cell pathway taken from the IEA report ‘Prospects for Hydrogen and Fuel Cells’

- A grid electricity PHEV pathway (running in electric-only mode for 100% of the vehicle km, so effectively acting as an EV, with the electricity derived from a 50% energy efficient power plant) also taken from Prospects for Hydrogen and Fuel Cells'
- A renewable electricity PHEV pathway (running in electric-only mode for 100% of the vehicle km, so effectively acting as an EV, with 100% of electricity derived from renewables) developed by WWF

The WWF estimated that the hydrogen fuel cell pathway would achieve an energy efficiency of 28% compared to 34% for the PHEV pathway running on Grid electricity and 69% for the renewable electricity PHEV pathway.

A report by the European Conference of Ministers of Transport [10] (ECMT) in 2007 provides data on the well-to-wheel CO_2 emissions from fuel cells for various hydrogen pathways, which is illustrated in Table 1. For comparison, the report estimates that conventional petrol and diesel cars are expected to achieve 164gCO_2/km and 162gCO_2/km respectively by 2010.

Table 6.1 – Well-to-wheel CO_2 emissions of various hydrogen pathways

Hydrogen 'source'	Grams of CO_2 equivalent per km
Electrolysis of water, using the existing EU electricity mix	196
Electrolysis of water, using nuclear-powered electricity generation	7
Electrolysis of water, using wind-powered electricity generation	9
Reformation of natural gas (using natural gas from within the EU and where reformation takes place at the site of extraction)	98

Therefore, according to the ECMT report, the latter three pathways would produce very significant carbon saving compared to current petrol and diesel cars. It should be noted that the new European 130g/km CO_2 emissions limit for cars will be phased in between 2012 and 2015. However, this limit is only on Tank-to-Wheel (TTW) emissions and this is 0gCO2 for H2FC vehicles (except for FCV with on-board reformers. The European Commission has also proposed a tougher limit of 95g/km by 2020. In the future it is anticipated that legislation will move to a lifecycle emissions (i.e. well-to-wheel, WTW) basis to reflect the different nature of the alternatives to conventional fuels and powertrains. Therefore, the advantage that the reformation of natural gas pathway currently enjoys of conventional vehicles may be eroded over the next decade or so if these targets, which are backed up with a suite of fines for non-compliance, are met. This is particularly the case given that advanced diesel technology should allow conventional vehicles to meet the 95g/km limit.

The cost of each element of the various hydrogen pathways, which are comprised of hydrogen production, transportation and end use, are often cited as a key barrier to widespread uptake in a transport context. Taking hydrogen production first, the IEA's comprehensive 2005 report 'Prospects for Hydrogen and Fuel Cells' estimates the current cost of de-centralised hydrogen production via small-scale electrolysis at \$50/GJ H_2. Whilst acknowledging that future prices are dependent on electricity and gas prices the IEA suggests prices could fall below \$20/GJ H_2 and \$15/GJ H_2 for small-scale electrolysis and gas reforming by 2030. Overall the IEA take the view that hydrogen production costs need to be reduced 3 to 10 fold depending on the technology [13].

The IEA projects it would cost \$2.5trillion worldwide (although this is very much an order of magnitude guide cost) to develop a worldwide hydrogen transport infrastructure i.e. a network of dedicated pipelines. It could be argued that this enormous cost strengthens the case for a long term hydrogen pathway comprising of the electrolysis of water and a decarbonised electricity supply. Whilst it would be hard to justify any investment of that magnitude, the kind of dramatic decarbonisation of say, road transport, which *could* be delivered by electrolysis would allow the best possible chance of meeting investment criteria. In other words it would provide the greatest chance of achieving a high benefit to cost ratio, which is one of the key criteria Governments use to assess the wisdom of investments.

In terms of the cost of fuel cells themselves a 2007 study by E4tech [11] estimated their cost at around $280/kW compared to a target of $50 to $100/kW. The IEA estimate the fuel cell costs need to reduce by 10 to 50 times (depending on the technology) to become competitive[13]. In a recent National Academies of Science (USA) study the cost is estimated at ~$100 /kW if current technology is used for mass production (500 000 units per year). Using newer laboratory based techniques this could (already) drop to $67/kW [27].

