Energy Options for Transport: Phase I

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The Energy Research Partnership

The Energy Research Partnership is a high-level forum bringing together key stakeholders and funders of energy research, development, demonstration and deployment in Government, industry and academia, plus other interested bodies, to identify and work together towards shared goals.

The Partnership has been designed to give strategic direction to UK energy innovation, seeking to influence the development of new technologies and enabling timely, focussed investments to be made. It does this by (i) influencing members in their respective individual roles and capacities and (ii) communicating views more widely to other stakeholders and decision makers as appropriate. ERP's remit covers the whole energy system, including supply (nuclear, fossil fuels, renewables), infrastructure, and the demand side (built environment, energy efficiency, transport).

The ERP is co-chaired by Professor John Loughhead, Chief Scientific Advisor at the Department of Energy and Climate Change and Dr Keith MacLean (formerly Director of Policy & Research at Scottish and Southern Energy). A small in-house team provides independent and rigorous analysis to underpin the ERP's work. The ERP is supported through members' contributions.

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Prof John Loughhead FREng	Chief Scientific Advisor	DECC
Dr Keith MacLean	Independent industry co-chair	Formerly of SSE

Members

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Tom Delay	Chief Executive	Carbon Trust
Miles Elsden	Acting Chief Scientific Advisor	DfT
Peter Emery	Production Director	Drax Power Limited
Angus Gillespie	Vice President CO_2	Shell Int'l Petroleum Co. Ltd
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Phillip Sellwood	Chief Executive Officer	Energy Saving Trust
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Dr Jim Watson	Executive Director	UK Energy Research Centre
Nick Winser FREng	Executive Director, Transmission	National Grid
Jonathan Yewdall	Assistant Director, Green Growth Team	BIS

Observers

David Joffe	Head of Modelling	Committee on Climate Change
Andrew Wright	Finance Director	Ofgem

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The Energy Research Partnership Reports

ERP Reports provide an overarching insight into the development challenges for key low-carbon technologies. Using the expertise of the ERP membership and wider stakeholder engagement, each report identifies the challenges for a particular cross-cutting issue, the state-of-the-art in addressing these challenges and the organisational landscape (including funding and RD&D) active in the area. The work seeks to identify critical gaps in activities that will prevent key low-carbon technologies from reaching their full potential and makes recommendations for investors and Government to address these gaps.

This project was guided by a steering group made up of experts from ERP members and other key organisations, as listed below. The views in this report are not the official point of view of any organisation or individual and do not constitute government policy.

Analysts

Tom Watson	Energy Research Partnership
Simon Cran-McGreehin	Energy Research Partnership

Steering Group

Neville Jackson (chair)	Ricardo
John Miles	ARUP/Cambridge University
Rachel Squire	Shell
Tom Delay	Carbon Trust
Andrew Benfield	Energy Saving Trust
Rupert Wilmouth	Government Office for Science
Rob Wakely	Department for Transport
Ian Llewellyn	Department of Energy and Climate Change

We would like to thank all those who helped inform this work.

If you have any queries please contact Tom Watson (tom.watson@erpuk.org) or Simon Cran-McGreehin (simon.cran-mcgreehinp@erpuk.org).

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Summary

This report is the first output of a two-stage piece of research undertaken on behalf of the Energy Research Partnership and the Government Office for Science. It aims to explore how the transport sector fits into the wider energy system within the context of decarbonisation and other policy objectives within the transport sector and interactions with the energy sector. Phase 1 seeks to provide a high level examination of the options for powering each mode of transport and to examine competing objectives and trade-offs. Phase 2 will use this work to develop high-level scenarios, with the aim of developing a view on the 'best use' of certain energy resources.

Overview of UK transport sector and modes

In 2013 the transport sector accounted for the consumption of 53.4Mtoe – 36% – of the UK's final energy use, and domestic transport was responsible for the release of 116.7MtCO_2e, slightly over 25% of the UK's total. If the country is to meet its legally-binding obligation to reduce total emissions by 80% by 2050, the transport sector must make a substantial contribution.

Road travel has accounted for 90% of domestic transport emissions since at least 2000, with the bulk of this coming from cars and taxis, HGVs and light vans. Across all modes of transport petroleum products continue to dominate, accounting for approximately 97% of energy use in the transport sector, with alternative fuel sources reaching 1% only in 2008, mostly in the form of biofuels.

Options for decarbonisation

Transport emissions can be reduced by travelling less far and less often (or reduced tonnage and distance in the case of freight), by shifting journeys to a more efficient mode, or by substituting low carbon fuels for petroleum products. There is in addition an array of issues beyond carbon reduction that are fundamental to the transport sector (such as the role it plays in supporting economic growth, local air quality concerns and passenger safety) many of which may interact with decarbonisation efforts. There is a need of further study of the interactions between: the options for decarbonisation, the wider energy system and other drivers in the transport sector.

Below are listed some brief hypothetical sketches that give a sense of the magnitude of the carbon consequences of certain actions. They are merely intended to illustrate the relative scales of these changes; the real-world outcomes would be likely to be far more complex and unpredictable.

- Shifting all domestic air freight and passenger journeys to rail would in theory avoid the 1.7MtCO_2e emitted by air travel (less than 1% of transport emissions) whilst increasing rail passenger kilometre by 0.18% and rail freight by 0.06%.
- Doubling rail passenger kilometres by transferring those journeys away from roads could, if emissions fall relative to the reduction in road passenger kilometres (15.5%), save 10MtCO_2e – the same as rail, domestic aviation, domestic shipping combined, military aircraft and shipping and aircraft support vehicles combined. Any rise in rail emissions would be dependent on a range of factors but a doubling of current rail emissions would lead to a further 2.1MtCO_2e.
- Shifting journeys from road to bicycle sufficient to double bicycle kilometres (equivalent to the annual travel of 376,943 cars (1.3% of the total fleet), saving 0.84MtCO_2e (less than 1% of road emissions).

Energy sources

The extent to which road travel is overwhelmingly responsible for the transport sector's carbon emissions, together with the limited carbon-saving potential suggested by the mode-switching scenarios above, points towards fuel switching as the primary way in which to reduce emissions. Pareto analysis indicates that tackling the highest-emitting vehicle types would have the greatest impact, suggesting that the deployment of zero tailpipe emissions technologies for light vehicles travelling short distances, and lower-carbon fuels in the case of heavy duty vehicles moving over greater distances, could contribute the most to climate goals.

Most modes of transport have technical requirements (primar9ly high energy density) that limit fuel options. In particular, aviation requires a dense liquid fuel, and so has less technical flexibility to use alternatives such as electricity, natural gas or hydrogen

Each mode of transport must also satisfy other criteria (e.g. safety, comfort, convenience, air quality, etc.) that can place further restrictions upon energy options. For example, whilst nuclear power is technically suited to shipping, the risk of wrecks essentially prevents its use in commercial shipping.

Some energy sources could face constraints. Some resources could be fundamentally limited, e.g. fossil fuels under international agreements. Other resources could be available in theory, but are competed for: e.g., biofuels are likely to be affected by social and environmental factors associated with land use change. And other energy options may face competition for use of infrastructure, e.g. electricity networks for urban transport, or gas networks for heavy road transport.

Conclusions and next steps

Our work on Phase 1 has confirmed the view that there has not yet been sufficient study of the potential future interactions between different transport modes and the energy sector. To address this issue, Phase 2 of this project will develop scenarios to assess the possible outcomes of different decarbonisation strategies for transport, taking into account other priorities in the sector and interactions with the energy sector. This will be based, in part, on the assessment of each option, as summarised in the tables in Annex 1. A broad exploratory analysis of interactions and trade-offs could identify the areas where more a more detailed research and development is required and draw attention to those areas where the greatest certainty or uncertainty lies.

These scenarios will be of broad scope, covering the transport and energy sectors as well as any key non-energy implications that may be appropriate. The objective is not to arrive at detailed and costed future pathways, but to explore the interactions and trade-offs that exist when making strategic decisions. The scenarios devised as part of this analysis will seek to explore the outcomes given a series of inputs, rather than to optimise outputs (e.g. costs).

- ***We will seek input from a range of experts, including at the ERP plenary in April, on topics including:***
    - ***the scale and extent of interactions between the transport and energy sectors;***
    - ***the potential impacts of energy sources and technologies;***
    - ***the level of confidence around the future development of these technologies;***
    - ***probable and/or plausible rates of uptake.***

1. Introduction

The transport sector accounts for a third of the UK's energy consumption and a quarter of its greenhouse gas emissions, and will therefore need to make a contribution to the 2050 target of 80% emissions reductions legally required under the Climate Change Act 2008. Currently, 97% of the energy used in the sector comes in the form of liquid fossil fuels with a high energy density and carbon content. These fuels are delivered via a highly developed infrastructure which, like the vehicles it serves, has benefited from vast economies of scale and steady technical improvement over the last century.

This project is considering how transport fits into the wider energy sector within the context of decarbonisation, taking into the account the various trade-offs that exist between the different modes, fuel sources and objectives within the sector. This report on Phase 1 of the project provides an overview of the energy options for powering road, rail, aviation and shipping, discussing the potential contribution to emissions reductions and technological maturity of each. Drawing on this, Phase 2 will develop a small number of high-level decarbonisation pathways to identify the 'best use' of fuels given the various options and constraints.

The project is being undertaken by the Energy Research Partnership (ERP) on behalf of its members and the Government Office for Science (GO-Science). It is being carried out under the guidance of a steering group composed of public and private sector members, and has drawn on desk-based research as well as discussions with experts from the field.

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2. Overview of UK transport energy and emissions

This section presents an overview of transport in the UK. It starts by presenting the contribution of transport to UK energy usage and emissions, and then breaks this down by different modes of transport to identify the most significant factors.

2.1. UK energy and emissions

The UK's energy use and emissions vary from year to year, owing to economic performance, fuel mixes in electricity generation and winter temperatures, so it can be useful to use averages from several years. Over recent years the UK has typically used around 2400TWh of primary energy annually (to meet final energy demand of approximately 1700TWh)[1]resulting in emissions of about 575MtCO_2e (including non-energy sources)[2]. The contributions of the major sectors are illustrated in Figure 1. These emissions are 25% lower than the 1990 level of approximately 800MtCO_2e, but will need to fall by 75% from now in order to reach the 2050 target of 160MtCO_2e. Whilst emissions reductions might not be spread evenly between sectors, it is prudent to consider 80% reductions on 1990 levels for all of the major sectors.

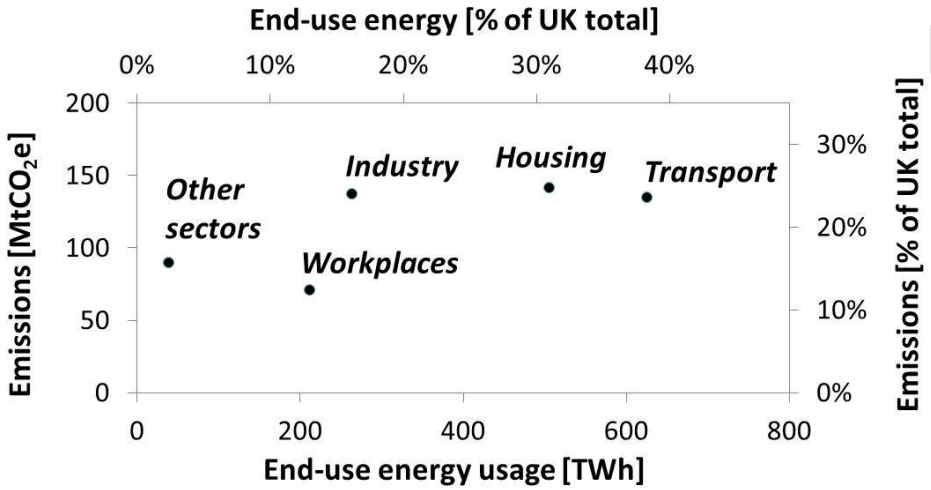

Figure 1: UK energy usage[3] and emissions[4] by sector (absolute values and percentages of totals)[5]

[1] Energy Consumption in the UK (DECC, 2014); and United Kingdom housing energy fact file: 2013 (DECC, 2014)
[2] Meeting Carbon Budgets – 2014 Progress Report to Parliament (CCC, 2014)
[3] Energy Consumption in the UK (DECC, 2014); and UK Housing Energy Factfile: 2013 (DECC, 2014)
[4] Meeting Carbon Budgets – 2014 Progress Report to Parliament (CCC, 2014). By end-use (not source) sector.
[5] Note that differing definitions affect the exact splits of energy and emissions between workplaces and industry. "Other sectors" includes agriculture, construction and miscellaneous sectors.

2.2. Transport sector energy use and emissions

In 2013 the transport sector accounted for the consumption of 53.4Mtoe – 36% – of the UK's final energy use[6], and domestic transport was responsible for the release of 116.7MtCO_2e, slightly over 25% of the UK's total[7]. If the country is to meet its legally-binding obligation to reduce total emissions by 80% by 2050, the transport sector must make a substantial contribution. In addition to the Climate Change Act, Europe's Renewable Energy Directive established a target of 10% for renewably-sourced fuels in the road transport of each member state by 2020, and the Fuel Quality Directive requires all fuel suppliers to achieve a 6% reduction in greenhouse gases from each fuel sold by 2020.

Error! Reference source not found. shows a breakdown by mode of energy demand and emissions from the transport sector in 2011, the most recent data available[8]. Road travel has accounted for 90% of domestic transport emissions since at least 2000, and the bulk of this comes from cars, taxis, HGVs and light vans. Of these major contributors, HGV emissions have since 2000 remained relatively constant, whilst those from light vans have risen by 18.8% and those from cars and taxis have fallen by 14.8%.

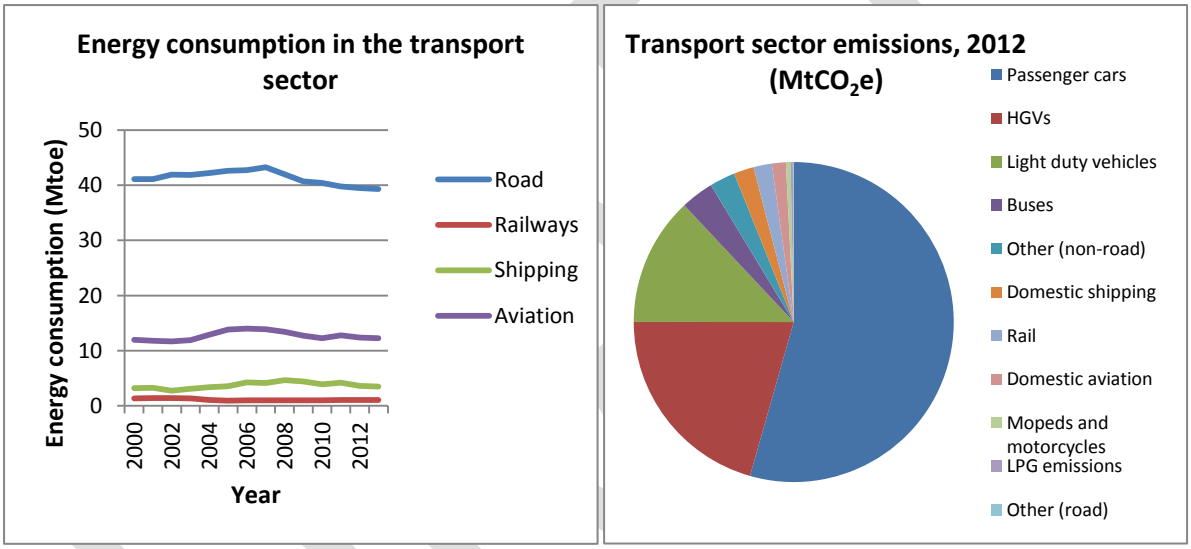

Figure 2: Energy consumption in the transport sector (including fuel sold in the UK but used in international shipping and aviation)[9]; and breakdown of transport sector emissions (excluding international shipping and aviation).[10]

Figure 3 shows how this energy use is split between the different modes of transport and how it has fluctuated since 2000 (this includes fuel sold in the UK but used in international shipping and aviation). Approximately 70% of transport energy usage occurs on Britain's roads.

