Energy Options for Transport: Annex: Overview of Options
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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<tr>
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<tbody>
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<td>David Wright</td>
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<td>Mary McAllan</td>
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<td>Andrew Wright</td>
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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.

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

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The UK’s transport sector accounts for a third of the UK’s energy consumption, and UK domestic transport causes about a quarter of its greenhouse gas (GHG) emissions. International shipping and aviation that can be attributed to the UK cause emissions of about a third above and beyond domestic transport. The transport sector will need to reduce its emissions significantly in order to contribute to the UK’s target of reducing GHG emissions by 80% by 2050 (from 1990 levels).

This project considers how transport fits into the wider energy sector within the context of decarbonisation, taking into account:

- **Technical criteria for each mode:**
  - energy density and portability, to allow sufficient range between refuelling;
  - speed of refuelling, especially if done more frequently.

- **Key priorities for the transport sector, and trade-offs between them:**
  - cost, affordability, safety, air quality, and GHG emissions;
  - flexibility of operation (e.g. cars undertaking different trips and tasks).

- **Interactions with the wider energy sector:**
  - availability of, and competition for, fuels (and their feedstocks);
  - life-cycle energy efficiency of fuel (affecting primary energy demand);
  - use of infrastructure (pressure on existing, and costs of new).

This project focusses on energy sources, particularly those that appear to offer the largest potential GHG emissions reductions (although being aware that fuels and technologies that appear to have limited potential could make larger contributions if circumstances change). The project is considers other potential developments that could make valuable contributions, such as mode switching, energy efficiency, changing trends in use of transport, and new business models.

This Annex summarises the energy options for the main modes of transport: light road, heavy road, rail, shipping, and aviation. This Annex is structured as follows:

- Section 2 presents an overview of UK transport demand, and its energy and emissions (broken down by modes and fuel types).
- Section 3 discusses how decarbonisation options are affected by transport’s technical criteria and key priorities (e.g. range, cost, affordability, safety, air quality).
- Section 4 discusses how transport’s GHG emissions can be reduced, and presents illustrative examples of energy efficiency, switching to other transport modes, and switching to lower-carbon fuels. It highlights the importance of switching to lower-carbon fuels, particularly for road transport that dominates GHG emissions.
- Section 5 outlines the energy options for transport, highlighting which are most suited given the criteria for each mode (see Section 3). It also considers how these options could be affected by interactions with the energy sector (e.g. competition for fuels, life-cycle energy efficiency, and use of infrastructure).
- Section 6 summarises the key conclusions in terms of “impact and confidence” to highlight the combinations of energy options and modes that are most likely to have the largest impacts on decarbonisation.

The project was undertaken jointly by the Energy Research Partnership (ERP) and the Government Office for Science (GO-Science). The work was being carried out under the guidance of a steering group composed of public and private sector members of the ERP, and has drawn on a review of literature and discussions with experts from the sector.
2. Overview of UK transport

Transport is a key sector that needs to be decarbonised. UK domestic transport is responsible for about a quarter (~130MtCO₂e/yr) of UK GHG emissions. UK international transport adds an additional third to these transport emissions (~40MtCO₂e/yr), beyond those currently counted in UK totals. This section highlights the main sources of transport emissions and recent trends.

Figure 1 presents UK transport emissions using Pareto analysis that ranks the modes according to their emissions to identify those that must be considered as priorities. The key points are:

- **Light road** vehicles (cars, vans) are the largest source of transport emissions at 67%.
- **Heavy road** vehicles (buses, coaches, HGVs) are the second largest source at 24%.
- **Rail** (including metros and trams), **domestic shipping** and **domestic aviation** contribute 7%.
- **Other modes** (e.g. off-road) account for 3% of emissions.
- **International shipping** and **international aviation** attributed to the UK add 7% and 24%, respectively, on top of UK domestic transport emissions.