In contrast, the cost of FCVs is harder to establish since manufacturers are keen to protect their commercial interests. A 2008 article in 'Car' magazine suggests the true cost of the Honda FCX Clarity is around $500,000 per vehicle. 200 of the FCX clarity are being leased to consumers in the US and Japan at a price of $600 a month [12]. The 2005 IEA Report 'Prospects for Hydrogen and Fuel Cells' estimates that the cost of the complete drive system for a demonstration FCV was in the order of a few thousand US Dollars per kW [13]. However, it did acknowledge that car manufacturers believed this could be reduced by a factor of 10 through technology learning. This indicates fuel cells and in turn fuel cell vehicles have some way to go before they are commercially viable.

These cost concerns are consistent with remarks in the WWF and ECMT reports respectively: *"As an energy storage medium, especially to provide stationary backup power, hydrogen may play a role in the long-term. It is not likely to be a commercially viable automotive transportation fuel, unless we witness a technology breakthrough whereby hydrogen gas can be 'distilled' locally with no carbon inputs from tanks of water combining algae and sunlight close to the point of use".*

ECMT: *"While hydrogen powered fuel cells are a likely transport future, this future is a long way off. Promotion of hydrogen as a transport fuel is unlikely to achieve any* CO_2 *abatement in the near to medium term."*

A shift to a so-called 'hydrogen economy' would require an enormous investment in a range of infrastructure. Firstly, whilst hydrogen is already produced commercially (mainly for the synthesis of ammonia [1]) the production levels would need to be ramped up dramatically to supply a significant proportion of transport energy demand [1]. This is where fuel cell vehicles, and the hydrogen economy as a whole, differs from electric vehicles. There are already high and low voltage networks in most countries around the world. Whilst these networks would need to be supplemented to facilitate widespread uptake of EVs (e.g. charging points installed and in due course, the networks may need to be strengthened) they do at least help to minimise the costs whilst the technology is in its infancy. Hydrogen does not start from a similarly advantageous position [14], which is a key barrier to uptake.

However, there are also strong potential niche applications, for example trolley buses (electric buses that draws its electricity from overhead wires) are significantly cheaper than trams. Longer buses with fuel cells could also be cheaper compared to a tram. In these examples, the H_2 fuel cell could make commercial sense.

Next there is the issue of transporting hydrogen, which according to the IEA would necessitate a dedicated network of stainless steel pipes [13]. The IEA estimate the average cost of the pipeline in the US would be $0.1 million per km (2005 prices). This is six times higher than the cost of natural gas pipelines. This is largely because of hydrogen's low energy density, which in turn necessitates higher pressures and pipeline diameters to supply the same amount of energy. Overall the IEA estimate that the worldwide investment to develop a hydrogen pipeline network might be in the order of $2.5 trillion [13]. However, there has also been some consideration of using existing NG distribution systems to deliver a mixture of hydrogen and natural gas to end use applications as a bridging step to a hydrogen economy. According the EC's NATURALHY project[11], which has investigated this possibility at some length, there are also various membrane materials under consideration for hydrogen separation at the other end for use in dedicated H_2-only applications.

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[11] More information on the NATURALHY project is available at: http://www.naturalhy.net/

Once the hydrogen had been transported to its point of use the chemical energy stored in the H_2 bond would then be converted into motive energy using a fuel cell [1]. Estimates of the cost of fuel cells are provided earlier in this section.

The aforementioned barriers a UK Government-funded study by AEA [14] identified the key economic and institutional barriers to a hydrogen future:

- Lack of immediate CO_2 reductions associated with using hydrogen for transport applications;
- Investment in hydrogen infrastructure vs investment in hydrogen vehicle technology;
- Technical and cost barriers associated with hydrogen infrastructure;
- Technical and cost barriers associated with hydrogen vehicles;
- Lack of a sufficiently clear policy framework for hydrogen in the UK;
- Lack of public awareness/understanding;
- The phenomenon of “technological lock-in” means that the incumbent fossil fuel energy infrastructure will retain an economic advantage over hydrogen;
- Absence of codes and standards for hydrogen

However, as illustrated earlier in this section, perhaps the greatest barrier is the diminishing support from Government’s around the world. The quote earlier in this section from the European Conference of Ministers of Transport was followed recently by a public statement from Steven Chu the US Secretary of State for Energy, who questioned the ability of hydrogen to make a contribution in the medium term:

"We asked ourselves: is it likely in the next 10 or 15, or even 20, years that we will convert to a hydrogen car economy?" Chu explained. "The answer, we felt, was no."[15]

Whilst there are some barriers and disbenefits to a prominent role for hydrogen in the transport sector there are certainly some significant advantages. Many of these advantages are the same or similar to those for electricity (discussed in Section 5), although the net energy efficiency of hydrogen fuelled vehicles is generally significantly lower. Firstly, as described earlier in this section there are clearly some significant carbon benefits, particularly if hydrogen is produced from the electrolysis of water powered by renewables. Secondly, a transport sector powered by hydrogen fuel cells would also benefit from improved energy security [13]. Instability in the oil producing regions of the world would no longer have such potential to disrupt supply and impact on price. Thirdly, hydrogen fuelled vehicles would also improve local air quality in urban areas where traffic levels can lead to high levels of pollutants such as particular matter and NO_x. This is because water vapour is the only by-product from hydrogen fuel cells apart from electricity.