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[6] DECC (2014), *Energy consumption in the UK (2014)*, available at https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/337454/ecuk_chapter_2_transport_factsheet.pdf, accessed 8th January 2015.

[7] DECC (2014), 2013 UK greenhouse gas emissions, provisional figures and 2012 UK greenhouse gas emissions, final figures by fuel type and end-user, available at https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/295968/20140327_2013_UK_Greenhouse_Gas_Emissions_Provisional_Figures.pdf, accessed 8th January 2015.

[8] These figures include domestic aviation and shipping but exclude international aviation and shipping.

[9] Department for Transport, ENV0102 (TSGB0302) Energy consumption by transport mode and source of energy: United Kingdom, 2000-2013

[10] See: Department of Energy & Climate Change, *2012 final UK figures: data tables*

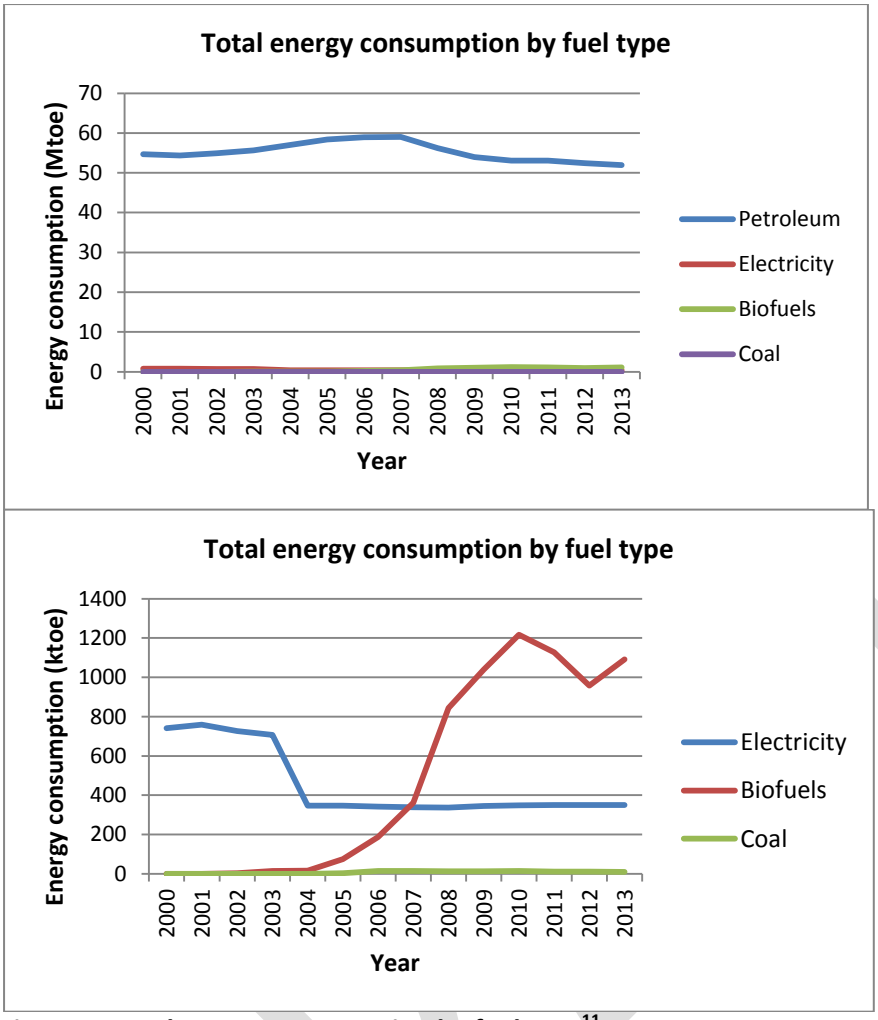

Figure 3: Total energy consumption by fuel type[11]

The first graph above shows that across all modes of transport petroleum products continue to dominate, accounting for approximately 97% of energy use in the transport sector. The second excludes petroleum products, showing how alternative fuel sources reached 1% only in 2008, mostly in the form of biofuels (the drop on electricity consumption is due to a change in accounting method).

- **Petroleum**-based fuels used for road transport, which is responsible for almost 75% of total transport energy consumption, are used overwhelmingly in the form of petrol and diesel, and whilst the total consumption of these fuels has remained relatively constant since 2000, the contribution of each has changed markedly, as shown in **Error! Reference source not found.**.
- **Biofuels** represent only a fraction of overall consumption, but whilst the absolute figure is very low, it grew steadily from zero in 2000 and 2001 to a peak of 1.22Mtoe in 2010, before falling to 1.09Mtoe in 2013 – 3% of transport energy consumption. Figure 14 shows how the various biofuels used in the UK are comprised overwhelmingly of biodiesel (fatty acid methyl esters) and bioethanol sourced from all over the world.
- The sudden drop in the amount of **electricity** being used is due to a change in the way data is recorded: before 2004 electricity use at railway stations was included with electricity used to move locomotives – after 2004 it was not. Accounting for this change, electricity consumption in the transport sector has remained relatively constant.

[11] Department for Transport: Energy consumption in the UK (ECUK), transport data tables, 2014 update)

Carbon dioxide emissions per passenger kilometre are used to compare the emissions rates of different modes of passenger transport, and also different categories within the same mode. Modal comparisons are highly reliant on assumptions around, for example, load factor, engine type and journey type and distance. However, it is broadly the case that air travel and single-occupancy car journeys are high emitters, whilst travel by train, bus and coach have a substantially lower carbon impact[12]. Attempts to assess emissions per tonne kilometre in the case of freight transport are confronted with similar difficulties, plus additional complications where journeys are multi-modal, international or both. Operators may compare maximum load factors for their own mode with average load factors for competing modes, resulting in favourable emissions outcomes[13]. However, whilst HGVs make up the bulk of freight emissions, air transport is responsible for by far the highest level of emissions per tonne kilometre.

Pareto analysis is a formal approach used to prioritise the tackling of problems. It list problems (seen on the horizontal axis) based on the number of times they occur (left-hand vertical axis) and their cumulative frequency (right-hand vertical axis), thus illustrating how a small number of issues are often responsible for a high percentage of total problems.

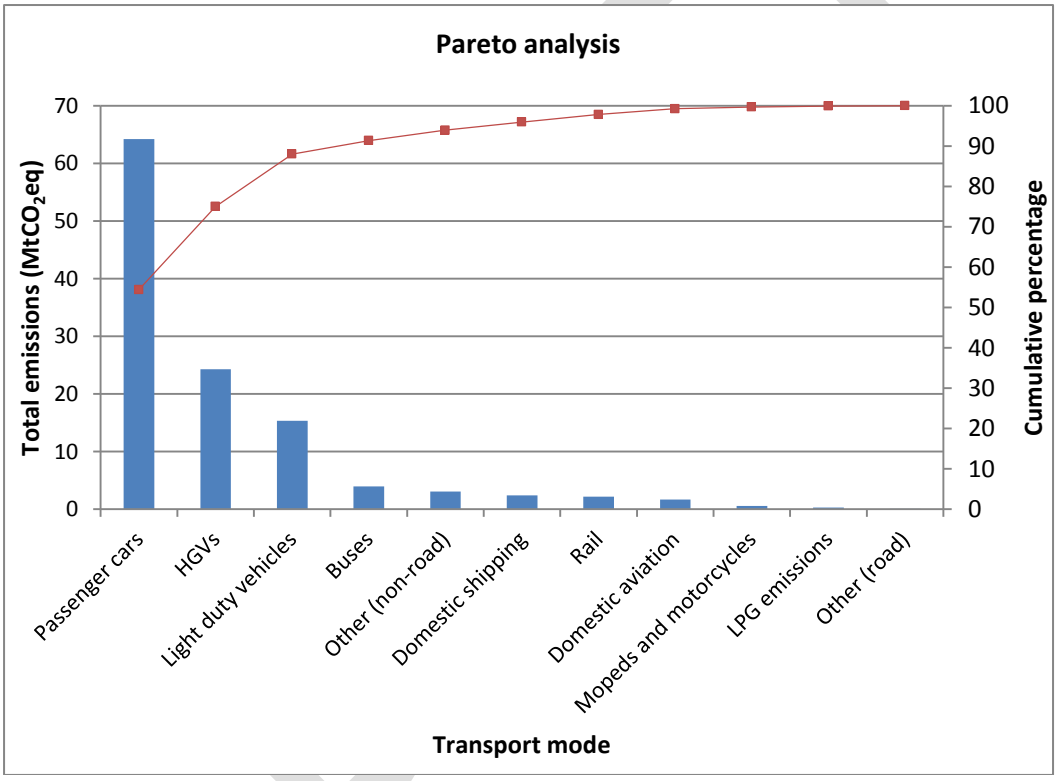

Figure 4: Pareto analysis of emissions for each mode of transport.

Figure 4 shows the various modes of transport, presented in decreasing size of emissions, and demonstrates how just three types of road vehicle – passenger cars, HGVs and light duty vehicles – together account for 88% of domestic UK transport emissions. On the basis of this analysis it is anticipated that Phase 2 of this report, which will follow the overview of energy options given in Phase 1, will concentrate on these sources of emissions.

12 http://www.dft.gov.uk/about/strategy/whitepapers/whitepapercm7176/railwhitepapertechnicalstrategy/pdfrailtechstrategyrts1.pdf

13 http://www.greenlogistics.org/SiteResources/d82cc048-4b92-4c2a-a014-af1eea7d76d0_CO2%20Emissions%20from%20Freight%20Transport%20-%20An%20Analysis%20of%20UK%20Data.pdf

3. Transport modes

This chapter considers the drivers and the criteria that are important for each mode of transport, including those that affect suitability: for example, the requirements of certain modes may make some energy sources unsuitable. The suitability of energy sources can also be affected by other priorities within the transport sector (for example, social and environmental criteria) and interactions between the transport and energy sectors (such as the use of infrastructure). These points are summarised in the tables in Annex 1.

3.1. Road

Of road, rail, domestic shipping and domestic aviation, road travel is responsible for the largest amount of emissions (92%). Average UK new car emissions have been declining steadily year on year, falling to 128.3gCO_2/km in 2013 (Figure 5), meeting the 2015 target and making progress towards the 2020 target of 95 gCO_2/km[14]. This improvement has been driven by consumer demand for greater fuel efficiency in the context of a challenging economic context, fiscal incentives for ultra-low emitting vehicles and regulation and legislation requiring lower vehicle emissions.

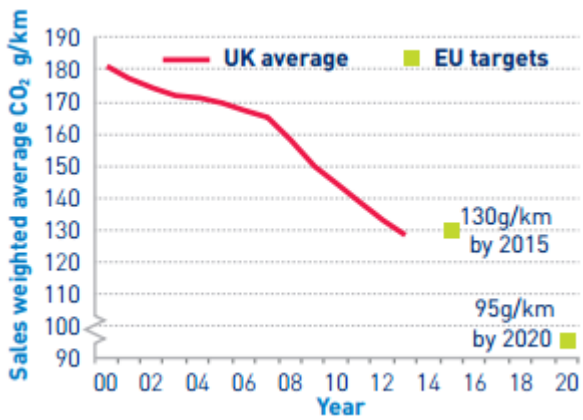

Figure 5: Average CO_2 emissions of new cars in UK[15]

Road transport faces an array of drivers in addition to carbon reduction. For example, poor **air quality** can cause breathing problems, trigger asthma, reduce lung function and increase the risk of cardiovascular disease and lung cancer[16], and is therefore a major driver for change in the transport sector. A variety of measures have been put in place due reduce air pollution, such as European-level agreements on monitoring and annual reporting on pollutants including sulphur dioxide, nitrogen dioxide and oxides of nitrogen, particulate matter, lead, benzene, carbon monoxide and ozone[17][18]. There are a number of UN and EU level regulations that aim to bring down the level of harmful

[14] http://www.smmt.co.uk/wp-content/uploads/sites/2/SMMT-New-Car-CO2-Report-2014-final1.pdf
[15] http://www.smmt.co.uk/wp-content/uploads/sites/2/SMMT-New-Car-CO2-Report-2014-final1.pdf
[16] https://www.gov.uk/government/statistics/emissions-of-air-pollutants
[17] http://www.endseurope.com/39157/france-moves-to-end-diesel-dominance
[18] http://ec.europa.eu/environment/air/quality/legislation/reporting.htm

pollutants caused by the combustion of transport fuels[19][20], the majority of which the UK meets; the primary challenge lies in addressing nitrogen dioxide levels alongside roads in towns and cities[21]. In the early 2000s, with a policy focus on carbon dioxide, UK vehicle excise duty regime was overhauled so that engines emitting more CO_2 would be taxed at a higher rate. This led to a steep rise in the number of diesel vehicles on the roads – up from 1.6m to 11m in the last 10 years – because of their efficiency advantages over petrol-fuelled engines, and caused a rise in nitrogen dioxide levels, leaving the UK facing legal action by the European Commission over its failure to meet targets[22]. Whilst NO_X and NO_2 emissions from diesel engines remain higher than their petrol counterparts, they are unlikely to be as significant a long-term driver as the need to reduce carbon dioxide emissions due to tightening EU emissions standards and the phase-out of older vehicles.

The US Centre for Economics and Business Research projects that costs resulting from **road congestion** will rise 63% to more than £21bn by 2030 across the UK economy as a whole[23]. The CBI estimates that 19.2 seconds were lost per mile due to congestion in 2010 and that new financial and operational models are needed to address the shortage of investment and the uncertainty caused by short term funding cycles by taking the road network out of the government's budget[24]. In December 2014 George Osborne announced a £15bn programme intended to ease congestion at many sites including the north, the south west and the M25, a move resisted by campaigners who argue that in addition to air quality concerns the Chancellor risks encouraging investment in high carbon infrastructure assets that risk either becoming stranded by the constraints of future carbon budgets or making those budgets harder to meet[25]. Furthermore, it is claimed that the economic rationale for road-building at a time when car use appears to have peaked is unclear[26].
Vehicle sizes have been growing across all passenger car classes due to **safety** imperatives and consumer demand for larger vehicles. Demands by regulators and consumers have led to crash protection features, such as airbags and greater space between bumpers, passengers and engines[27][28]. Features like air conditioning also now often come as standard, all of which adds to the weight, size and emissions of the vehicle. Some drivers also opt for larger, heavier cars because of their lower fatality rates in collisions[29]. A 2014 report suggested that vehicle damage costs car drivers up to £760m a year, and that this is due to steadily increasing car sizes, which are not being matched by the dimensions of parking spaces[30].