The relative significance of each mode has been broadly similar for several decades, but the absolute levels have changed in response to changes in user behaviour, technology and regulations. Figure 2, Figure 3 and Figure 4 illustrate annual UK data for 2000 to 2013 in: transportation of passengers and freight; energy and emissions by mode; and energy and emissions by fuel. Key points include:

- **Road accounts for the vast majority of passenger travel and freight:**
  - Light road vehicles account for ~85% of passenger travel and ~5% of freight.
  - Heavy road vehicles account for ~5% of passenger travel and ~65% of freight.
- **Rail transport has increased** by ~50% for passengers and by ~5% for freight since 2000.
- **Emissions have fallen** by ~15% in the light road vehicle fleet, largely due to improved fuel efficiency of new vehicles and increased use of diesel (see Section 5.1).
- **Petroleum** products account for ~97% of energy use and emissions, including for road; the mix of petrol and diesel have changed markedly since 2000 (see Figure 5 in Section 5.1).
- **Biofuel use has risen sharply**, and now accounts for ~3% of transport energy (all for road).
- **Electricity** demand has been stable at ~1% of UK transport energy, almost all for rail.

Figure 1: Pareto analysis of GHG emissions for each UK mode of transport. International shipping and aviation are not currently included in UK totals, but are shown for comparison.

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1. However, smaller modes can make useful impacts, and some technologies might have more impact than expected.
2. GHG emissions from international shipping and aviation are not included in the UK total. They are estimated from fuel use (which is included in UK energy demand), and are reported under UNFCCC guidelines as memo items in national GHG inventories. The UK government will decide in 2016 how to treat these emissions in the 4th carbon budget. See: 2013 UK Greenhouse Gas Emissions, Final Figures (DECC, 2015), and International Aviation & Shipping Review (CCC, 2012)
4. Rail uses twice as much diesel as it does electricity, but the emissions are split roughly equally at ~2MtCO₂ each; i.e. the emissions intensity is currently higher for electricity, but this can be reduced by grid decarbonisation.
Figure 2: Transport demand (left) passenger and (right) freight, lower charts show smaller values.

Figure 3: Transport modes’ (left) energy use and (right) GHG emissions.

Figure 4: Transport fuels’ (left) energy use and (right) GHG emissions.

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5 Rail includes urban rail. Transport Statistics GB, Tables TSB0101, NT80305, TSB0401 and RFS0107 (DT, 2014)

6 Transport Statistics GB, Table ENV0102 (TSGB0302) (DT, 2014); and 2012 final UK figures: data tables (DECC, 2014)

7 Pre-2004 rail energy data included stations’ energy use and is not shown here. Biofuels’ GHG emissions do not include those caused by indirect land use change. Energy consumption in the UK (DECC, 2014); Transport Statistics GB, Table ENV0102 (DT, 2014); and Final UK greenhouse gas emissions national statistics 1990-2013 (DECC, 2015)
3. Key priorities for transport modes

Energy options for each transport mode are limited by technical criteria (e.g. energy density that limits range). They are further affected by key priorities for the transport sector (e.g. affordability of mobility), as discussed in this section (and summarised in Figure 7, in the Annex).

3.1. Road (light and heavy)

Reductions in GHG emissions for light road vehicles are linked to energy efficiency of new vehicles. Diesel engines (more efficient than petrol engines) increased their market share, reducing energy demand from light transport (see Figure 5 in Section 5). New cars’ GHG emissions intensity (per vehicle) fell by ~30% from ~180gCO₂/km in 2000 to 128.3gCO₂/km in 2013 (according to regulated drive cycle tests, whereas real-world savings are lower). 8 Hence, the overall sector’s performance improved: from 2000 to 2012, energy intensity fell by ~15% (per pkm) for passengers (despite occupancy rates being stable at ~1.6), and GHG emissions intensity fell by ~20% for passengers (per pkm). Heavy road transport has also had improvements in energy efficiency (and has increased carrying capacity), but these have been negated by logistical issues (e.g. part-empty HGVs) such that for freight from 2000 to 2012 energy intensity and GHG emissions intensity rose by ~10-15%.