6.4 Aviation

Whilst hydrogen (H_2) has been viewed for some time as a long-term option for fuelling the automotive sector, this is not the case for aviation. However, there is a growing interest in the use of fuel cells as a power source for all-electric aircraft propulsion as a means to substantially reduce or eliminate environmentally harmful emissions. Among the technologies under consideration for these concepts are advanced fuel cells, alternative fuels and fuel processing, and fuel storage. A multidisciplinary effort is underway at the NASA Glenn Research Center to develop and evaluate concepts for revolutionary, non-traditional fuel cell power and propulsion systems for aircraft applications ▯. According to the abstract for a study by Witchita University and Cessna [19] the key barriers to hydrogen-fuelled aviation are as follows:

- The low density of hydrogen (meaning large or very strong fuel tanks are required to cope with either a large volume of H_2 or highly pressurized H_2).
- The high mass to power ratio of fuel cell electric power systems compared to conventional internal combustion piston engines or gas turbines. In other words the

power system for a hydrogen fuel cell plane would be significantly heavier than a conventionally powered plane.

- The high volume vs power systems compared to conventional internal combustion piston engines or gas turbines.

There are other aviation-specific barriers to a hydrogen future. For instance, the stringent safety requirements implemented by the Civil Aviation Authority and Federal Aviation Authority mean that new aviation technologies must be very rigorously tested and certified before being launched. This can be a time consuming and costly process. Many of the concerns raised in section 6.3 would also apply to aviation. For example, any airline purchasing a hydrogen fuelled plane would need to be convinced that a robust refueling infrastructure was in place with excellent security of supply. A shortage of fuel leading to planes being grounded is an unthinkable scenario for airlines.

In view of these perceived barriers hydrogen fuelled aviation has certainly not attracted the same level of R&D focus or Government support as the automotive sector. Whilst it may not have attracted a great deal of attention researchers have investigated the potential for hydrogen-fuelled flight. In 2007 Boeing completed tests on a hydrogen-fuelled engine for HALE, the extreme endurance plane that will be able to fly for seven days non-stop [16]. Crucially, HALE is unmanned and as yet not hydrogen fuelled passenger flights have taken place.

That said, FlyH2, a small South African company are developing what they hope will be the first commercial hydrogen fuelled passenger aircraft. They are also developing an unmanned hydrogen fuelled aircraft [17].

Whilst these pockets of innovation do exist they are very much early stage research so it is too early to estimate the marginal capital cost of hydrogen-fuelled aviation or indeed the carbon savings. However, even if the technical barriers are overcome it seems likely that the current high cost of fuel cells per se, regardless of the application, will rule out commercial applications for the foreseeable future.

In addition there is an additional concern over increased emissions of water-vapour at high altitudes, which has other climate impacts through radiative forcing. The scale of these impacts is still a matter of significant scientific uncertainty, but could significantly counteract benefits in terms of net GHG emission reductions.

6.5 Shipping

In theory hydrogen fuel cells could be used to power ships along with most other modes of transport. However, a recent study by a consortium led by AEA for the UK's Committee on Climate Change (who advise Government on GHG emissions targets and the means by which they could be met) concluded that hydrogen fuelled ships are not currently viable option [23]. This is due to a need in the shipping sector to reduce costs, improve durability and improve power density. Unfortunately these are all issues that hydrogen fuelled ship would actually worsen rather than improve since they are key shortcomings of the current fuel cell technology. However, in terms of H_2 refueling infrastructure at least there are fewer disadvantages compared to road transport as there due to lower complexity - there are far less refueling points (i.e. at ports) for marine transport.

The AEA study also points out that very low fleet turnover rates will also act as a significant barrier to hydrogen fuelled ships. It also concludes that it is difficult to envisage hydrogen playing a significant role in shipping even up to 2050.

That said, researchers are still working on early stage designs for hydrogen-fuelled ships. For instance, in 2006 a group at Southampton University developed the 'Oceanjet' conceptual design [25] for a hydrogen ship capable of traveling at 64 knots. Powered by liquid hydrogen the gas turbine propulsion system (similar to that of a Boeing jet engine) would require 0.86kg of liquid hydrogen per second with a total storage capacity of 14,500m^3.