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[19] http://www.unece.org/env/lrtap/multi_h1.html
[20] http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2008:152:0001:0044:EN:PDF
[21] https://www.gov.uk/government/policies/protecting-and-enhancing-our-urban-and-natural-environment-to-improve-public-health-and-wellbeing/supporting-pages/international-european-and-national-standards-for-air-quality
[22] http://www.telegraph.co.uk/motoring/news/11007326/Diesel-car-drivers-betrayed-as-EU-cracks-down-on-Britain-over-air-pollution.html
[23] http://www.cebr.com/reports/the-future-economic-and-environmental-costs-of-gridlock/
[24] http://www.cbi.org.uk/media/1775599/cbi_roads_funding_report.pdf
[25] http://www.airqualitynews.com/2014/12/05/air-quality-groups-slam-15-billion-roads-revolution/
[26] http://www.foe.co.uk/sites/default/files/downloads/budget_march_20130.pdf
[27] http://blog.greenflag.com/tag/accident-exchange/
[28] http://www.iihs.org/iihs/topics/t/vehicle-size-and-weight/qanda
[29] https://www.esurance.com/safety/car-size-and-safety
[30] http://blog.greenflag.com/2014/parking-spaces-fail-to-match-big-cars/

3.2. Rail

Energy use by railways is split between diesel and electricity, roughly 50/50.Figure 6, below, includes the energy content of primary and secondary fuels. The sudden drop in electricity consumption reflects a change in the method: prior to 2004 the figures include electricity use at railways stations, whereas afterwards they do not. In 2012, UK rail transport and was responsible for overall emissions of 4.5 $MtCO_2e$ of greenhouse gases (including energy consumed for electricity generation). Passenger train emissions for 2013/4 stood at 44.8gCO_2/pkm[31], a 4.9% decrease on the previous year. Freight emissions were 25.9g/tkm[32], down 8.1% on 2012-13[33].

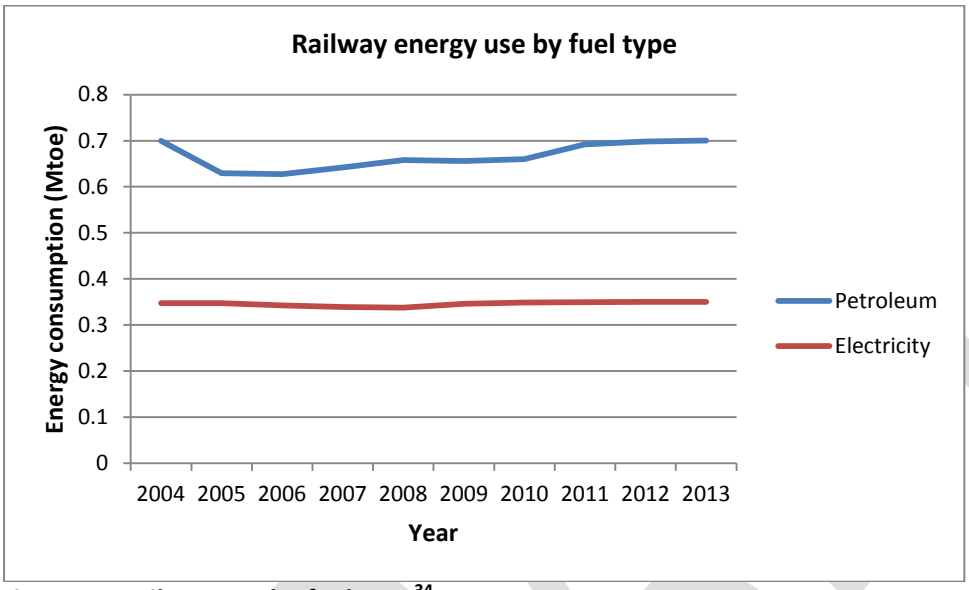

Figure 6: Railway use by fuel type[34]

Passenger growth in recent years of 5-6% on British railways has led to acknowledgement of the looming need to improve **rail capacity** in order to mitigate the associated risks[35][36], which include increased congestion, timetabling difficulties, loss of reliability, slowing of services, reduced stopping at smaller stations, difficulty justifying the construction of new stations due to their adverse impact of overall route capacity, turning away freight, as well as impairing the ability of rail to contribute to emissions reductions[37].

There are a number of ongoing projects aimed at strengthening rail capacity, such as the Northern Hub, the Thameslink programme, the Intercity Express Programme and the Rail Investment Strategy, which will allow an additional 140,000 commuting journeys into cities. Even with these improvements, greater capacity will be needed by the mid-2020s, by which point conventional methods for boosting capacity on existing rail links to the north and west of the country will be exhausted[38] – hence the proposal for new lines such as HS2[39][40]. Whilst carbon mitigation have never

[31] Passenger kilometre
[32] Tonne kilometre
[33] http://orr.gov.uk/__data/assets/pdf_file/0015/15063/rail-infrastructure-assets-environment-2013-14.pdf
[34] Source: ENV0102 (TSGB0302) Energy consumption by transport mode and source of energy: United Kingdom, 2000-2013
[35] http://www.publications.parliament.uk/pa/cm201011/cmselect/cmpubacc/471/471.pdf
[36] http://www.nao.org.uk/wp-content/uploads/2010/06/101133es.pdf
[37] http://www.appghsr.co.uk/upload/APPG%20for%20High-Speed%20Rail%20Inquiry%20Report.pdf
[38] https://www.gov.uk/government/policies/expanding-and-improving-the-rail-network
[39] http://www.networkrail.co.uk/5886_NewLineStudy_synopsis.pdf

been used as a primary argument in favour of HS2, the environmental credentials of high speed rail have been brought into question and a view has emerged that any carbon savings from HS2 are likely to be relatively small[41]. Proponents of the new line instead focus on its role facilitating economic growth in the cities it connects.

3.3. Shipping

Maritime transport accounts for over 80% of world trade by volume and for approximately 3% of global greenhouse gas emissions, while it is also a contributor to localised air pollution close to coastal areas and ports. The global merchant fleet currently consumes approximately 330 million tonnes of fuel annually. 80-85% of this is residual fuel oil with a high sulphur content, whilst the remainder are distillate fuels complying with stricter regulations.

As with other sectors, the main drivers of interest in alternative fuels for shipping are the need to reduce greenhouse gas emissions – as well as further concerns around the release of sulphur oxides and nitrogen oxides – and the availability and cost of conventional fuels. A number of international regulations exist in order to promote energy efficiency[42], but the prospect of pricing carbon through more complex and all-encompassing mechanisms such as emissions trading remains distant. Furthermore, a 2011 study suggested that whilst these measures have offset the growth in emissions they have not reduced them in absolute terms[43].

Figure 7 shows that greenhouse gas emissions from international shipping are between two and four times the size of domestic emissions.

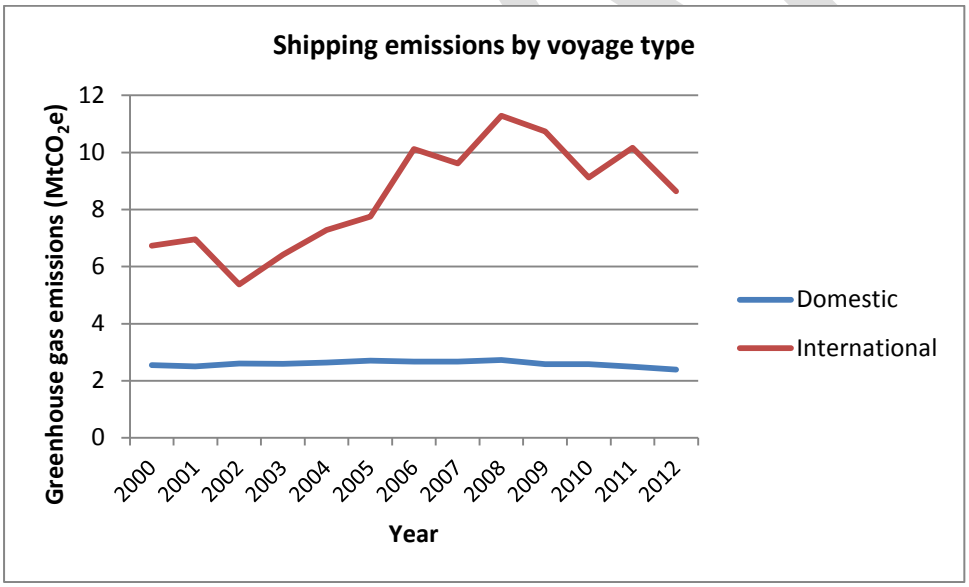

Figure 7: Shipping emissions by voyage type

[40] https://www.gov.uk/government/policies/expanding-and-improving-the-rail-network
[41] http://www.publications.parliament.uk/pa/cm201314/cmselect/cmenvaud/1076/107608.htm
[42] Put simply, the Energy Efficiency Design Index stipulates a minimum design energy efficiency relative to the size of newly built vessels, and the Ship Energy Efficiency Management Plan assists operators with the improvement of operational energy efficiency.
[43] Bazari and Longva, 2011, Assessment of IMO mandated energy efficiency measures for international shipping

3.4. Aviation

Whilst it currently represents only a small percentage of overall global emissions, aviation is one of the fastest growing sources of carbon dioxide, and levels by 2020 are projected to be around 70% higher than in 2005, even with annual fuel efficiency improvements of 2%. The International Civil Aviation Organization forecasts that emissions may grow a further 300-700% by 2050[44].
Like shipping, the mostly international nature of air transport makes attributing emissions to individual countries complex. In contrast with ships, however, there is a narrower range of fuels available for aviation, which must generally meet more exacting requirements for use on aircraft – needing in particular to have a high energy density in relation to both mass and volume, and be resistant to extremely cold temperature – as low as 40°C.

Figure 8 shows how international aviation greenhouse gas emissions are over ten times as large as domestic emissions.

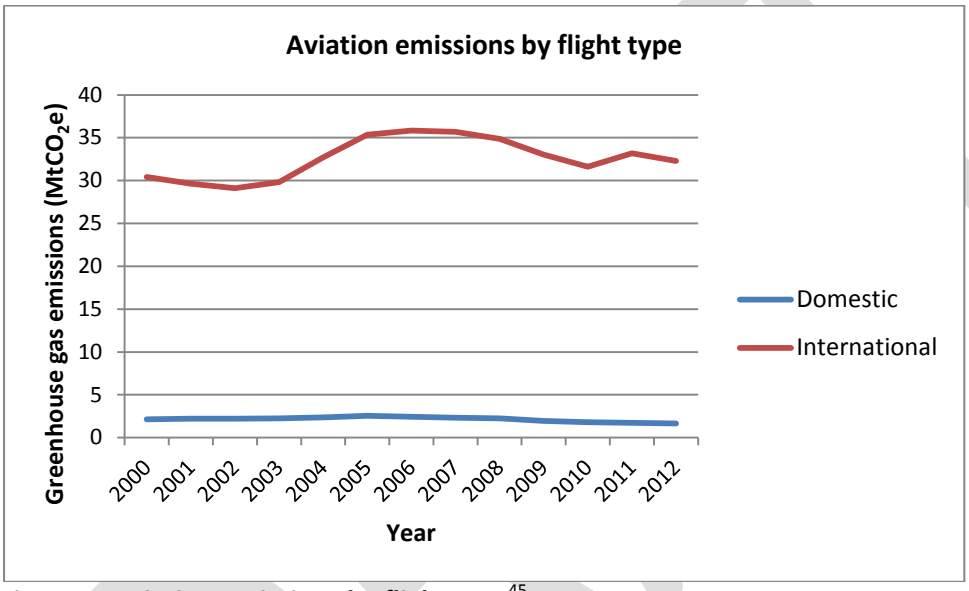

Figure 8: Aviation emissions by flight type[45]

[44] http://ec.europa.eu/clima/policies/transport/aviation/index_en.htm
[45] Source: Table ENV0201 (TSGB0306) Greenhouse gas emissions by transport mode: United Kingdom, 2000-2012

3.5. Mode switching

A number of hypothetical cases are presented here to illustrate the relative magnitude of various approaches to mode switching. Transferring passengers and freight from one mode to another is complex – we do not take into account the demand creation or destruction that may result from mode switching, for example – and this is not intended as a projection or forecast.

Case 1: Full rail electrification. The cost of electrifying train lines can vary significantly depending on the characteristics of the route, and can be influenced by its overall length, the number of tracks, depots and sidings, the number of junctions, bridges and tunnels, the grid supply requirements, and signalling. However, a 2007 study by Atkins quoted electrification costs per single kilometre as being between £500,000 and £650,000, and whilst Network Rail has since stated that it believes there is some opportunity for reducing this on specific routes, correspondence with Atkins indicates that the real cost is in fact likely to be substantially higher.

The Office of Rail Regulation states that the total length of the rail network open to passenger and freight traffic in 2013-4 was 15,753km and that 5,268km of the total has already been electrified. 10,485km therefore remains non-electrified. Whilst full electrification may be neither practical nor desirable, these figures point to a lower cost scenario of £5.25bn and an upper cost scenario of £6.8bn. Removing the need for any diesel locomotion would save approximately 2.1MtCO_2e which, at a central cost scenario of £6.025bn, represents emissions reductions at a cost of £2869/tCO_2e.

Case 2: Taking traffic off roads to double passenger rail kilometres. 59.7bn passenger kilometres took place on the rail network in 2013/14, and 386bn passenger kilometres were travelled on British roads. Using the same ratio for reduced emissions as for reduced passenger kilometres (15.5%), shifting these journeys away from road transport might reduce emissions from passenger cars by roughly 10MtCO_2e – the same as rail, domestic aviation, domestic shipping combined, military aircraft and shipping and aircraft support vehicles combined. Any change in emissions from rail would be dependent on, among others things, the energy source used, the extent of electricity decarbonisation, occupancy rates, the timing and location of the additional demand and whether new lines are constructed. A doubling of current rail emissions would result in a further 2.1MtCO_2e.

Case 2: All scheduled domestic passenger air journeys and air freight shifted to rail. 109m domestic passenger kilometres were flown in 2013 (compared to 59.7bn rail passenger kilometres) and 66.5 thousand tonnes of cargo was uplifted (compared to 116.6 million tonnes moved by rail). Shifting the entirety of both air passenger kilometres and freight cargo to the rail network might therefore avoid roughly 1.7MtCO_2e of emissions from aviation (equivalent to 80% of the rail total), whilst generating a demand increase of around 0.18% in terms of passenger kilometres and 0.06% for rail freight.

Case 3: Journeys by bicycle double, shifting away from cars. 5bn vehicle kilometres were made on bicycles in 2013; 386bn passenger kilometres were made by car. Shifting journeys from cars to bicycles to the point where overall bicycle kilometres are doubled could take 376,943 cars off the road (1.3%), if we reduce the overall number of cars in proportion to the reduction in vehicle kilometres, and reduce carbon dioxide emissions by 0.84 tonnes – less than one percent of road emissions.

Case 4: Using 100% second generation biofuels in aviation. In 2013 the UK consumed 12.3Mtoe of jet fuel (this includes international and military aviation), which indicates that using jatropha as a feedstock to grow biofuels for aviation would take up an area slight over 166,000km^2 – more than England and Wales combined. Using algae would require 918km^2 – about three times the size of inner London. The UK would be very unlikely, however, to seek to satisfy its entire biofuel demand

through domestic production. The release of approximately 1.7 $MtCO_2e$ from the combustion of jet fuel would be avoided if domestic aircraft ceased to consume fossil fuels altogether, which amounts to slightly over 1% of domestic transport emissions.