- **Cost** of fuel is the main running cost, and key issues are price (two-thirds of which is UK tax) and price volatility (e.g. in 1970s and since 2008). Financial incentives for lower-carbon vehicles have diminished; and, in the longer term, taxation will shift to low-carbon fuels.

- **Range** of several hundred miles between refuelling is expected especially for HGVs, placing lower limits on energy density for fuels; and refuelling has traditionally taken a few minutes. These expectations limit the use of some low carbon options without user behaviour change.

- **Flexibility** of operation is important for cars: trips can be short or long, and contents can range from one person to large amounts of cargo. Other vehicles tend to be single-purpose.

- **Un-laden vehicle weight** has increased (hence so have fuel use and GHG emissions) due to crash protection features, and customers desiring more amenities. Weight can be reduced by new materials, but with challenges of costs, manufacture, and embedded GHG emissions.

- **Air pollution** contributes to a range of health problems, 9 caused by pollutants including soot (especially from heavier fuels) and other particulates, sulphur dioxide (SO₂) (from sulphur in fuels), and nitrous oxides (NOₓ) (from combustion with air). The main challenge is NOₓ levels alongside main roads 10 that have risen partly due to more diesel use. NO₂ is also a GHG.

- **Congestion** adds journey time, 11 and adds costs for the economy. 12 The issue is worsening, but capacity built in an attempt to solve congestion could increase GHG emissions and air pollution; and new capacity could become stranded assets as GHG emissions are curbed.

- **Ownership models** for passenger vehicles are changing: fewer young people are learning to drive and owning cars; innovative car ownership / rental models are reframing mobility as a service; and vehicles are increasingly automated. Such changes could mean fewer private cars (lower embedded GHG emissions), and more efficient use of fuel (lower in-use GHG emissions), and could provide business models for uptake of lower-emissions vehicles.

- **Personal ICT technology** allows access to transport data for door-to-door journey planning; automation could reduce inefficiencies, but could increase transport demand.

- **Replacement lifetimes** (10-20 years) of road vehicles allow fairly rapid uptake of new technology compared with other transport modes and other sectors (e.g. buildings).

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8 New Car CO₂ Report 2014 (SMMT, 2014); and Travelcard Nederland BV data source document (TNO, 2013)
9 Emissions of air pollutants in the UK, 1970 to 2013 (Defra, 2014)
10 2010 to 2015 government policy: environmental quality, Appendix 5 (Defra, 2015)
11 A model to fund our future roads (CBI, 2012)
12 Economic & Environmental Impact of Traffic Congestion in Europe & the US (Cebé & INRIX, 2014)
3.2. Rail

Rail’s GHG emissions have remained at ~4.5MtCO₂e per year\(^\text{13}\) whilst travel has increased: emissions intensity has fallen (e.g. in the year to 2012/13 by 4.9% for passengers (to 44.8gCO₂/pkm) and by 8.1% for freight (to 25.9g/tkm)), due to more electric trains, new rolling stock, and higher loading.\(^\text{14}\)

- **Rail capacity** (existing and new lines) will have to increase to accommodate demand growth (recently 5-6% per year),\(^\text{15}\) that could increase rail’s energy use and GHG emissions.\(^\text{16}\)

- **Cost** of rail travel is a key political issue, both for rail fares and public subsidies. Costs of electric networks could limit the scope for further electrification as a low-carbon option, particularly on low-use routes. On-board low-carbon energy sources could be more suited.

- **Long lifetimes** of trains mean that fleet-wide uptake of new technology takes decades.