Furthermore, a 2008 article on the Environmental News Network website [24] highlighted what it claimed to be the first hydrogen-equipped commercial vessel. The 'Elding' is a whale watching boat based in Iceland, which has been equipped with a fuel cell to provide lighting. This allows the guests to observe the whales in silence when the main engines are turned off. Later in the same article Dolf Gielen a Senior Energy Researcher at the IEA points out that "whilst hydrogen it is challenging for most shipping applications because of the long distances traveled and therefore significant amounts of hydrogen storage volume needed". Therefore, it seems likely that hydrogen will be limited to very niche applications in the shipping sector even into the long term.

6.6 Rail

As described earlier in section 6.3, hydrogen fuel cells have been investigated as a means of supplying traction power for many years. In recent times, various attempts have been made to power trains using PEM fuel cells. The East Japan Rail Company is currently testing an experimental fuel-cell railcar and another is expected to beginning testing in Denmark in 2010 [21]. In addition, BNSF in the US has just begun testing a hydrogen fuel cell powered shunting locomotive. They are investigating the feasibility of hydrogen as a fuel because of the energy security benefits (it would reliance on oil) and the reduction in carbon emissions [21]. The reduction in carbon emissions arises because hydrogen powertrains tend to be significantly more energy efficient than conventional internal combustion engine powertrains as detailed in section 6.3.

These two key benefits are reiterated in AEA's 2005 report for the Rail Safety and Standards Board (RSSB) [22]. However, whilst it is true that hydrogen fuelled trains would produces GHG emissions savings compared to diesel trains, they are inherently less energy efficient (and hence produce more GHG emissions) than electric trains. Once again this is covered in detail in section 6.3 and reinforced up by a 2005 article in the Railway Gazette [20].

Interesting, AEA's report also highlighted the possibility of using solid oxide fuel cells for auxiliary power units (APUs) [21]. The fuel cell could supply power when the engine would otherwise be idling at stations or during cleaning operations at the end of the train's 'shift'. It is anticipated that such a move could achieve significant GHG savings since leaving a large locomotive engine idling consumes significantly more fuel than a far smaller fuel cell operating at its optimum efficiency.

Another key element of AEA report was the investigation of the feasibility of powering a class 66 freight locomotive using a fuel cell. The study concluded that, whilst a fuel cell system would take up more space than a conventional diesel engine, in theory it could be possible to fit such a system within the space available. Assuming a fuel cell stack cost of £72 per kW, the analysis found that a fuel cell stack capable of supplying power for a Class 66 would cost in the region of £172,000. Once additional costs for cooling equipment and other ancillaries were taken into account, it was estimated that a full fuel cell powertrain for the Class 66 would cost in the region of £344,000. This compares to a cost of approximately £250,000 for the conventional diesel engine currently fitted to the Class 66 locomotive.

However, there are some important caveats to those figures. Firstly, the AEA report concluded the current operational lifetime of fuel cells is not sufficient for rail applications. In addition, there was significant uncertainty surrounding the costs. Furthermore, there is also the important issue of hydrogen storage to take into account. The AEA report found that the cost of a hydrogen tank or metal hydride storage system (one of the main alternatives to simply compressing gaseous hydrogen and storing it in a tank) would be in the region of £1 million. However, it did state that the cost of the metal hydride storage system could fall to around £200k by 2010. Once again the authors were keen to stress that more detailed assessments would need to be undertaken the make more robust estimates of costs.

In terms of CO_2 savings the AEA report estimated that a 2% switch from diesel to hydrogen fuel cells in the UK rail sector would save 4,500 tonnes of CO_2 (based on hydrogen produced from natural gas). A 10% switch would achieve a reduction of 22,600. Further analysis would be required to establish whether these savings could scaled up and applied to the whole of Europe.

6.7 Gaps in Identified Information

- *Road Transport:*
  - Further evidence for current and future cost of fuel cell road vehicles;
  - Car manufacturers perspective on the lifecycle emissions from FCVs versus conventional vehicles and EVs/PHEVs;
  - Total GHG savings for the whole of Europe.
- *Aviation:*
  - GHG savings on an individual plane basis and European potential
- *Shipping:*
  - GHG savings on an individual ship basis and European potential
- *Rail:*
  - GHG savings on an individual train basis and European potential

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7 Summary of Key Findings and Conclusions

The following sub-sections present a summary of the key findings from the material reviewed for this paper, including:

- An overview of reduction potentials of the options covered in this paper
- The main barriers for introduction/ widespread implementation;
- Links with relevant European policies;
- The main gaps in the information identified/available.