Case 5: 100% use of LNG across domestic shipping. The UK marine sector emitted 2.5$MtCO_2e$ in 2011 (excluding international shipping). The complete adoption of LNG across the industry, coupled with the widespread application of best practice, could lead to carbon reductions of around 25%, avoiding 0.63$MtCO_2e$ and reducing total domestic transport emissions by 1.6%.
These scenarios suggest that mode switching alone, even overlooking such limitations to mode switching as rail capacity, will not be sufficient to reduce emissions from the transport sector by the extent required. Road transport can be seen as the main problem and fuel switching will be essential for progress to be made towards 80% decarbonisation.

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4. Energy sources

This section considers the potential for each energy source. It presents examples to illustrate their potential contribution for different modes, as well as constraints that can arise from competition between modes and interactions with the energy sector. This will lead to an assessment of the 'best use' of different energy sources in Phase 2 of the project.

4.1. Conventional fossil fuels

In 2013 petroleum products accounted for over 97% of total energy used for UK **road transport**[46]. This was divided principally between petrol (12.6m tonnes) and diesel (21.9m tonnes), although just under 0.1m tonnes of liquefied petroleum gas (LPG – also known as autogas) was also used. Figure 9 shows the differing applications of petrol and diesel: petrol is overwhelmingly used in lighter vehicles such as cars, taxis, mopeds, motorcycles and light vans, whereas diesel consumption is more broadly split between cars and taxis, light vans and HGVs, with a smaller amount going to buses and coaches. Road freight uses diesel almost exclusively, where fuel economy is a primary concern, along with durability and availability, and where the engines' ability to produce high torque at low revs makes them more suitable for pulling heavy loads.

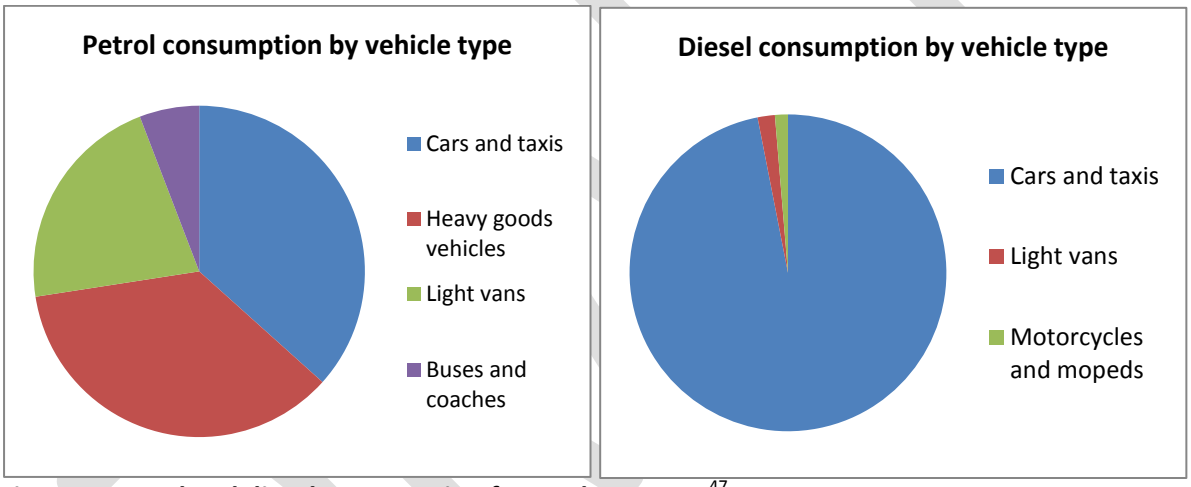

Figure 9: Petrol and diesel consumption for road transport[47]

Since 2000 the amount of diesel consumed by cars and taxis has more than doubled and use by light vans has gone up by over 40%. This rise has been matched by a roughly equivalent decline in petrol consumption, as Figure 10 shows. In addition to more favourable regulation, better fuel economy and better value retention, the US Energy Information Administration has said that preferential taxes for diesel-powered vehicles have contributed to what is a global trend of increasing demand for diesel[48].

[46] ENV0102 (TSGB0302)
[47] Department for Transport: ENV0101 (TSGB0301) Petroleum consumption by transport mode and fuel type: United Kingdom, 2000-2013)
[48] http://ww.parliament.uk/briefing-papers/sn04712.pdf

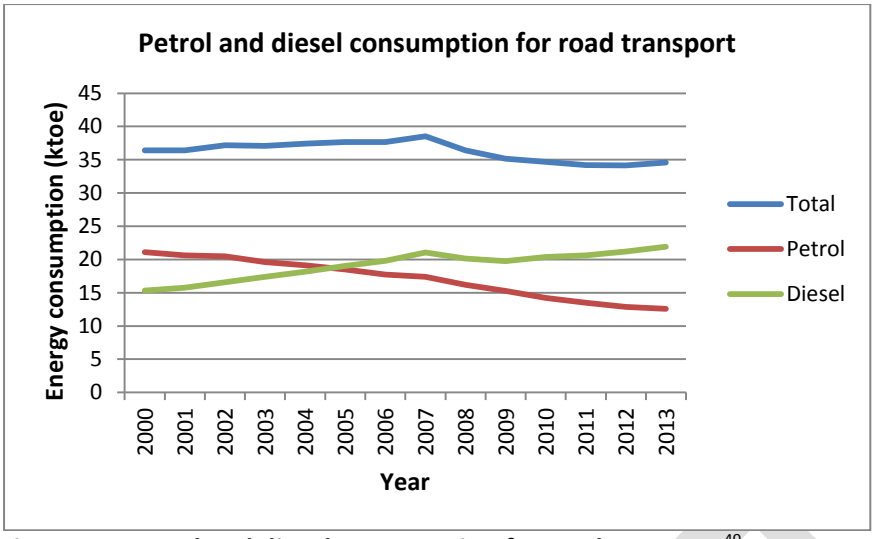

Figure 10: Petrol and diesel consumption for road transport[49]

Diesel-hauled **rail locomotives** consumed 0.7Mtoe in 2013 and currently have a greater reach across the UK rail network owing to impartial electrification, which means a large proportion of both passenger train miles (51%) and freight train miles (95%) is still reliant on diesel engines, in many cases 'running under the wires' of electrified lines. The ability of diesel engines to go from any destination to any other destination gives it an advantage over overhead electrification, although it also results in lower efficiency across the network and higher overall costs and carbon emissions. The status of diesel-powered rail is particularly important to the freight sector, carrying around 95% of all traffic – whether measured in train miles or tonne miles. Whilst the overall volumes and distances over which freight is carried on the UK rail network has grown steadily since the mid-1990s, the nature of the cargo has changed markedly over the last thirty or forty years, in tandem with the rebalancing of the national economy away from heavy manufacturing. Traditional bulk markets, such as domestic coal and steel, have shrunk considerably, whilst products imported on container ships has grown a great deal, and the upshot is that deep sea intermodal freight has become the largest single commodity found on the rail network[50]. Network Rail's *Freight Market Study 2013* supports the DUKES 2012 forecast of a 90% drop in the amount of coal being moved by rail by 2030 (relative to 2011), but raises the possibility of biomass freight for power generation expanding significantly. Although there is a high degree of uncertainty investment is already taking place in this area; a central figure of 14 million tonnes by 2023 has been proposed. Freight market sectors other than intermodal, coal and biomass are likely to see much less change.

New environmental legislation came into force in 2012 setting tougher emission targets for diesel locomotives. A future with rising fossil fuel prices may provide Network Rail with a stronger business case for further electrification of the network, and as a consequence emissions per train kilometre may decrease further in the coming years.

Number 6 fuel oil and diesel are the most widespread **shipping fuels** today. Otherwise known as bunker fuel, number 6 fuel oil is a heavy residual oil that remains after the lighter cuts of crude have boiled off. The various impurities it contains, such as sulphur, and the handling difficulties resulting from its high viscosity, contribute to its low price. It has been projected that bunker fuel will

[49] Source: Table ENV0101 (TSGB0301) Petroleum consumption by transport mode and fuel type: United Kingdom, 2000-2013
[50] Network Rail, Freight Market Study, 2013

represent a declining proportion of the overall fuel mix, but that between now and 2030 absolute demand will remain roughly stable once overall demand growth is taken into account[51].
Due to air quality regulations many ships switch to diesel oil on arrival at ports, which reduces the emission of CO_2, SO_x, NO_x and particulate matter considerably, although bunker fuel is preferred for deep sea shipping due to its markedly lower price.

In 2013 the UK consumed 3.3Mtoe of shipping fuels. This includes international and military shipping and marine bunkers, and is less than a tenth of the fuel consumed by road transport over the same year.

Piston engines in **aviation** use aviation gasoline. Most modern jets, however, are powered by turbines, the earliest of which were turbojet engines, which perform well at high altitudes and high speeds but are less efficient than the earlier piston engines at low altitudes and low speeds. They were followed by turbofan engines, which combined the best features of both and produce lower noise levels. Turbofan engines use the exhaust gases to drive a low-pressure turbine connected to a gearbox, in turn connected to propellers or rotor in the case of helicopters[52]. Fuels for use in aircraft needs to be tailored to engine type, and must possess certain characteristics in order that they perform well in challenging conditions: they must ignite at low temperatures, burn with controlled radiation, not produce smoke, not attack hot turbine components and possess good flow properties, thermal stability and storage stability. Energy density and combustion quality are key fuel performance properties[53][54].

Of aviation turbine fuels (jet fuels) kerosene-grade Jet A-1 is most widespread, whilst Jet A is found primarily in the USA. Jet B, a distillate covering the naphtha and kerosene fractions, is used in colder climate owing to its ability to withstand lower temperatures. UK consumption of aviation turbine fuel has remained relatively constant since 2000, in 2013 standing at 11.1 million tonnes[55] (see Figure 2).

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[51] https://www.bartlett.ucl.ac.uk/energy/news/documents/Global_Marine_Fuel_Trends_2030_single_page_v2_tcm155-249392.pdf
[52] https://www.cgabusinessdesk.com/document/aviation_tech_review.pdf
[53] http://www.alglas.com/jet_fuel.htm
[54] http://www.sustainableaviation.co.uk/wp-content/uploads/alternative-aviation-fuel-briefing-paper.pdf
[55] Env0101 – this figure includes international and military aviation

4.2. Alternative fossil fuels

LPG has an energy content in between that of natural gas and diesel and is principally composed of propane and butane, or a mix of these and other gases, liquefied under relatively low pressure at 15°C. These properties have made it a popular cooking gas in many developing countries[56]. As a fuel for **road transport** it has operating emissions 11% lower than those of an identical petrol vehicle – 15% on a well-to-wheel basis – but does not reach reductions as great as those offered by natural gas vehicles, and steady improvements in the efficiency of conventional engines have eroded some of the LPG advantage[57][58][59]. Figure 11 illustrates where LPG's emissions place it in relation to other fuels for various applications.

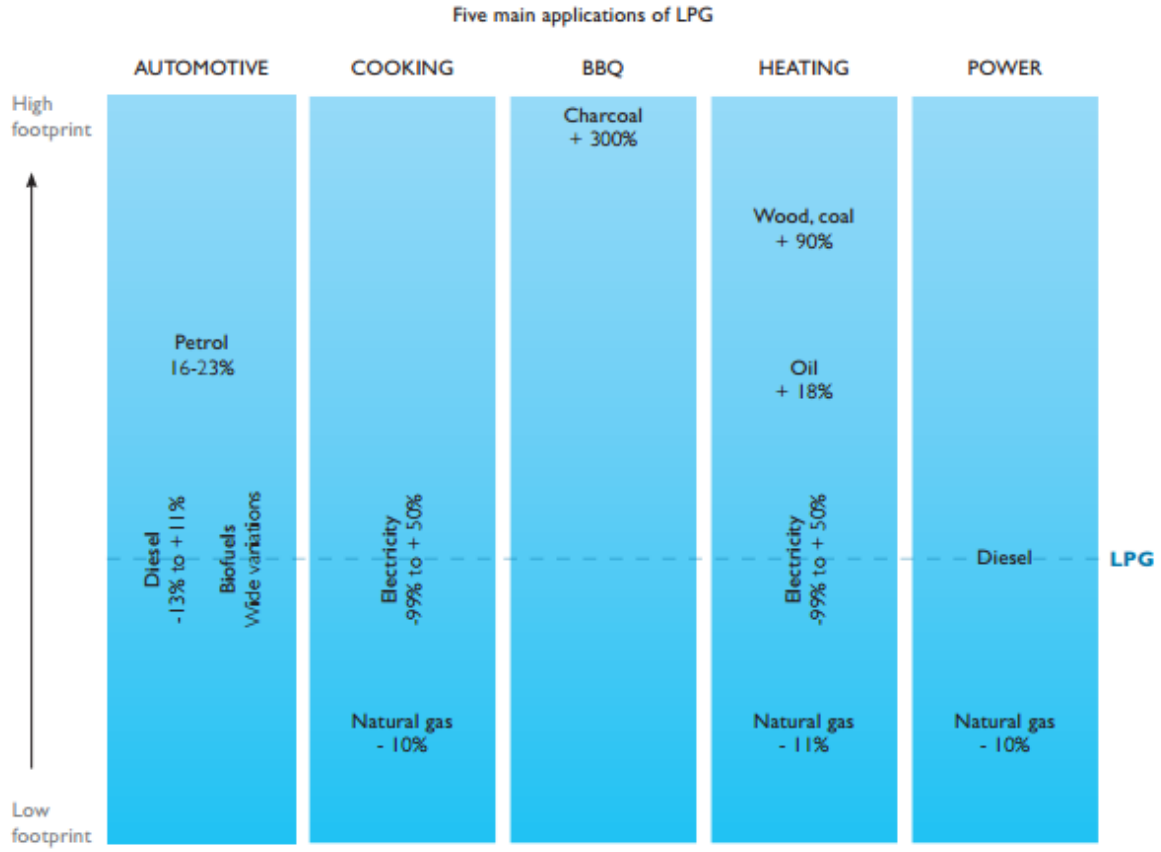

Figure 11: Uses of LPG and its emissions relative to other fuels[60]

LPG does not have the high global warming potential of natural gas should it escape into the atmosphere before combustion[61] (although since the gas is heavier than air, any leaks may present a safety hazard). Although around 90% of petrol cars registered in the UK could be converted to run on LPG as well as petrol, less than 1% of vehicles use the fuel owing to the initial cost of conversion (£1200 to £2000), doubts around the lifespan of tax benefits, and concerns around refuelling[62] although they appear to be reasonably widespread in comparison with public electric charge points.

[56] http://www.brighthubengineering.com/power-plants/40017-lng-cng-and-lpg-what-is-the-difference/
[57] http://www.nextgreencar.com/lpg-cng.php
[58] http://www.propane101.com/propanevsnaturalgas.htm
[59] http://www.dft.gov.uk/vca/fcb/cars-and-fuel-options.asp
[60] Source: http://www.aegpl.eu/media/21020/atlantic%20consulting%20scientific%20review%20carbon%20footprint,%20ed.%202009.pdf
[61] http://www.drivelpg.co.uk/about-autogas/environmental-benefits/
[62] http://www.moneysupermarket.com/c/news/drivers-could-lpg-save-you-a-fortune/0015327/

Furthermore, diesel engines cannot be converted at all and conversions raise the question of where to locate the LPG tank – often the spare wheel is forfeited to accommodate it.