3.3. Shipping

UK shipping is a small contributor to energy demand and emissions (although international shipping adds an extra 7% on top of UK transport emissions), but globally shipping accounts for ~3% of global GHG emissions and transports 80% of world trade (by volume). International shipping uses residual fuel oils (called bunker fuel) for ~80-85% of its energy demand, with distillate fuels (e.g. diesel) making up the remainder. Recent energy efficiency measures have reduced GHG emissions per tkm, but shipping use has increased, so the total GHG emissions have been roughly constant.\(^\text{17}\)

- **Fuel costs** can be a significant cost (and risk) for shipping: it uses ~330million tonnes per year globally, at typically ~£500 per tonne, giving a total cost of ~£15-20bn per year and posing a risk from oil price changes. Costs and risk can be reduced by efficiency in design\(^\text{18}\) and use.\(^\text{19}\)

- **Air pollution** of various types near ports causes health problems (see road transport). The main issue for shipping is the high sulphur content of residual fuel oils.

- **International operation** makes it hard to agree on attributing emissions to each country.

- **Long lifetimes** of ships mean that fleet-wide uptake of new technology takes decades.

3.4. Aviation

UK domestic aviation accounts for ~1% of UK transport energy, and ~2% of domestic UK GHG emissions. The use of fuels from the UK in international aviation accounts for ~21% of UK transport energy, and is equivalent to an extra ~24% of emissions on top of UK transport emissions (but are not counted as part of UK emissions).\(^\text{20}\) Globally, aviation currently represents a small, but rapidly increasing, percentage of overall GHG emissions.

- **Demand growth** is high, with projected increases of 70% between 2005 and 2020, and further increases of 300-700% by 2050.\(^\text{21}\)

- **Energy efficiency** is improving by ~2% per year, but is counteracted by demand growth.

- **Fuel type** is limited due to stringent requirements: high energy density (both per mass and per volume); operation down to -40°C; and compatibility with highly specialised engines.

- **International operation** makes it hard to agree on attributing emissions to each country.

- **Long lifetimes** of aircraft mean that fleet-wide uptake of new technology takes decades.
4. Options for reducing GHG emissions

GHG emissions from transport can be reduced by: improving efficiency (technical performance or vehicle utilisation); using a fuel with lower emissions intensity; and using a mode with higher efficiency or lower emissions intensity. This section gives examples of each approach, noting their limitations and wider implications; Section 5 gives more detail about energy options.

4.1. Energy efficiency

Energy use and GHG emissions can be reduced by: reducing the amount of energy that vehicles need, and by reducing the amount of energy that they waste. The amount of energy needed can be reduced by: reducing the speed, reducing the vehicle’s weight, and increasing utilisation (i.e. the number of passengers or weight of freight per trip, and hence the number of vehicles and / or trips needed). The amount of energy wasted can be reduced by: improvements in driving behaviour, vehicle design and efficiency, and more efficient upstream fuel production. The following examples provide rough estimates of potential impacts of measures; they do not consider all factors in detail.

- **Utilisation:** The UK’s cars use ~240TWh of fuel that emits ~70MtCO₂e of GHGs (in-use). Increasing occupancy from the current average of 1.6 to 4.0 (i.e. if most cars were full for most journeys) could reduce energy demand and in-use emissions by ~60%. Logistical challenges of car sharing prevent most of this potential from being realised for the current fleet. Similarly, better utilisation of freight transport would reduce energy demand and GHG emissions, but would require major changes to depots, co-ordination, and cost allocation by hauliers.

- **Weight:** A typical UK car has a mass of ~1,200kg, which is at least 10 times its contents. Car weight is partly due to amenities (that users expect) and safety features (that have increased partly in response to higher weights), creating a feedback loop of increasing weight. It could be reduced by half (to levels seen in the 1950s), using novel construction techniques and lightweight materials. This would reduce in-use energy and GHG emissions (but by less than half), but some materials would add embedded energy and GHG emissions.

- **Energy efficiency:** The average operating efficiency of internal combustion engines is ~15-20% for petrol engines and ~30% for diesel engines. There is limited scope to increase operating efficiency: improvements of a few percentage points (e.g. to ~20% for petrol and ~35% for diesel) could reduce road transport’s energy and emissions by ~10-15%. A car’s energy use could be halved by engine down-sizing and hybridisation (see main report).