In general it should be noted that future CO_2 reduction depends not only on technology options but also on market acceptance, market demands and cost-effectiveness. At the moment there are significant uncertainties and barriers in all of the technology areas reviewed, suggesting an integrated approach is necessary to mitigate the risk from focussing too much on a particular solution. It should also be noted that whilst the focus of this paper has been on the potential for GHG emissions savings, other impacts also need to be factored into a balanced assessment, i.e. wider impacts on the environment, economy, society and industry. Finally, all the alternative fuel/technology areas discussed are (to varying degree) reliant on the development of sound infrastructure policy (e.g. particularly for refuelling) to allow significant uptake of the new technologies. An active role for Member States is therefore critical in this area.

7.1 General Summary

Liquid Biofuels and Biogas

- Biofuels can theoretically save significant levels of greenhouse gas emissions. However, this is very sensitive to the feedstock and production pathway used, as well as fundamental assumptions in the calculation of savings.
- There are a number of issues which need to be resolved and questions which need to be answered before these savings can be confidently quantified and agreed upon. These issues include the potential for both Direct and Indirect Land Use change (LUC).
- In the short-term, current biofuels are likely to offer only a small/limited potential with greater savings possible in the medium term as advanced feedstocks and production processes are developed/mature.
- In the long term their potential may be constrained by competition for land use (and water) to feed an increasing global population and replace petrochemical derived products (e.g. textiles, plastics and chemicals) with those produced from biomass.
- Application in other than the road transport sector is generally immature and still under development. In the longer term biofuel use may need to be focused in aviation and shipping (and potentially long-range road freight transport) due to potentially limited biomass resource availability and fewer alternatives for abatement in these transport sectors.

CNG, LNG and LPG

- LPG is generally not considered to be a long-term option for GHG reduction. There are some more limited possibilities for further improvements in the shorter- (and possibly medium-) term, including ‘bio-LPG’ (a blend of 70% LPG and 30% bio-DME).
- In road transport natural gas vehicles (NGVs) using either CNG or LNG are generally a short-term option. In the long-term they may also provide some limited potential when powered by biomethane. However, the uncertainty of whether there will be enough sustainable feedstock to produce biomethane in significant quantities (together with competition with uses in other

sectors) may hamper significant uptake of such vehicles. There has also been some consideration of using existing NG distribution systems to deliver a mixture of hydrogen and natural gas either directly to end use applications or for subsequent separation via membranes as a bridging step to a hydrogen economy.

- In aviation neither LPG nor natural gas is a suitable alternative fuel, primarily because of the need for fuels with much greater energy density.
- In shipping liquefied natural gas is a promising future fuel for ships delivering significant reduction potential in NOx and SOx and PM emissions as well as GHG emissions;
- In rail there is some limited experience in using natural gas, usually driven by reductions in air quality emissions unless biogas/biomethane are utilised. Only niche applications seem likely in the future.

Pure Electric and Plug-in Hybrids

- Pure electric powered transport holds the greatest potential for GHG emissions reductions, since it can be produced from essentially carbon-neutral sources and utilized directly at higher net efficiency compared to hydrogen fuel (except perhaps for biological H_2 pathways).
- Significant challenges remain principally in the area of electricity storage – in terms of cost, weight, volume, efficiency and power delivery. These limitations also impact on the useful range of electric vehicles compared to conventional equivalents. These and other barriers mean the mainstream utilization of electric vehicles is still seen as being in the long-term, although smaller scale penetration is already progressing in the short-term.
- Plug-in hybrid electric vehicles are seen as an intermediate (short- to medium-term) technology on the pathway to electric vehicles in the road transport sector, enabling performance characteristics and range similar to conventional equivalents at lower capital costs. They also may have an important role to play in the long-term where range is critical.
- Electric trolley busses are an existing technology that potentially in the long-term might be extended further to trolley systems for trucks or even passenger cars on highways.
- There appears to be no significant interest on research into pure electric aircraft or ships applicable for passenger or freight operations.
- Electric rail is a mature technology that already accounts for over 80% of rail propulsion across Europe. It is uncertain to what degree this proportion could be increased in the future.