Natural gas vehicles use either liquefied natural gas (LNG) or compressed natural gas (CNG), both of which mix readily with air, burning cleanly and at lower emissions levels. There are estimated to be almost 18 million worldwide as of late 2013, with over 2 million in each of Iran, Pakistan and Argentina[63]. The majority of the 559[64] in the UK are medium duty and heavy duty. Many natural gas vehicles are also able to run on conventional fuels, and may have been converted from single fuel vehicles by the addition of a second fuel tank to allow them to do so. Conversion requires a number of modifications to the engines, although if these are poorly carried out, they may lead to higher emissions, higher fuel consumption and high ongoing maintenance costs[65]. Heavy duty diesel engines can run on diesel or a blend with natural gas – but not 100% gas – and the investment required typically makes this a preferable option only for larger vehicle fleets. However, price differences between diesel and natural gas have resulted in a high degree of interest in switching across transport modes, with potential savings having been estimated at £15,000 a year for HGVs[66,67].

In order to liquefy natural gas it requires cooling to -162°C, at which temperature it is reduced to 1/600th of volume as room temperature (which also eliminates the risk of costly and destructive oil spills in transit). Although this makes it easier to carry large volumes of the fuel – on LNG tankers, for example – the process carries a high energy cost: in the order of 8-10% of the feed gas[68]. It is also highly capital intensive – costing $2-4bn to construct a liquefaction facility – and so requires long-term supply contracts to justify the investment, which may also limit options available in the future[69].

LNG in **shipping** has attracted increasing attention in recent years. It offers major environmental benefits over both bunker fuel and diesel. It is regarded as emitting greenhouse gases in the region of 20-25% lower than conventional fuels[70]. LNG also emits much lower levels of SO_X (by 90-95%) and NO_x, presenting a compelling case for its use onboard vessels operating in those zones specified as emission control areas by the International Maritime Organization (IMO). From the start of 2015 new regulations came into force decreeing that ships operating in these areas use fuels with no more the 0.1% sulphur content – down 90% on the previous 1% limit – and from 2020 a 0.5% limit will apply globally[71].

As with biofuels for road transport, consideration must be given to the upstream carbon costs of extracting, processing and distributing LNG, as well as loss during usage: the carbon advantage of LNG has been shown to be strongly contingent on the avoidance of methane 'slip' – i.e. gas that escapes unburnt into the atmosphere, where it has 25 times the global warming potential of carbon

63 http://www.ngvaeurope.eu/downloads/statistics/20130923/Worldwide/Worldwide_NGVs__Refuelling_Stations_Jun_2013.xlsx

64 As of late 2011

65 http://www.afsglobal.com/faq/diesel-to-natural-gas-conversion.html

66 http://www.technologyreview.com/news/519641/cleaner-long-haul-engines-guzzle-diesel-or-natural-gas/

67 http://www.cleanairpower.com/

68 http://www.total.com/en/energies-expertise/oil-gas/exploration-production/strategic-sectors/lng/expertise/liquefaction

69 http://www.brighthubengineering.com/power-plants/40017-lng-cng-and-lpg-what-is-the-difference/

70 http://www.gl-group.com/pdf/GL_MAN_LNG_study_web.pdf From 2015 SO_X emissions in these zones must be no more than 0.1%.

71 http://www.imo.org/OurWork/Environment/PollutionPrevention/AirPollution/Pages/Sulphur-oxides-(SOx)-%E2%80%93-Regulation-14.aspx

dioxide (although a shorter lifespan). Taking this into account could be counterproductive, adding a further 5% to emissions depending on the rate of methane slip (currently around 3%), which across the LNG fuel cycle has been estimated at between 2.7% and 5.4%[72], although the application of best practice could lead to emissions savings of 12-27%.

A 2014 report developed a number of pathways to 2030, finding across the board that fuel oil is very likely to remain the primary energy source for deep sea shipping. One scenario shows LNG reached an 11% share of the fuel mix – and much higher in certain subsectors. However, the familiar catch-22 that often plagues other parts of the low carbon transitions can be seen here too: the lack of fuel bunkering infrastructure and the concomitant supply chain prevents ship owners from moving towards LNG and the consequent lack of demand inhibits infrastructure investment[73]. In addition to this difficulty, the principal challenges facing LNG aboard ocean-going vessels are the price difference between LNG and other fuels that meet sulphur regulations, and the extent of the overall global emissions regulation programme[74]. Brittany Ferries recently cancelled a €270m order for a newly-built LNG passenger ferry after failing to secure exemptions from the new sulphur emissions regulations[75].

The low global price of natural gas strengthens the case for **rail transport** to move from diesel to liquefied natural gas, with initial estimates suggesting that the application of LNG for rail operations could reduce carbon emissions by 30% and NO_X emissions by up to 70%[76] - although some diesel blending would be required for ignition. Czech national rail operator ČD is currently testing compressed natural gas in converted diesel engines with the hope of halving fuel costs[77], and a prototype natural gas-fired turbine-electric locomotive has been developed in Russia[78]. However, the adoption of these fuels threatens to lock the rail sector into carbon-based fuel consumption for the lifetime of the engines – 20 to 30 years – and presents a range of 'operational, financial, regulatory and mechanical challenges' (on the US rail network, for example, no tank cars are currently permitted to carry LNG). The US Energy Information Administration (EIA) estimates that at $3m the cost of a new LNG locomotive and tender is half as much again as an equivalent diesel vehicle, a price tag that does not include the provision of infrastructure for delivering fuel at -161°C[79]. The EIA considers three scenarios in which LNG use rises and diesel consumption falls (Figure 12[80]), and notes that 'because the transportation sector is a relatively small consumer of natural gas compared to other sectors, the seemingly dramatic fuel switch from the perspective of freight rail is only a minor change in overall U.S. natural gas consumption.' Even under the highest scenario, overall demand for natural gas would increase by less than 1% and have a minimal impact on prices.

[72] http://www.theicct.org/sites/default/files/publications/ICCTwhitepaper_MarineLNG_130513.pdf
[73] http://www.lr.org/en/_images/213-35922_LR_bunkering_study_Final_for_web_tcm155-243482.pdf
[74] http://www.porttechnology.org/images/uploads/technical_papers/LNG_LR.pdf
[75] http://theloadstar.co.uk/brittany-ferries-sulphur-emission-control-area/
[76] http://www.railway-technology.com/features/featurehydrail-lng-future-railway-propulsion-fuel/
[77] http://www.railwaygazette.com/news/traction-rolling-stock/single-view/view/gas-fuelled-locomotive-enters-passenger-service.html
[78] http://www.railwaygazette.com/news/traction-rolling-stock/single-view/view/gas-fuelled-turbine-electric-locomotive-prototype.html
[79] US IEA, Annual Energy Outlook 2014, p.IF-16
[80] http://www.eia.gov/todayinenergy/detail.cfm?id=15831

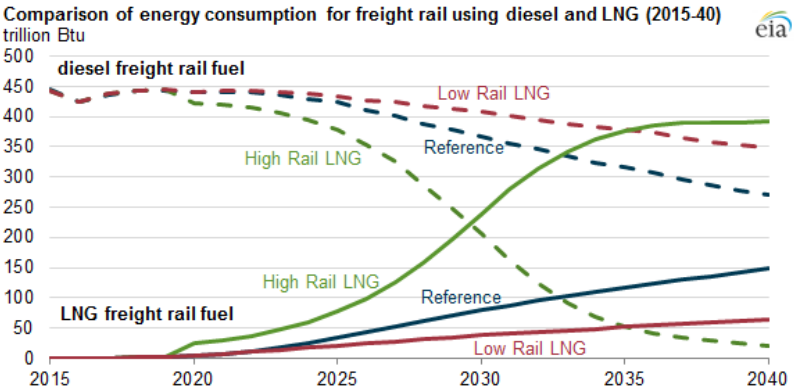

Figure 12: Energy consumption for freight using diesel and LNG[81]

CNG is stored in a gaseous state under high pressure, reducing the gas to 1% of its initial volume and avoiding the costs of liquefaction. The overall reduction in volume is not as large as with LNG, however, and so a much larger tank is needed to store the same mass, and CNG therefore has a lower energy density – 25% lower in relation to conventional gasoline. Figure 13 compares the energy densities of various fuels. CNG-powered vehicles also require a big, bulky fuel tank, making the fuel suitable principally for lorries, buses and other large vehicles[82]. The authorities in New Delhi have introduced a raft of measured over the last 20 years or so designed to improve the city's air quality, of which perhaps the most well-known has been the mandated conversion of all commercial vehicles to CNG. Subsequent studies suggest improvements across a range of air quality indicators, but raise the possibility that the progress seen in bus emissions has not been matched by other vehicle types – notably three-wheelers – due to poorly carried out CNG conversions, and that the sheer increase in kilometres travelled in the city may overwhelm any air quality improvements[83].

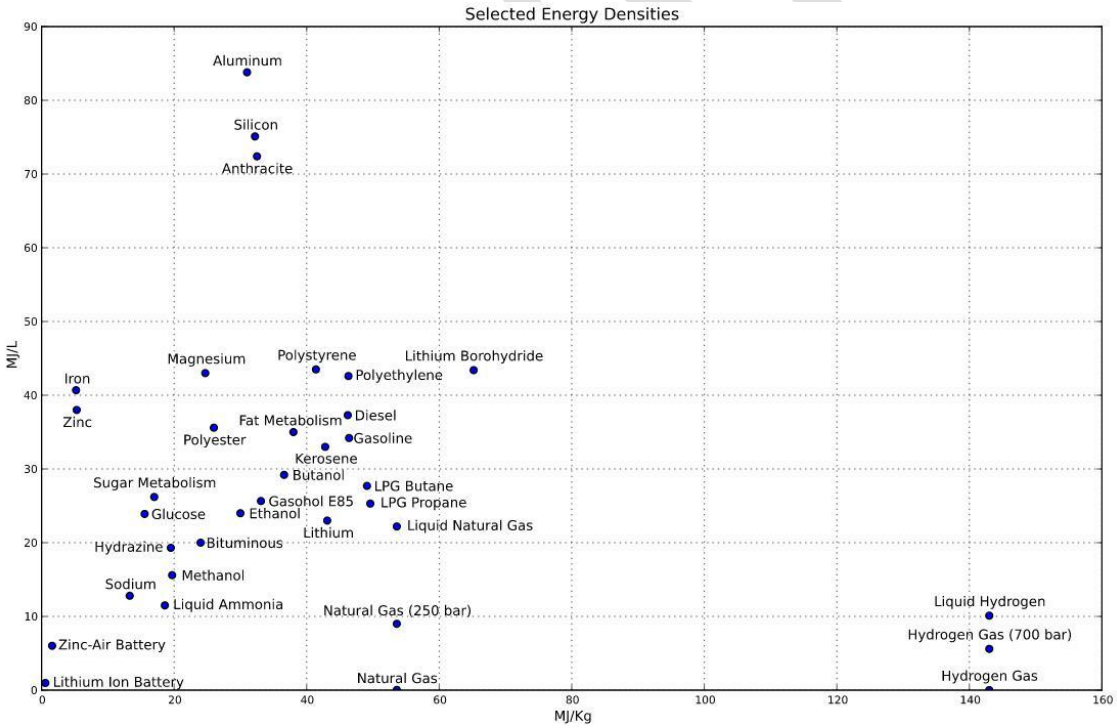

Figure 13: Energy densities of fuels, per unit mass (horizontal) and per unit volume (vertical).[84]

[81] Source: U.S. Energy Information Administration, Annual Energy Outlook 2014, Issues in Focus
[82] http://www.ucsusa.org/clean_energy/our-energy-choices/coal-and-other-fossil-fuels/uses-of-natural-gas.html#.VQhc29KsUVA
[83] http://www.rff.org/documents/rff-dp-07-06.pdf
[84] Source: http://en.wikipedia.org/wiki/Energy_density

4.3. Bio-energy

OECD provisional figures for 2013 indicate global production of 104,852.43 million litres of ethanol and 26,208.55 million litres of biodiesel[85], with the US and Brazil leading production. UK biofuels production currently stands at over 1500m litres[86], or around 1.4% of the global total. , whist consumption for 2012 was slightly less than production at 1340m litres, split broadly 50:50 between biodiesel and bioethanol. However, trade flows are far more complex that these figures suggest, with feedstock underlying overall EU consumption of biodiesel and bioethanol being imported from countries ranging from Argentina and Indonesia to Ukraine and Egypt.

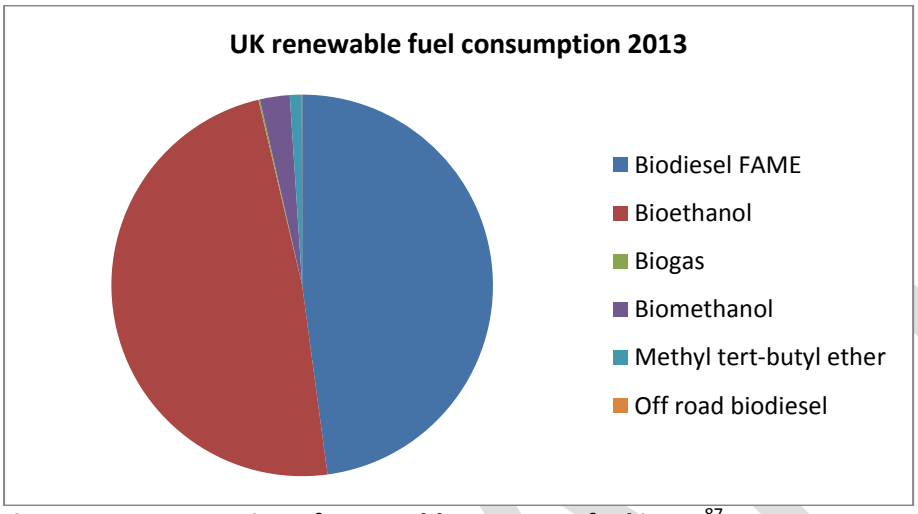

Figure 14: Consumption of renewable transport fuel in UK[87]

The dominant first generation biofuels ('conventional' biofuels) used in **road transport** are ethanol and biodiesel. First generation ethanol is produced via the fermentation of sugars and starches found mostly in agricultural crops such as sugar cane, wheat, corn among many others. Biodiesel is manufactured through the chemical reaction of vegetable oils or animal fats with certain alcohols (largely methanol or ethanol). Feedstocks for biodiesel can include soy, rapeseed, palm oil and various vegetable oils.

Due to the liquid form and high energy density of biofuels, they present an attractive low-carbon alternative to conventional liquid fossil fuels used in cars and have been promoted by transport policies throughout the world. Brazil, in particular, where it has been mandatory to blend gasoline with biofuels since the oil shocks of the 1970s, has a highly developed ethanol industry. Mandated ethanol blends of E20 (20% ethanol) have been maintained since the early 1990s and unblended gasoline is no longer available at pumps. A range of 'flexible fuel' vehicles, capable of running off higher ratio blends of ethanol than conventional international combustion engines can tolerate (i.e. over E10), has also developed alongside the fuels.

The European transport sector consumed 14.4Mtoe in 2011, 20 times more than in 2000[88], a rapid rise which has brought feedstocks intended for biofuel use into competition with food crops, contributing to the 2007-2008 commodity price spike[89], the extent and nature of this contribution is

[85] http://stats.oecd.org/viewhtml.aspx?QueryId=58648&vh=0000&vf=0&l&il=&lang=en
[86] https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/266090/ecofys-uk-biofuel-industry-overview-v1.5.pdf
[87] Source: Department for Transport, Table RTFO 01 Volumes of fuels by fuel type
[88] http://www.ieep.eu/assets/1359/IEEP_re-examining_EU_biofuels_policy_-_A_2030_perspective.pdf
[89] http://www.oecd.org/trade/agricultural-trade/40990370.pdf

not certain. For example, it has been widely suggested that Brazilian ethanol production was responsible for very little of the overall jump in food prices because the country's sugar cane production and exports nearly trebled between 2000 and 2008 and its share of global exports rose from 20% to 40%[90].