- **Driving behaviour:** Some freight hauliers provide energy efficiency training for drivers and pay incentives based upon driving performance, offering cost-effective emissions savings (16% in some cases). Training has lower impacts for car drivers: one source quotes improvements of 15% on the day of the training, but long-term savings maintained at only 1-6%.

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22 Transport Statistics GB, Tables ENV0101 and ENV0201 (DfT, 2014)
23 Assuming average occupancy of 1.6, passenger weight of 65kg (average across ages), and that some luggage is on board.
24 Advanced Internal Combustion Engines Workstream (Automotive Council, 2013)
25 The average operating efficiency is measured across different journey types, and is limited by actions such as acceleration and deceleration. The maximum efficiency is higher: it is measured under ideal, steady-state conditions, and is limited by the thermal tolerance of engine materials (to ~25% for petrol and ~40% for diesel).
26 See, for example: SAFED course: www.system-training.com/training/safe-and-fuel-efficient-driver-training
27 Analysis by Ricardo on: Cost vs. Benefit of Low Carbon Technologies for Medium/Heavy Duty Vehicles
28 Article about smarter driving training (Energy Saving Trust): www.energysavingtrust.org.uk/domestic/drive-smarter
4. Options for reducing GHG emissions

4.2. Fuel switching in non-road sectors

Changing fuel for a mode can offer GHG emissions reductions. The following simple examples illustrate the relative magnitudes of reductions, but also some of the challenges of costs and practicalities. These examples suggest that even complete fuel switching in non-road sectors offers only small emissions reductions (given their small contribution to overall transport emissions).

- **Rail electrification**: Rail emits ~4MtCO$_2$e (~3% of UK transport GHGs); one third of UK rail routes are electrified, and electric trains account for 50% of passenger travel and 5% of freight. Electrifying the two-thirds (10,000km) of unelectrified railways could cost £5-7bn, allowing the avoidance of ~2MtCO$_2$e emissions from diesel trains. Moving all passengers to electric trains (doubling the present number) would add back the ~2MtCO$_2$e of GHG emissions (based on today’s electricity emissions intensity); moving all freight to electric trains (20 times the current level) would add further emissions.

- **Biofuels in UK aviation** (domestic and international): Biofuels from non-waste sources would use large areas of land: 100% crop biofuels for aviation would use ~30,000km$^2$ (~15% of UK land area); algae would use ~4,000km$^2$, but can have other requirements (e.g. CO$_2$ enriched water). Emissions are currently ~30MtCO$_2$e; reductions would depend upon feed stocks and counterfactuals used (that take into account any indirect land-use change, ILUC).

- **LNG in shipping**: Retro-fitting all ships (domestic, and international that refuel in the UK) to use 100% LNG in place of diesel and fuel oil, would reduce emissions by 25% (~3MtCO$_2$e), provided that methane slip was avoided.

4.3. Mode switching

Moving passengers or freight between certain transport modes can offer GHG emissions reductions. The following simple examples illustrate the magnitudes of reductions. They show that mode switching alone will be insufficient to provide the necessary reductions in GHG emissions. These calculations do not consider complexities such as time and location of demand, or embedded emissions of new capacity, or the creation of new demand.

- **Switching all domestic passenger air travel and freight to rail**: net savings of ~1.6MtCO$_2$e (~1.3% of UK domestic transport emissions). Capacity impacts on rail use would be small: an extra ~0.2% rail passenger travel (pkm) and an extra ~0.06% rail freight (tkm).

- **Switching traffic off roads to double rail passenger travel**: net saving of ~3.9MtCO$_2$e (~3% of UK domestic transport emissions), by reducing road GHG emissions by ~6.5MtCO$_2$e (if light and heavy traffic reduced in same proportion) and increasing rail emissions by 2.7MtCO$_2$e (for the current share of diesel and electric trains, and the current electricity emissions intensity). This mode switch would require significant extra rail capacity (track and stock).