Hydrogen and Fuel Cells

- Hydrogen fuel cells offer significant potential to reduce GHGs from road transport in the long-term (depending on the hydrogen production pathway). Contribution to GHG emissions reductions in the medium term are not anticipated to be high.
- The contribution of FCVs (fuel cell vehicles) will depend on developments in hydrogen / fuel cell technologies as well as in electrical energy storage for competing pure electric vehicles (EVs). FCVs currently have an advantage in range over EVs due to greater energy storage densities for hydrogen relative to electrical energy storage.
- The cost of developing new hydrogen refueling infrastructure is enormous (much higher in comparison to developing a recharging infrastructure for pure EVs). However, as discussed earlier for natural gas vehicles, there has also been some consideration of using existing natural gas distribution systems to transport a mix of hydrogen and natural gas to act as a bridging step to a hydrogen economy.
- Hydrogen powered aircraft or ships appear to be unlikely propositions even by 2050.
- Hydrogen fuel cell powered rail vehicles may have the potential to replace diesel rail in the long term in areas where further line electrification is not economic.

7.2 Overview of Reduction Potentials

Table 7.1 Summary of GHG reduction potential for alternative energy carriers and powertrains

Area	Mode	Individual Vehicle Potential	Scale of Application	Total European Potential
Liquid Biofuels and Biogas	*Road Transport*	Currently being used in road transport – bus, private cars, vans and HGVs.	Going forward it will be widely applicable in blends	The RED suggests 10% of biofuels use in transport by 2020 subject to sustainability criteria being met
	Air	Potential use in the longer term 2020-2050	At demonstration phase at present	Depends on a number of factors
	Shipping	Potential in the longer term 2020-2050	At demonstration phase at present	Depends on a number of factors
	Rail	Increased potential in the longer term 2020-2050	Limited implementation at present. Could increase in longer term	Depends on a number of factors
CNG, LNG and LPG	*Road Transport*	Short-term: Similar or slightly lower than diesel for vehicles powered by natural gas or LPG. Significant savings (60-200%) for vehicles powered by biogas/biomethane, depending on source/production pathway. Much less significant savings for LPG vehicles using a 30% mix of bio-DME. Long term: **No information identified/available.** However, likely to be similar to short-term.	LPG: Generally not considered to be a long-term option. Potential for use with a blend of 30% bio-DME to improve reduction potential in the short-medium term. CNG/LNG: Natural Gas vehicles are predicted to grow in the short and medium-term (2020) and is a valid technology option in the long-term when being used in form of biomethane and biogas	LPG vehicles could serve up to 10% of the European market according to AEGPL LNG/CNG: **No information identified/available**
	Air	**No information identified/available**	As for the high volume and weight requirements of natural gas and LPG storage systems both are not being considered as a viable alternative fuel for shipping.	**No information identified/available**
	Shipping	**No information identified/available**	LNG is a promising future fuel for ships, mostly driven by emission reduction. LPG is not being considered as a viable alternative fuel.	**No information identified/available**

Area	**Mode**	**Individual Vehicle Potential**	**Scale of Application**	**Total European Potential**
	Rail	**No information identified/available**	Although there has been some limited experience in using natural gas in rail applications the high volume and weight requirements of natural gas and LPG storage systems will pose significant limitation for an uptake of the application.	**No information identified/available**
Pure Electric and Plug-in Hybrids	*Road Transport*	With the current European grid mix EVs would produce CO_2 savings of around 50% to 60%. If grid mix electricity is decarbonised this will rise significantly in line with the proportion of renewables, nuclear and fossil fuel plantfitted with carbon capture and storage (CCS) in the energy mix. With the current grid mix PHEVs would produce CO_2 savings of around 25% to 35%. Once again this will rise as the grid is decarbonised. Eureletric has indicated there is a good prospect for the 2050 electricity mix to be essentially decarbonised.	The uptake of EVs will be negligible before 2015 and will remain a niche product until at least 2020. Best case uptake will be around 5% of new cars by early 2020's. Unless battery costs reduce dramatically uptake will be heavily dependent upon sufficient Government incentives (both up front price support and softer measures like free parking, use of bus lanes etc) being put in place. The uptake of PHEVs will also be negligible before 2015. Uptake is expected to grow more quickly than EVs but still at a modest rate. Best case uptake will be around 8 or 9% of new cars by early 2020's. Uptake will also be heavily dependent on Government incentives	Negligible by 2015 Less than 1% by early 2020's GHG savings will only become significant (i.e. more than a few percent) by late 2020's or early 2030's once EVs and PHEVs make up a significant proportion of the overall vehicle fleet.
	Air	None	None anticipated by 2050	None
	Shipping	Very limited	None for the foreseeable future (before 2030)	None
	Rail	Electric traction for rail typically produces 60% to 70% less GHG than diesel traction.	Whilst only 51% of tracks are electrified, 80% of rail kms are already undertaken by electric traction so further savings are likely to be more limited than for other modes since it will not be cost effective to electrify 100% of un-electrified lines.	**No information identified/available**. However, cost effectiveness will limit further potential.