Growth of crops intended for biofuel production can also lead to the displacement of the original food crops, demand for which remains unchanged, onto non-cropland such as grasslands and forests, a process known as indirect land use change (ILUC). The destruction of carbon-rich habitats like these and their conversion to agricultural land risks offsetting or even negating any of the greenhouse gas reduction benefits that may arise from the substitution of biofuels for oil. This has been raised as an issue for Malaysian and Indonesian palm oil in particular, because of the crop's high productivity and much lower price in relation to other feedstocks[91], and represents a major trade-off for policymakers seeking to satisfy competing environmental objectives. Biofuels have also faced criticism for the inefficient rates at which solar energy is converted into sugar, which is then used to produce biofuels: a recent study claimed that sugar cane may ultimately convert as little as 0.2% of solar energy into ethanol, whereas solar panels on the same area of land can generate 100 time the usable energy[92].

Comparisons of first generation biofuels indicate that sugar cane ethanol, such as that produced by Brazil, has significantly higher lifetime carbon savings (relative to fossil fuels) than either ethanol from corn, sugar beet or wheat, as well as rapeseed biodiesel[93]. The US Environmental Protection Agency carried out very detailed regulatory impact analysis of the Renewable Fuels Standard[94], which includes: feedstock agriculture, feedstock transport, feedstock processing and biofuel production, biofuel transport and distribution, and biofuel tailpipe emissions. Scope is an important consideration, and whilst the analysis factors in emissions associated with the use of farming machinery, it excludes the emissions from the manufacturer of such vehicles[95]. The mandate of the research was to include 'direct emissions and significant indirect emissions' (p.312).

Calculating well-to-wheel emissions for biofuels (or life cycle emissions – which also includes energy and emissions from the building of facilities and vehicles, and end-of-life impacts[96]) is complex and dependent on factors including the feedstock used, distribution channels, production processes and the source of the energy used to power them. For an extremely thorough explanation, breakdown and analysis of biofuel production from various feedstocks, see the European Commission's Joint Research Centre 2014 publication on the subject[97]. As an approximate indication, Figure 15 shows estimates by the US Environmental Protection Agency of the greenhouse gas emissions of various types of first generation biofuels as a percentage of the conventional fuel they replace.

[90] http://www-wds.worldbank.org/external/default/WDSContentServer/IW3P/IB/2008/07/28/000020439_20080728103002/Rendered/PDF/WP4682.pdf
[91] http://www.foe.co.uk/sites/default/files/downloads/iluc_palm_oil.pdf
[92] http://www.wri.org/publication/avoiding-bioenergy-competition-food-crops-and-land
[93] http://oxfamilibrary.openrepository.com/oxfam/bitstream/10546/114084/1/bp114-another-inconvenient-truth-250608-en.pdf
[94] http://www.epa.gov/otaq/renewablefuels/420r10006.pdf
[95] For comparison, the analysis includes in its calculations the following aspects of fossil fuel life cycle emissions: crude extraction, crude transport, refining, fuel transport and distribution, and tailpipe emissions.
[96] http://iet.jrc.ec.europa.eu/about-jec/jec-well-wheels-analyses-wtw
[97] http://iet.jrc.ec.europa.eu/about-jec/sites/iet.jrc.ec.europa.eu.about-jec/files/documents/report_2014/wtt_report_v4a.pdf

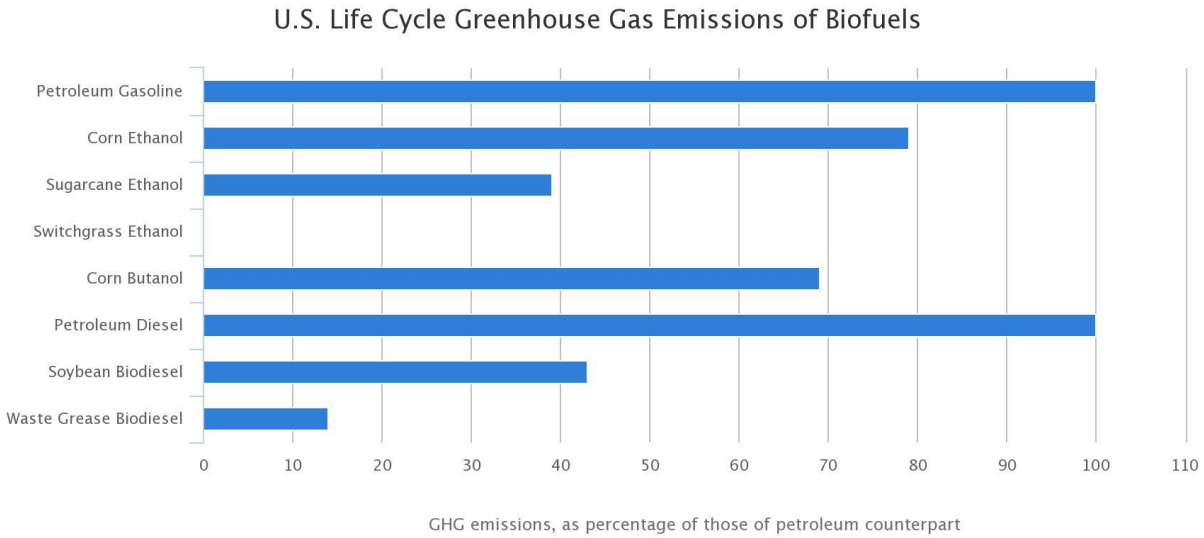

Figure 15: Life cycle emissions of biofuels[98]

After the food price spikes of 2008, a growing consensus emerged around the notion that in order to contribute meaningfully to climate change mitigation whilst minimising environmental externalities biofuels would need to be low carbon across their life cycle as well as socially and environmentally sustainable. In practice this would mean that biofuels other than sugar cane ethanol are likely to have limited applicability, and so interest has grown in second generation biofuels that do not compete with food crops or lead to harmful land use outcomes. Feedstocks for second generation biofuels include lignocellulosic biomass (such as agricultural and forestry residues) and non-food crops like grasses or miscanthus. Production of fuels from such sources is often a more complex and costly process than for conventional biofuels.

Whilst conventional biofuels are at a stage of technological and commercial maturity, second generation are much less developed, and data used to calculate life cycle emissions is generally taken from demonstration and pilot plants. Nevertheless, a study by the IEA estimated life cycle emissions savings of 60%-120%, although dedicating land to second generation biofuels would be likely to require drastic improvements in farming practices and infrastructure across large parts of the developing world[99]. If and when such barriers are overcome, though, there is significant potential for second generation biofuels: 'even if only 10% of the global agricultural and forestry residues were available in 2030, about half of the forecasted biofuel demand in the World Energy Outlook 2009 450 Scenario could be covered – equal to around 5% of the projected total transport fuel demand by that time'[100].

Third generation biofuels refer to those derived from algae, which are capable of much higher yields than other feedstocks (between 10 and 100 times)[101]: the US Department of Energy has estimated that replacing all the petroleum fuel with algal biofuels would require 38,850km^2 [102]. Algae produce oils that can be relatively easily refined into biodiesel, and can be genetically manipulated to produce a range of fuels including butanol, which is very similar emissions profile and energy density

[98] Source: http://www.afdc.energy.gov/data/10328
[99] http://www.iea.org/publications/freepublications/publication/biofuels_exec_summary.pdf
[100] https://www.iea.org/Textbase/npsum/2nd_gen_biofuelsSUM.pdf, p.15
[101] http://rsif.royalsocietypublishing.org/content/7/46/703
[102] http://www.washingtonpost.com/wp-dyn/content/article/2008/01/03/AR2008010303907.html

to gasoline[103]. Third generation biofuels are far from commercialisation, however, with no large-scale production currently taking place.

There is a range of biofuels available that could, with a greater or lesser amount of engine modification, be used in **shipping**. These include biodiesel, di-methyl ether, vegetable oil, gas-to-liquid and biomass-to-liquid, bio-methane and bio-ethanol. However, application of these fuels to shipping is in an early stage of development, and despite a small number of research and development projects (mostly taking place at private firms) the industry has been little practical experience in handling biofuels: no significant consumption currently occurs in Europe[104]. In general biofuels also have a lower energy density than conventional fuels. One study found that from a technical integration perspective, biodiesel blends of up to 20% with marine diesel oil seem the most promising option, although limiting factors such as availability, technological development, technical integration and operational consequences, as well as the concern around biofuel availability reported by one trial, limit further progress[105]. Furthermore, the carbon reduction advantage of biofuels over current fuels, considered on a 'field-to-hull' basis, is questionable[106] and with pressure to move away from unsustainable conventional biofuels, as a fuel group they may be more suitably applied elsewhere in the economy. Second generation lignocellulosic/algal biofuels are likely to be more attractive to the industry, although require further research and development.
Biofuels also present a drop-in alternative for **aviation**, although again the full social and environmental life cycle impacts of biofuel growth, production and distribution need to be taken into account. Non-food biomass sources available include camelina, halophytes, jatropha, switchgrass, used cooking oil, agricultural and forestry by-products, municipal waste and algae. Around ten airlines and a small number of aircraft manufacturers tested biofuel blends of up to 50% between 2008 and 2011, concluding that no engine modifications were needed, that biofuels can be blended with conventional fuels, and that in some cases engine efficiency can actually be improved through the use of biofuels[107].

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[103] http://biofuel.org.uk/third-generation-biofuels.html
[104] http://www.biofuelstp.eu/shipping-biofuels.html
[105] http://www.ecofys.com/files/files/ecofys_2012_potential_of_biofuels_in_shipping_02.pdf
[106] https://www.bartlett.ucl.ac.uk/energy/news/documents/Low_Carbon_Shipping_A_Systems_Approach_2014.pdf
[107] http://www.iata.org/pressroom/facts_figures/fact_sheets/pages/alt-fuels.aspx

4.4. Electricity

Demand for electric **road** vehicles (EVs) has grown considerably in recent years, with models from Nissan, Toyota, Mitsubishi, Vauxhall and BMW among the manufacturers with various electric offerings. Hybrid electric vehicles (HEVs) contain an electric motor and a battery that is charged by a conventional car engine and regenerative braking. Plug-in hybrid electric vehicles (PHEVs) can, in addition to this, be recharged from an external electricity source. Battery electric vehicles (BEVs) are powered fully by a rechargeable drivetrain with no onboard internal combustion engine. Incentives are currently available in the form of a grant of 35%, up to £5000, of the price of a car (as of April 2015) and 20% of a van (up to £8000), and the number of EV registrations has risen at an increasing rate since the beginning on 2010. Figure 16 shows how the uptake of the vehicles – in particular cars – has risen steeply. Taken together, however, these roughly electric and hybrid electric vehicles constituted only slightly over 0.5% of cars licensed in 2013 – still less when considered as a percentage of total vehicles on the road[108].

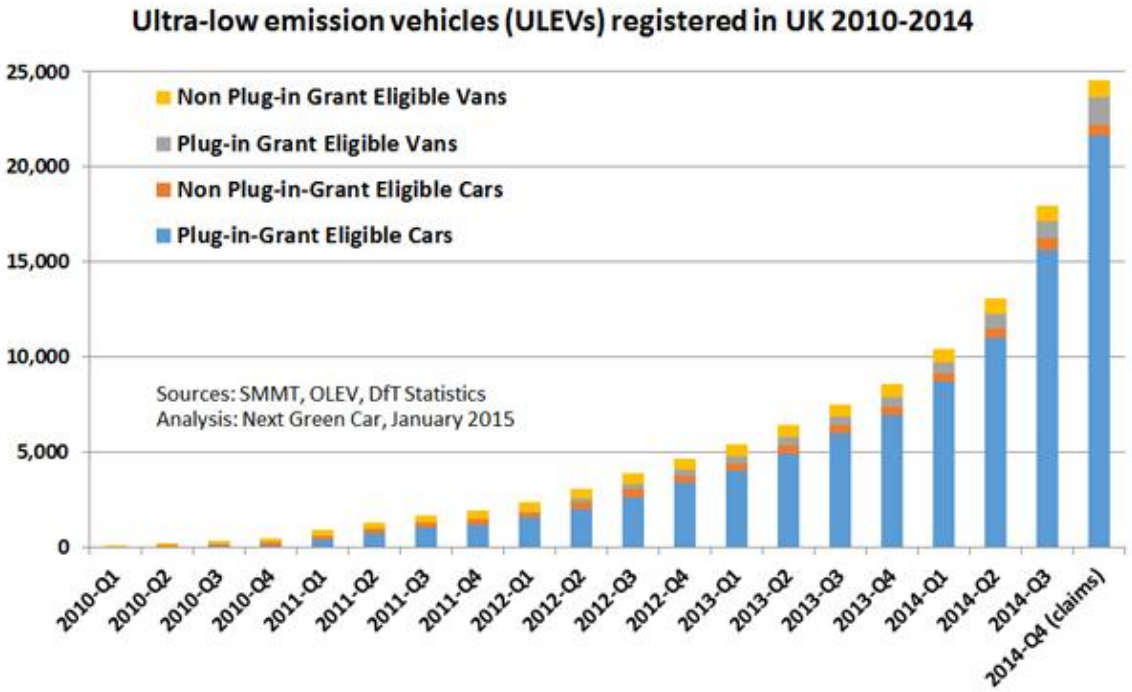

Figure 16: Numbers of ULEVs registered in the UK[109]

Range anxiety is often cited as a major barrier to EV uptake[110], and although it has been suggested that that these fears are felt more strongly by those driving conventional vehicles[111], that the response to range anxiety is highly subjective[112], and that surveys of EV drivers indicate high levels of satisfaction[113], there are still range-limiting factors that are outside drivers' control, such as cold conditions and unreliable mileage gauges[114]. EV battery technology may currently be suitable for many short journeys – particularly those in urban environments not far from home – but it cannot

[108] Table VEH0203
[109] Source: http://www.ecolane.co.uk/?p=341
[110] http://papers.sae.org/2008-01-0458/
[111] http://theweeklydriver.com/range-anxiety-still-deterent-electric-car-sales/
[112] http://www.plugincars.com/researchers-ev-drivers-respond-range-anxiety-distinct-ways-129209.html
[113] http://energycenter.org/sites/default/files/docs/nav/transportation/cvrp/survey-results/California_Plug-in_Electric_Vehicle_Driver_Survey_Results-May_2013.pdf
[114] http://news.nationalgeographic.com/news/energy/2011/03/110310-electric-car-range-anxiety/

currently compete with the mileage offered by petroleum fuels and the supporting infrastructure. Various approaches have been put forward to reduce or eliminate peoples' concerns that they will be left high and dry with no access to a power source, including:

- **Range extension.** Any internal or external energy source that acts to increase the electric capacity and therefore driveable distance of an EV acts as a range extender. Most often, however, range extension vehicles come with an internal combustion engine that generates electricity which recharges the vehicle's battery, resulting in tailpipe emissions similar of 10-50gCO_2/km, similar to those of an HEV[115].
- **Electric charging infrastructure.** The Plugged-in Places scheme introduced by the last government has contributed to the installation of 8500 charge points – mostly in urban areas such as Milton Keynes, Manchester and London – and details of funding up to 2020 have recently been announced[116][117]. There are several ways in which to charge EV batteries, depending on the power supply and maximum current. Those with longer charging times are more appropriate for household use – the industry preference is for dedicated connector and circuits with communications functions that future-proof the installation in advance of smart applications and improved energy management[118] – whilst those that provide rapid charging are better suited to public locations. These operate at a much higher voltage and current, with a recharge time of 15-20 minutes[119], but place a much higher demand on the local distribution networks, which are often not strong at roadside locations where power demand in generally lower. There are about 900 rapid charge points across the UK at present[120].
- **Battery swapping.** Battery swapping is already commonplace for forklift trucks and milk floats, Israeli company Better Place was for some years the market leader in battery swapping technology for road vehicles, and with a backing of $850m worth of private capital established battery swapping stations in Israel, Denmark, and the US before going bankrupt in 2013[121]. Although presented as a solution for EVs making journeys outside their range limits, battery swap stations have been found to be up to 10 times the cost of quick charging points[122], and require a sufficient rate of EV adoption parallel with the supporting infrastructure. Swapping stations also rely on technical standardisation and interoperability between the manufacturers and operators of the vehicles, batteries and battery swapping technology – something Better Place was unable to achieve, limiting its customer to just one type of vehicle; Tesla has also refocused its efforts away from battery swapping[123].
- **Wireless charging.** Based on the principle of resonant inductive coupling, wireless charging is being pursued by a number of vehicle manufacturers and is currently at demonstration stage. It has been suggested that a significant portion of the industry believes the technology to represent the future for plug-in electric vehicles, and that the market for wireless charging equipment will grow at an annual rate of 108% between 2013 and 2022, reaching

[115] http://www.smmt.co.uk/2014/09/five-things-need-know-going-ultra-low-2/
[116] http://www.smmt.co.uk/2014/09/five-things-need-know-going-ultra-low-2/
[117] https://www.gov.uk/government/news/43-million-for-infrastructure-and-research-and-development-plug-in-vehicle-funding
[118] http://www.beama.org.uk/download.cfm/docid/6f7151f9-6a92-49a1-b7d542a5bd78ddc9
[119] http://www.afdc.energy.gov/fuels/electricity_infrastructure.html
[120] https://www.zap-map.com/
[121] http://www.theatlantic.com/technology/archive/2013/05/another-clean-tech-startup-goes-down-better-place-is-bankrupt/276257/
[122] http://www.northsearegion.eu/files/repository/20130716113831_Acitivty_5.2_report_FDT.pdf
[123] http://www.forbes.com/sites/markrogowsky/2013/06/21/6-reasons-teslas-battery-swapping-could-take-it-to-a-better-place/

sales of 302,00 units per year[124]. Laying transmitter coils under road surfaces could also recharge vehicles moving at highway speeds, although this is likely to be costly and many years away[125].

- **Portable charging.** One company has developed an 'angel car' that will be able to recharge vehicles that have become stranded after running out of power. It is not designed as a routine way of recharging, but could provide valuable services and allay range anxiety for some customers[126].

The carbon reduction potential of each type of EV depends importantly on factors that include the characteristics of the engine, vehicle and battery, the emissions associated with manufacturing, the carbon intensity of electricity generation, transmission and distribution (and that of any liquid fuels used), and whether the power EVs draw from the electricity system is considered marginal load or part of the total. If regarded as a marginal load, consideration would have to be given to the emissions involved in ramping up and despatching additional electricity supply and to the construction of new power plants needed to meet this demand. Emissions from end-of-life have been shown to be small in relation to earlier phases of the vehicle life cycle[127].A British consultancy found in 2011 that, based on the UK's grid mix, EVs could be responsible for emissions of 75gCO_2/km (85gCO_2/km including upstream emissions)[128].

Electrification of road freight is at an early stage of research and development, with energy density improvements to battery technology still required. Concepts similar to electric rail – with overhead lines and hybrid diesel engines – have been explored although they are currently very far from market readiness and are likely to require large infrastructure spending commitments[129].
In the case of **rail**, electrification by overhead lines or conductor rails presents the only currently available and economically viable technology for substantially reducing emissions from the rail sector – notwithstanding its reliance on the decarbonisation of power generation. In January 2015 a timetabled, five-week battery electric service was launched between Harwich International and Manningtree stations, which will be used for the collection of data that will help determine the future of battery electric power on railways[130]. A diesel-battery hybrid engine rated for use in marshalling yards has recently come into service in China, which it is estimated could reduce fuel consumption by 40%[131]. Yet, whilst battery-powered electrification is a less capital-intensive alternative to overheard wires or conductor rails, the technology is much less developed and so it is not discussed at length here.

The Association of Train Operating Companies (ATOC) estimated the carbon intensity of electrified passenger rail to stand at 54gCO_2/pkm, compared to a figure of 71gCO_2/pkm for diesel passenger rail, although this figure may have changed significantly since 2005/6.

Electrified lines generally carry the busiest parts of the network and have the highest traffic density. 33.4% of Britain's of Britain's total route length is electrified[132], and this carries just under half of all

[124] http://www.navigantresearch.com/research/wireless-charging-systems-for-electric-vehicles
[125] http://news.stanford.edu/news/2012/february/wireless-vehicle-charge-020112.html
[126] http://www.foxnews.com/leisure/2010/09/16/elecric-car-juice-pray-angel/
[127] http://web.mit.edu/2.813/www/readings/LCAforPHEVs.pdf
[128] http://ecometrica.com/assets/electric_car_emits_75_gCO2_per_km.pdf
[129] http://www.mobility.siemens.com/mobility/global/en/interurban-mobility/road-solutions/electric-powered-hgv-traffic-ehighway/pages/electric-powered-hgv-traffic-ehighway.aspx
[130] http://www.networkrailmediacentre.co.uk/News-Releases/Batteries-included-Prototype-battery-powered-train-carries-passengers-for-first-time-2230.aspx
[131] http://www.railwaygazette.com/news/traction-rolling-stock/single-view/view/battery-diesel-and-dual-fuel-locos-roll-out.html
[132] http://orr.gov.uk/__data/assets/pdf_file/0015/15063/rail-infrastructure-assets-environment-2013-14.pdf

passenger miles and approximately 5% of freight miles: a large amount of both passenger and freight transport is therefore still reliant on diesel engines running under the wires[133], and additional electrification on certain parts of diesel routes could allow some of this traffic to convert to electric traction[134]. This would be likely to result in a significant increase in power demand in parts of the electricity distribution networks, and would require a thorough understand of available capacity. Similarly, the maximum capacity of some parts of the distribution networks around electrified lines is lower than the peak capacity of the line, which may pose congestion problems where there is a large rise in power demand.

Rail electrification presents cost-saving advantages over diesel across many fronts. For example, it has lower rolling stock operating costs than diesel equivalents, which for passenger vehicles equates to a saving of between 19 and 26 pence per vehicle mile – a reduction of around 50%. Maintenance costs, at 20p per vehicle mile, are estimated to be a third lower than for diesel vehicles[135]. Historical correlation between the two fuel types also suggests that the relative price of each is more important that absolute price fluctuations.

Electric trains also have lower vehicle leasing costs, reduced maintenance time and therefore increased rolling stock availability, a lower power-to-weight ratio, the ability for freight to haul greater trailing loads, larger passenger seating capacity and, where stops are frequent, reduced journey times. These last two in particular contribute to reduced carbon dioxide emissions. Some of these advantages are offset by the risk of failure in electrical fixed equipment. Despite these advantages, between 1990 and 2010 the overall length of the electrified rail network was extended by just nine miles[136].

Direct emissions from diesel passenger rail transport are dependent on vehicle efficiency, vehicle kilometres and passenger kilometres, with the latter two being subject to the greatest change. Vehicle kilometres increased 22% between 1995/6 and 2005/6 and over the same period passenger kilometres rose 46%, resulting in a fall of 16% to 74gCO_2/pkm. By contrast, emissions from electric passenger vehicles are measured in grams of CO_2 per passenger kilometre (gCO2/pkm), and depend on the energy consumption per vehicle kilometre, the load factor and the electricity generation mix. Greenhouse gas emissions from electric train vehicles are typically lower than those from diesel engines, having been estimated at 1664g per vehicle mile in comparison to 2100g for diesel engines. This differential may be lower for freight vehicles. Box 1 considers

Assessments of the extent of the superior energy efficiency of electric rail over diesel rail are dependent on a wide range of assumptions, but the Department for Transport has in the past estimated savings of around 18%[137]. The greater carrying capacity of high speed electric trains improves this further, as does continued decarbonisation of the electricity grid. Network Rail – which receives 90% of its electricity from low carbon sources thanks to a ten-year deal with EDF[138][139] – has found the under the current generation mix over 80% of the emissions from electric rail comes from vehicle operation. However, this falls to around 28% when the 30-year use of new trains from 2025

[133] http://www.networkrail.co.uk/browse%20documents/rus%20documents/route%20utilisation%20strategies/ network/working%20group%204%20-%20electrification%20strategy/networkrus_electrification.pdf
[134] Network Rail document, p.27
[135] Network Rail
[136] House of Commons, p.1
[137] https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/243207/7176.pdf
[138] Network Rail RUS
[139] http://www.networkrailmediacentre.co.uk/News-Releases/Ten-year-deal-powers-Britain-s-biggest-rail-electrification-programme-in-a-generation-1c78.aspx

and the rapid grid decarbonisation proposed by the CC are taken into account. Under such a scenario the construction of new infrastructure accounts for around 70% of total emissions, and so concentrating efforts on decarbonising heavy industry – concrete and steel in this case – could have a massive impact on overall emissions[140].

The potential for battery electrification of **ships** remains minimal in the absence of major technological breakthroughs, particularly in the field of energy storage, and little work has been undertaken in this area. Improvements to electric drive train technology, however, have reduced the size and weight of the components and may allow efficiency gains of up to 20%[141]. Nuclear power has received little attention due to the associated onboard safety risks. The world's first nuclear-powered cargo-passenger ship launched in 1959 but visions of a global nuclear fleet were scuppered by construction costs, fear of leakages, a build-up of nuclear waste, the frequency with which ocean-going vessels sink and concerns around nuclear proliferation[142]. Nevertheless, the need to reduce carbon dioxide emissions has led to renewed interest in compact nuclear reactor concepts[143].

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[140] Network Rail: Comparing environmental impact of conventional and high speed rail
[141] http://www.economist.com/node/10202790
[142] http://www.bbc.co.uk/news/magazine-28439159
[143] http://www.sciencedirect.com/science/article/pii/S0149197009000171

4.5. Hydrogen

Hydrogen can be used in **road transport** either through internal conversion to electricity or onboard combustion. The hydrogen internal combustion engine burns hydrogen in the presence of oxygen, producing only water vapour as an exhaust. The chemical properties of hydrogen (its wide range of flammability and low density) mean that combustion engine designs have so far favoured spark ignition (as in a petrol engine) over compression ignition (diesel), although such engines have lower power at reduced engine speeds and a lower theoretical efficiency[144].

Hydrogen fuel cell electric vehicles (FCEVs) ionise hydrogen atoms, resulting in positively charged protons and the negatively charged electrons that form an electric current that then powers the drivetrain. The two then recombine in the presence of oxygen to give water. Hydrogen is stored onboard at high pressure (up to three times that of CNG[145]) in order to allow sufficient vehicle range. Hydrogen already has a number of real-world applications, most prominently in fuel cells in the forklift truck industry, which is sometimes seen as a niche for technological learning, development and real-life trialling, although the buzz generated by a 2011 projection that forklifts could be responsible for 36% of total US hydrogen demand by 2020 (5200 refuelling stations) appears to have cooled in recent years[146][147]. Hydrogen buses are also being trialled or have been brought into regular service in a handful of cities around the world, including Madrid, Hamburg, Perth, Reykjavik and Berlin – and in London and Aberdeen in the UK.

To see widespread adoption of hydrogen, the industry will need to overcome the lack of a widespread hydrogen distribution network for refuelling, as well as the huge capital cost of developing the vehicles. In 2013 UK H_2 Mobility, a joint government-industry partnership, published the results of a study into the potential for hydrogen FCEVs in the UK. It sought to quantify the potential demand for hydrogen mobility, the amount of infrastructure needed to satisfy this demand, and the benefits of establishing a UK FCEV market. It envisages 65 refuelling stations situated strategically across the UK as enough to provide reassurance to drivers, with full national coverage of 1150 by 2030. This would be a number sufficient to ensure close-to-home refuelling for the whole country. It estimates financing required to break even in the early 2020s at £418m and acknowledges the likely unprofitability of early fuelling stations, proposing seed funding to support market creation.

Hydrogen vehicles have the potential to contribute to greenhouse gas emissions reduction through greater operational energy efficiency and avoided fossil fuel consumption. In order for these savings to be realised, however, it will be necessary to establish a cost-effective low-carbon means of producing large quantities of hydrogen, since lifecycle emissions depend largely on the way in which the fuel is produced. Hydrogen is generally produced via hydrocarbon reforming (using fossil fuels or biomass feedstocks), water electrolysis (using electricity from various sources), and gasification (or waste, coal and biomass), and carbon capture and storage is seen as unlikely to form part of the process before 2030[148].

Steam methane reforming using natural gas is the most efficient and economical way of producing hydrogen for industrial applications, and has been used widely in the oil refinery and fertiliser

[144] http://www.yale.edu/gillingham/hydrogenICE.pdf
[145] http://www.c2es.org/technology/factsheet/HydrogenFuelCellVehicles
[146] http://www.navigantresearch.com/newsroom/more-than-5200-hydrogen-fueling-stations-to-be-operational-by-2020
[147] http://www.environmentalleader.com/2011/07/20/hydrogen-fueling-stations-could-reach-5200-by-2020/
[148] https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/192440/13-799-uk-h2-mobility-phase-1-results.pdf

industries. Small-scale reforming may obviate the need for an expensive high volume delivery infrastructure, but would probably be too small for carbon capture to be applied. Electrolysis is the only other method that has been demonstrated on an industrial scale although electricity has a high cost relative to fossil fuels. However, it has significant potential in the near-to-medium term if the electricity used comes from low-carbon sources. High-temperature electrolysis at nuclear power stations, currently under development, may improve the efficiency of electrolysis further. Depending on the feedstock, gasification is generally more expensive that reforming. Coal gasification is a mature technology although less efficient than reforming (but more efficient than burning coal for electrolysis), and biomass gasification, which may be applicable on smaller-scales away from distribution networks, is in the early stages of development and yet to be applied industrially[149]. A US study has suggested that of these methods, biomass gasification and low-carbon electrolysis emit the least (around 40gCO_2/mile) whilst coal gasification with carbon capture may emit twice the amount and natural gas steam reforming may emits four times as much (95gCO_2/mile and 200 gCO_2/mile respectively)[150]. The Department of Energy and Climate Change is currently working towards ways to promote a UK market for green hydrogen[151].

The application of hydrogen to **rail** ('hydrail') is similar to its use in road vehicles: either as fuel for a hydrogen internal combustion engine or in a fuel cell to power electric motors, the technology on which most research to date has focused. Hydrail is in a much earlier stage of development than LNG but continues to be explored as a long-term solution to decarbonisation of the rail sector, partly because very high copper prices favour the use of fuels that can be carried onboard and also because electrolysing hydrogen during off-peak times may be more economical than placing further strain on the electricity system during peak hours[152].