- **Switching from cars to double journeys by bicycle**: reduce road emissions by ~0.5MtCO$_2$e (~0.4% of UK domestic transport emissions), and add none from bicycles. The extra 5billion pkm by bicycle (~1% of car travel) would require extra cycle capacity in some locations.

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26 Study on further electrification of Britain’s railway network (Atkins for RSSB, 2007)
27 Full rail electrification is considered in more detail in Pathway 5 of 2050 Pathways Analysis (UK Government, 2011)
28 Assuming demand of 12.3Mtoe (in 2013), and yields of 0.5W/m$^2$ for UK-grown crops and 4W/m$^2$ for algae.
5. Energy sources for transport modes

Energy options for transport are affected by technical criteria for each mode (e.g. range), priorities for the sector (e.g. cost), and interactions with the wider energy sector (e.g. life-cycle energy efficiency). This section discusses the suitability (and constraints) of each energy source (ordered roughly by current usage), noting points for each mode. Linkages are noted (e.g. interoperability of fossil fuels, biofuels, and synthetic fuels), and key points are summarised in Figure 7 (in the Annex).

5.1. Liquid fossil fuels

Oil-based fuels account for 97% of road transport energy, ~65% for rail, and ~100% for both shipping and aviation.\(^{32}\) The existing fuel distribution networks could accommodate other liquid fuels (e.g. biofuels and synthetic fuels, see below). Air pollution (particulates, \(\text{SO}_2\) and \(\text{NO}_x\)) is a key issue.

- **Light road vehicles** use ~13Mtoe (~150TWh) of petrol and ~13Mtoe of diesel; these have the necessary energy density. As shown in Figure 5, diesel use for light vehicles has increased by around a half since 2000 (due to lower costs per km and incentives to reduce GHG emissions). Diesel use for light passenger transport has doubled since 2000 to ~40% of total UK diesel use; and diesel use for light freight has increased by almost half to ~20% of total UK diesel use.

- **Heavy road vehicles** use almost only diesel, ~9.3Mtoe (~110TWh) thereof, ~40% of UK diesel use. Diesel meets the mode’s technical requirements of fuel economy, durability, availability, and high torque at low revolutions for pulling heavy loads.

- **Rail** uses diesel for ~65% of its energy, including for ~95% of freight (to provide necessary torque and weight for pulling heavy loads). Passenger trains can use diesel or electricity, although only one third of routes are electrified. Diesel has lower efficiency, higher running costs, and higher GHG emissions (but new emissions targets were introduced in 2012).

- **Shipping** (UK and domestic) uses ~2Mtoe of diesel and ~1.5Mtoe of bunker fuel (“number six fuel oil”) purchased in the UK. Bunker fuel is cheap because it is not used by other transport modes owing to its high viscosity and impurities (although there is competition from heating for some buildings). Diesel is used as a less polluting alternative near to ports and habitations.

- **Aviation** (UK domestic and international) uses ~12Mtoe of kerosene, offering the required energy density for long routes, and the required combustion quality in harsh conditions.\(^{33}\)

![Figure 5: Consumption of petrol and diesel by (left) light road and (right) heavy road vehicles.](image-url)
Liquefied petroleum gas (LPG, a propane/butane mix, also called autogas) provides ~0.2% of UK transport energy (all for road). Another option is natural gas (methane, CH4) either compressed (CNG) or liquefied (LNG). It has lower in-use emissions of pollutants and GHGs than liquid fossil fuels; but leakage of methane (“methane slip”) with its high global warming potential can offset GHG savings. Methane can be used in fuel cells, but most examples use combustion. Options include bio-methane (from organic waste) and synthetic methane (from a range of feedstocks).

- **Light road** transport can obtain sufficient energy density from LPG, but is less suited to CNG and LNG due to the extra equipment. LPG is more efficient than petrol (but petrol engine improvements are reducing this distinction), and has lower running costs (partly due to the tax regime). The UK has LPG fuelling infrastructure, and ~90% of petrol cars could be converted to use it as well as petrol (diesel cars cannot be). Conversion costs contribute to low market acceptance (under 1% of car fleet), which in turn deters development of new LPG cars.