Area	Mode	Individual Vehicle Potential	Scale of Application	Total European Potential
Hydrogen and Fuel Cells	*Road Transport*	Using reformation of natural gas to produce hydrogen would produce GHG savings of around 40% vs petrol and diesel. Using the current grid mix to produce hydrogen via electrolysis of water would actually increase GHG on a individual basis by around 20%. However, using a fully decarbonised energy mix (i.e. renewables and nuclear) would reduce GHG emissions by more than 95% to close to zero.	Negligible until post 2030 at the earliest. Government's across the world (Europe and US) are favouring electric vehicles in the medium term.	Negligible until post 2030 at the earliest.
	Air	**No information identified/available**	None anticipated by 2050 since no serious efforts to develop powered planes	None
	Shipping	**No information identified/available**	None anticipated by 2050 since no serious efforts to develop powered ships due to cost, durability and power density issues	None
	Rail	**No information identified/available**	None anticipated by 2050 since electric traction is more energy efficient and already powers 80% of rail kms	None

7.3 Main Barriers

Liquid Biofuels and Biogas

- The main barrier to the take up of biofuels are the potential sustainability impacts including Indirect Land Use Change and Socio-economic factors. There is a need to identify and implement mitigation measures.
- Cost may also be a barrier in certain modes – in particular rail and shipping.

CNG, LNG and LPG

- There are no significant drivers for LPG in terms of reducing greenhouse gas emissions in the short- or long- term compared to other alternative fuels.
- The main bottlenecks that pose barriers to the uptake of CNG and LNG include:
  - Technical bottlenecks, for example durability of some components, a large variation in economic returns due to variations in operational performance for road transport;
  - Availability (and cost) of suitable refuelling infrastructure;
  - Storage volume/weight (and range) and cost;
  - Availability of suitable engines is uncertain for rail applications;
  - The availability of LNG fuels in bunkering ports for shipping;
  - For shipping, at present, the LNG technology is only available for four-stroke engines.

Pure Electric and Plug-in Hybrids

- The current cost of lithium-ion batteries and other advanced batteries (leading to very high up-front vehicle capital costs);
- A lack of widespread charging infrastructure;
- Public perception of electric vehicles and willingness on the part of the general public to change their refuelling behaviour;
- Reduced range compared to conventional petrol and diesel vehicles;
- Charging time (6 to 8 hours with a conventional domestic mains connection);

Hydrogen and Fuel Cells

- Poor energy efficiency of the hydrogen ‘pathway’ compared to electric traction;
- Cost of fuel cells;
- Durability of fuel cells;
- Poor power density;
- Energy density and cost of hydrogen storage;
- Cost of infrastructure.

7.4 Links with Policies

Liquid Biofuels and Biogas

- In the medium term (2020) the Renewable Energy Directive is likely to be the key policy driver fro the take up of biofuels in the transport sector at the EU level.
- In the future, caps on carbon may drive forward use, though this would be dependent on sustainability concerns being addressed.

CNG, LNG and LPG

- *Road Transport:* In the EU, LNG/CNG is currently a comparable niche-market technology, but due to stricter emission standards and targets the applications have a considerable growth potential. The 130g/km European CO_2 emissions limits agreed in December 2008 and to be phased in between 2012 and 2015 will encourage car manufacturers to sell lower carbon cars in general. There are a few local policies supporting the use of biomethane, e.g. in Lille, France, where the local authority collects organic waste, produces biomethane and uses it to power local buses.
- *Aviation, Shipping and Rail:* No identified policy links.