In 2012 a fuel cell designed by a team from the University of Birmingham hauled four tonnes a distance of 2.7 kilometres[153], and research is being carried out in Denmark, Germany, Canada, Japan and at Southwest Jiaotong University in China. Dubai aims to launch a hydrogen-powered trolley system (inevitably dubbed a 'hydrolley')[154], and the Caribbean island of Aruba has introduced hybrid trams that contain both a rechargeable battery and hydrogen fuel cell[155].

Fuel cell technologies (powered by gas) on **ships** have also been demonstrated to be effective in trials, with a 55% fuel efficiency with heat recovery and no SO_X, NO_X or particulate emissions, which suggests that in future onboard fuel cells could be powered by hydrogen[156]. Fuel cells also have fewer moving parts, and so are less costly to maintain, and reduce noise and vibration onboard, although the relatively immature state of marine fuel cell technology means that further investment in research, development, demonstration and deployment will be needed.

[149] https://www.bartlett.ucl.ac.uk/energy/research/themes/energy-systems/hydrogen/WP6_Dodds_Production.pdf
[150] http://www.hydrogen.energy.gov/pdfs/10001_well_to_wheels_gge_petroleum_use.pdf
[151] https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/403774/Green_Hydrogen_Standard_Call_for_Evidence.pdf
[152] http://www.railway-technology.com/features/feature122016
[153] http://www.newscientist.com/blogs/nstv/2012/08/first-uk-hydrogen-train.html
[154] http://gulfnews.com/news/gulf/uae/dubai-trolley-new-rail-link-to-connect-downtown-1.1436003
[155] http://www.hydrogencarsnow.com/blog2/index.php/infrastructure/aruba-to-debut-1st-hydrogen-streetcar-fleet/
[156] http://www.dnv.com/binaries/fuel%20cell%20pospaper%20final_tcm4-525872.pdf

4.6. Synthetic fuels

After many years of incremental development the aviation fuel supply and storage infrastructure, and the design of engine and aircraft systems, is so orientated towards jet fuels that it would be desirable for any new fuel to be a 'drop-in' replacement, and one that could be applied globally. A 2009 study assessed a number of fuels across a range of criteria, and found that certain fuels would so adversely affect efficient engine operation as to preclude them from further consideration. The same study found that most fuels require more research and development before they present a viable commercial prospect; this included jet fuels produced from oil shale (likely to be negligible earlier than 2020, but a possible contender beyond then)[157].

Given these restrictions, and the availability and maturity of the various alternatives, only a small number of fuel groups appear to offer the most potential, of which Fischer-Tropsch synthetic fuels is one. Fuels synthesised using the Fisher-Tropsch process, by which feedstocks such as natural gas, coal and biomass are gasified before undergoing a catalysed chemical reaction to produce liquid fuels, are advantageous in as much as they contain next to no sulphur, and are very similar to conventional kerosene. The choice of feedstock stock does not affect the quality of the final product but does alter the economics of production as well as overall life cycle emissions, which is, like shipping fuel options, dependent on some degree on the availability of carbon capture and storage. Emissions reductions of up to 90% may be achievable using biomass as both a feedstock and to power the processes involved, although the technology is less developed and a very large amount of biomass would be required in return for a low yield of liquid fuel. Sasol has been synthetic fuel from coal since the 1950s; regulators first approved a 50/50 blend with kerosene before approving 100% coal-to-liquid synthetic fuel.

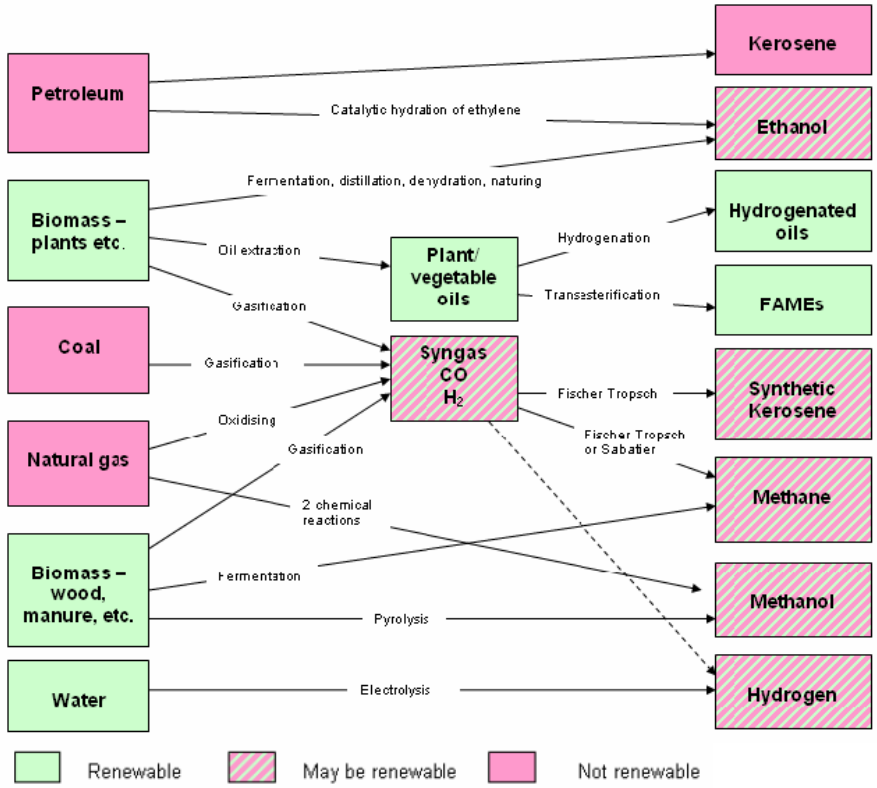

Figure 17: Illustration of processes for producing synthetic fuels[158]

[157] http://web.mit.edu/aeroastro/partner/reports/proj17/altfuelfeasrpt.pdf
[158] http://www.sustainableaviation.co.uk/wp-content/uploads/alternative-aviation-fuel-briefing-paper.pdf

4.7. Methanol

Chemically similar to LNG (CH_4), methanol (CH_3OH) possesses considerable versatility and can be produced using natural gas or other feedstocks, including biomass, which gives it the potential to be almost a zero carbon fuel for **shipping**. It is already in use, albeit in a small number of specialised applications, such as monster truck and motorcycle racing. Unlike LNG, it is liquid at room temperature and so can be transported and stored in relatively non-disruptive fashion, and engines require less extensive conversion to run from methanol than from LNG. Importantly, it does not carry the threat of methane slip as with LNG, and shares many of the benefits around SO_X, NO_X and particulate matter reductions. In advance of the 2015 tightening of sulphur emissions regulations, Swedish shipping company Stena conducted one test in which a diesel engine was converted to burn methanol, and another in which dimethyl ether (discussed below) was extracted from methanol. If successful, the company plans to convert 25 ships to run on methanol throughout the rest of the decade[159], with each reducing sulphur emissions by 99%, nitrogen emissions by 60%, particulate matter by 95% and carbon dioxide by 25%[160].
Methanol's lower energy density means the associated technology is currently less developed than LNG, and the recent fall in crude prices may perhaps hamper its prospects[161]. The fuel also requires care when handling due its toxicity and flammability, its flashpoint of approximately 11°C being considerably lower than that of both diesel and bunker fuel, so its penetration into the shipping fuels market will need to be preceded by appropriate regulation, which the IMO is currently drafting. Despite these drawbacks, one recent study indicates that it may be cost-effective to phase out oil over the coming decades in favour of LNG and methanol, and that in the presence of carbon capture and storage (CCS) methanol could dominate, satisfying 40-50% of aggregate fuel demand between 2020 and 2050[162]. A 2011 trial successfully demonstrated the use of methanol onboard a ship engaged in international trade and in full compliance with all the attendant regulations[163].

4.8. Renewables

Whilst onboard renewables, such as wind and solar, are generally unable to meet the operational needs of present-day **shipping** operators, some vessels are able to use kites to harness energy savings in the region of 10-35% (or 3-8% for the worldwide fleet). Such technologies remain unsuitable for many types of deep sea shipping although they may be applicable to certain specific conditions[164].

[159] http://www.lngbunkering.org/sites/default/files/2013%20stena%20line%20The_Methonal_Alternative.pdf
[160] http://www.ship-technology.com/news/newsmethanol-powered-stena-germanica-to-resume-operations-4514735
[161] http://www.bunkerworld.com/news/Low-oil-price-hampering-prospects-for-methanol-133916
[162] Grahn et al, Cost-effective choices of marine fuels under stringent carbon dioxide targets
[163] http://www.marindagen.se/wp-content/uploads/2010/11/Ed-Fort.pdf
[164] http://cnss.no/wp-content/uploads/2011/10/Summary-brochure10.pdf

5. Conclusions and next steps

This report shows that for each mode there is a greater or lesser range of fuels that could be used as alternatives to conventional hydrocarbons, and that these cannot always be applied easily to the specific requirements of each mode. The production of some fuels – for example, hydrogen and methanol – carries an energy cost, impacting their price and overall efficiency.

Different modes might also compete for finite fuels, particularly where – as with aviation – there are a limited number of alternatives. Where electricity is proposed as an alternative means of powering road transport, consideration must be given to the impact this may have on the demand for and distribution of electricity at both national and local levels.

Different energy sources for modes might also place pressures upon existing infrastructure (or require new infrastructure), or require interactions that are currently not considered. The technology and infrastructure currently in place for the extraction, refining and delivery of fuels for road transport are currently very separate from the generation, transmission and distribution of electricity. The pursuit of alternative fuels for transport is likely to impact directly or indirectly on the electricity system at a time when it is already under pressure to change radically.

There is therefore a need for a better understanding of possible future interaction between the two energy systems and of any constraints or opportunities that may emerge as new technologies are adopted. More detailed awareness of the confidence in the emergence of a given technology, coupled with the impact it could have may allow planners and policymakers to identify and exploit no-regrets decisions, maximise co-benefits and minimise negative impact. Figure 18 is a 'confidence-impact matrix' that represents the views on the potential impact for different technologies to reduce transport's greenhouse gas emissions, along with the level of confidence that each technology will deliver that potential. For example, advanced bio-gasoline for light road vehicles offers high confidence of having a large impact, whereas wind for shipping offers a high confidence of having a low impact. It is evident that several of the fuel options for the big emitters (light and heavy duty road vehicles) are generally thought to have both a high impact and high confidence.

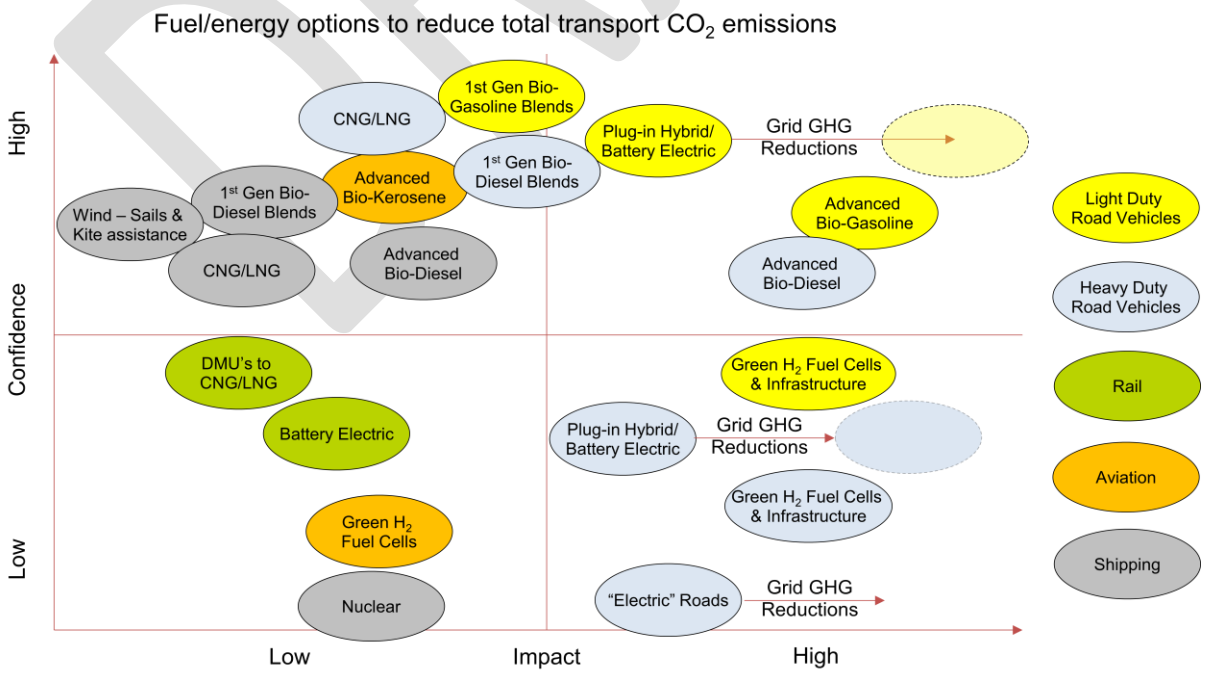

Figure 18: Fuel and energy options to reduce total transport CO_2 emissions

This assessment of impact and confidence can be used to guide future work. It confirms the value of pursuing solutions for road transport, providing optimism that those largest emissions can be reduced.

Phase 2 of this project will develop scenarios to assess the possible outcomes of different decarbonisation strategies for transport, taking into account other priorities in the sector and interactions with the energy sector. This will be based, in part, on the assessment of each option, as summarised in the tables in Annex 1. A broad exploratory analysis of interactions and trade-offs could identify the areas where more detailed research and development is required and draw attention to those areas where the greatest certainty or uncertainty lies.

The scenarios devised as part of this analysis should seek to explore the outcomes given a series of inputs, rather than to optimise costs or ask how best to achieve a particular goal. These scenarios will be of broad scope, covering the transport and energy sectors as well as any key non-energy implications that may be appropriate. The objective is not to arrive at detailed and costed future pathways, but to explore the interactions and trade-offs that exist when making strategic decisions.

- **We will seek input from a range of experts, including at the ERP plenary in April, on topics including:**
    - **the scale and extent of interactions between the transport and energy sectors**
    - **the potential impacts of energy sources and technologies**
    - **the level of confidence around the future development of these technologies**
    - **probable and/or plausible rates of uptake**

DRAFT

Annex 1: Summary of factors affecting energy options

Benefits | Issues to address | Not applicable

Energy type:	Alternative hydrcarbon fuels			(Part) electric			Renew-ables	Other	
Mode:	Fossil fuel gases	2nd gen. biofuels	Synthetic fuels	Electric hybrid	Plug-in hybrid / Battery	Pick-up / charge-on-move	Wind	Nuclear	Metals
Road (light)									
Road (heavy)									
Rail									
Shipping									
Aviation									

Figure 19: Summary table of fuel options: technical requirements (mainly energy density and portability)

Energy type:	Alternative hydrcarbon fuels			(Part) electric			Renew-ables	Other	
	Fossil fuel gases	2nd gen. biofuels	Synthetic fuels	Electric hybrid	Plug-in hybrid / Battery	Pick-up / charge-on-move	Wind	Nuclear	Metals
Global climate									
Local environment									
Safety									
Affordability									
Flexibility of operation									

Figure 20: Summary table of fuel options: transport sector priorities

Energy type:	Alternative hydrcarbon fuels			(Part) electric			Renew-ables	Other	
	Fossil fuel gases	2nd gen. biofuels	Synthetic fuels	Electric hybrid	Plug-in hybrid / Battery	Pick-up / charge-on-move	Wind	Nuclear	Metals
Resource availability									
Competition for resources									
Energy infra. capacity & management									

Figure 21: Summary table of fuel options: pressures for resources