- **Heavy road** vehicles can use LPG, CNG and LNG, having scope to accommodate the size and weight of equipment (e.g. fuel tanks, LNG refrigeration equipment). Vehicles can be built (or converted) for different regimes: natural gas only; dual-fuel to switch between natural gas and diesel; or co-injection of diesel and natural gas concurrently. Co-injection is estimated to save £15,000 a year for an HGV, but it has high conversion costs. LNG options would incur high costs for new distribution infrastructure. The scale of the heavy road vehicle sector means that use of natural gas (CNG or LNG) could create appreciable competition for natural gas with power generation and heating, and for use of capacity on gas networks.

- **Rail** can use LNG, having scope to accommodate the size and weight of equipment. The main driver for changing from diesel to LNG is the low cost of natural gas, but the upfront costs are higher. LNG could be used in gas turbines on trains, but with lower efficiency than internal combustion engines. A more efficient solution could be to convert internal combustion engines to dual fuel (diesel and LNG). LNG offers environmental advantages over diesel, reducing NOX and CO2 emissions. LNG for rail would require distribution infrastructure, and it risks locking the rail sector into carbon-based fuel consumption for the 20-30-year lifetime of locomotives. Diesel rail uses less than 1% of UK energy demand, so the move to LNG would cause only a small increase in competition for natural gas.

- **Shipping** has the scope to accommodate LNG fuel and equipment. It is particularly well-suited to LNG tankers where the cargo can be used as fuel, but a typical voyage could use ~8-10% of the cargo gas. Liquefaction facilities have high capital costs, but one scenario shows LNG at an 11% share of shipping fuel by 2030. Compared to diesel, LNG causes less air pollution. Compared to bunker fuel, LNG causes much less air pollution (90-95% less SOx, and lower NOx) and 20-25% lower in-use CO2 (but has upstream GHG emissions and methane slip).

- **Aviation** trials using LNG have been conducted, but its contribution is expected to be small.

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34 See, for example: Cars and fuel options: www.dft.gov.uk/vca/fcb/cars-and-fuel-options.asp
35 See, for example: Clean Air Power: www.cleanairpower.com
36 See a short article: Liquefied natural gas shows potential as a freight locomotive fuel (US EIA, 2014)
37 See, for example: the GT1h-002 locomotive built by Russia’s Sinara’s Lyudinovsky plant
38 See, for example: a short article on liquefaction (Total)
39 LNG-fuelled deep sea shipping (Lloyd’s Register, 2012)
40 Costs and benefits of LNG as ship fuel for container vessels (GL and MAN joint study)
41 Assessment of the fuel cycle impact of liquefied natural gas as used in international shipping (ICCT, 2013)
Liquids biofuels have high energy density (less so for bio-methane, a gas), and can be used neat or in mixtures. Drop-in biofuels are similar to fossil fuels, requiring no vehicle modifications. Blends are chemically more distinct, requiring (at higher concentrations) modifications to engines and fuel lines. Biodiesel degrades in long-term storage. Bio-energy sources can be feedstocks for synthetic fuels (see below). The following definitions are broadly applicable (but are not applied universally):

First generation (“conventional”) biofuels require comparatively simple processing (e.g. ethanol and biodiesel (FAME) from arable crops, and biodiesel from waste cooking oil). The UK uses blended first generation ethanol and biodiesel from imported and domestic sources. Early sector growth\(^{42}\) caused challenges: possible competition with food crops, life-time GHG emissions\(^{43}\) (including indirect land-use change (ILUC)),\(^{44}\) and air pollution\(^{45}\) (e.g. organics). New policies seek to reduce negative impacts.\(^{46}\) First generation biofuels are likely to play a significant role in some countries (e.g. ethanol in Brazil and the USA, and palm oil biodiesel in Indonesia and Malaysia) for reasons including security of supply, reducing dependence on energy imports, and support for rural economies.