Pure Electric and Plug-in Hybrids

- The 130g/km European CO_2 emissions limits agreed in December 2008 and to be phased in between 2012 and 2015 will encourage car manufacturers to sell lower carbon cars. Whilst this won't explicitly help EVs or PHEVs it is the first step in what is likely to be a progressively tighter CO_2 emissions limits for cars.
- The European Commission's proposed a 95g/km CO_2 emissions limit for cars for 2020 will reinforce the need for low-carbon vehicles. However, even this limit might be achievable with advanced diesel technology. Future limits below this beyond 2020 would likely stretch advanced diesel technology to the limit and may necessitate a shift to PHEVs and EVs.
- European Government's are offering various up front price support packages or registration tax exemptions for EVs and PHEVs (e.g. UK, France, Norway, Denmark, Sweden, Ireland, Netherlands, Belgium and Greece).
- The European Green Cars initiative[12] is one of the three PPPs included in the Commission's recovery package, which includes €1 billion through support to research, with equal contribution from the Seventh Framework Programme for Research (FP7) and from the private sector. Amongst other support, it includes research on electric and hybrid vehicles, notably research on: high density batteries; electric engines; and smart electricity grids and their interfaces with vehicles.
- Various Government programmes to provide R&D grants or loans to develop or demonstrate EVs and PHEVs
- Through policy statements various European Governments are making it clear that electric cars are part of the medium and long-term vision for de-carbonising the transport sector. For example, Spain recently announced its intention to have one million electric vehicles on the road by 2014.
- Due to the heavy subsidies most European Governments provide their rail sectors they have a powerful in determining policy. In view of the capital costs of electrification they are likely to be asked to fund part or all of the cost of further electrification. These decisions are likely to be taken on the basis of cost effectiveness but the carbon benefits of electrification will also play a part, particularly if the cost of carbon is included in the cost benefit analysis.

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[12] Information is available on the EC's website at: http://ec.europa.eu/research/industrial_technologies/lists/green-cars_en.html

Hydrogen and Fuel Cells

- The Fuel Cells and Hydrogen Joint Undertaking (FCH JU)[13] is a PPP (public-private partnership) aimed at accelerating market introduction these technologies, through support for RD&D activities, as part of achieving a low-carbon energy system.
- The European Council of Transport Ministers and US Government recently stated that they do not anticipate hydrogen vehicles making a contribution in the short to medium term i.e. not until post 2030 at the earliest. Therefore, whilst there is still funding available for fuel cell RD&D (e.g. RCH JU already mentioned), there are no significant incentives or policies aimed at introducing hydrogen fuel cell vehicles.

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[13] For further information see: http://ec.europa.eu/research/fch/index_en.cfm

7.5 Main Information Gaps

Table 7.2 Summary of main information gaps for alternative energy carriers and powertrains

Area	Gap No.	Description	Importance	Urgency	Complexity
Liquid Biofuels and Biogas	*Gap 1*	Improved understanding of sustainable development impacts: Includes the potential for indirect land use change and how this can be mitigated and the better understanding of socio-economic impacts	**High**	**High**	**High**
	Gap 2	Impact of current policies on encouraging sustainable biofuels	**High**	**High**	Medium
	Gap 3	Future fleet capability including issues around quality standards	Medium	Medium	Medium
	Gap 4	Demand for fuels in the aviation and shipping sectors	Medium	Low	Low
	Gap 5	Interaction of demand for aviation and shipping sectors with different sectors	Medium	Low	**High**
CNG, LNG and LPG	*Gap 1*	There is only little information on projections for CNG and LNG up to 2050 (and none for LPG). E.g. additional data are needed for GHG emissions, energy consumption and costs. The gap in identified information is partly due to the fact that CNG/LNG and are not considered to be a long-term option.	Low	Medium	Low
	Gap 2	Further research needs to be put into the availability of feedstock of biomethane, which is considered to be the only option with radical emission reductions	Medium	**High**	Medium
Pure Electric and Plug-in Hybrids	*Gap 1*	Latest costs of Li-ion battery variants (cobalt oxide cathode, iron-phosphate cathode, manganese oxide cathode, nickel oxide cathode and lithium titanate anode)	Medium	Medium	Low
	Gap 2	Data on the proportion of the car and LCV fleet that would need to be recharging from distribution network to cause significant capacity issues.	Medium	Medium	**High**
	Gap 3	Total carbon savings for Europe from uptake of EVs	**High**	**High**	**High**
	Gap 4	Total % of European rail kms that could be electrified bearing in mind 80% are already electrified.	Medium	Medium	**High**
Hydrogen and Fuel Cells	*Gap 1*	Further evidence for current and future cost of fuel cell road vehicles	Medium	Low	Low
	Gap 2	Car manufacturers perspective on the lifecycle emission from FCVs vs conventional vehicles and EVs/PHEVs	Medium	Low	Low
	Gap 3	Total carbon savings from FCVs for the whole of Europe	Low	Low	**High**
	Gap 4	Carbon savings on an individual plane basis	Low	Low	Medium
	Gap 5	Carbon savings on an individual ship basis	Low	Low	Medium
	Gap 6	Carbon savings on an individual train basis	Low	Low	Medium

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