Second generation (“advanced”) biofuels come from non-food sources that require more processing (e.g. solid municipal waste, cellulose from forestry residues). Compared to first generation biofuels, some could have substantially lower life-time GHG emissions, less competition with food crops, higher land use efficiency, and lower ILUC impacts.\(^{47}\) Some air pollution issues would remain. They are at an early development stage, face technical challenges, and are not yet cost competitive.

Third generation biofuels are from algae. They have much higher yields,\(^{48}\) but are at a very early stage. They incur costs, technical constraints (growth conditions), resource use (water, fertilisers), and environmental impacts (e.g. NO\(_x\) from fertilisers); growth at sea would avoid some issues.

- **Light road petrol vehicles** in the UK can use fuels with up to 10% (E10) ethanol (e.g. from UK wheat and sugar beet) without modification; the maximum currently used is 5% (E5).
- **Heavy (and light) diesel road** vehicles can use fuels of up to 7% biodiesel, but the maximum generally used in the UK is 5% (B5). Some fleets are adapted for blends of 20%, 50% or 100%.
- **Rail** locomotives can be adapted for 100% biodiesel, but with reduced engine power and the issue of degradation in storage.\(^{49}\) Since a 2007 trial of a 20% blend, UK work has been limited.
- **Shipping** makes limited use of first generation biofuels due to technical issues\(^{50}\) and uncertain life-time GHG emissions.\(^{51}\) Second and third generation biofuels could be more promising.
- **Aviation** has trialled blends up to 50% without engine modifications (some actually raised the fuel efficiency).\(^{52}\) Research focuses on compatibility and storage of second generation fuels.

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\(^{42}\) EU biofuel use grew 20-fold from 2000 to 2011; see: Re-examining EU Biofuels Policy – A 2030 Perspective (IEEP, 2014)

\(^{43}\) Well-to-Wheel Analysis (European Commission’s Joint Research Centre, 2014)

\(^{44}\) Biofuel crops, indirect land use change and emissions (Friends of the Earth Europe, 2010)

\(^{45}\) See, for example: Exhaust emissions and mutagenic effects of diesel fuel, biodiesel and biodiesel blends (Schröder, 2013)

\(^{46}\) See, for example, proposals to amend the EU’s Renewable Energy Directive and Fuel Quality Directive

\(^{47}\) Sustainable Production of Second-Generation Biofuels (IEA, 2010)

\(^{48}\) Placing microalgae on the biofuels priority list: a review of the technological challenges (Greenwell, 2010)

\(^{49}\) Railways and Biofuel (UIC and ATOC, 2007)

\(^{50}\) Potential of biofuels for shipping (ECOFYS, 2012)

\(^{51}\) Low Carbon Shipping – A Systemic Approach, Final Report (Smith, et al., 2014)

\(^{52}\) Fact Sheet: Alternative Fuels (IATA, 2015)
5.4. Electricity

Electricity provides ~0.01% of road transport energy and ~35% of rail energy (of which ~95% is for passenger trains). Currently, this is a small proportion of UK electricity use, and follows predictable patterns. There are no in-use GHG emissions or pollutants, but there are life-cycle impacts from electricity generation and vehicle production (e.g. toxicity in battery manufacture). External power sources (e.g. cables supplying power on-the-move) allow long range but only on certain routes; whereas on-board batteries limit the range but allow more route flexibility. Research is ongoing into battery safety (e.g. overheating, and risks from high voltages in crash-damaged vehicles). 53

Light road transport can use various types of electric vehicles (EVs). Battery electric vehicles (BEVs) are charged from an external source whilst stationary. BEVs raise the challenge of “range anxiety”, which is caused by low energy density that limits range, and low numbers of charging points that limit route flexibility. The challenge is augmented by the time taken to recharge, and by previous interoperability issues with charging points and payment methods. Options to address issues include: deploying more charging points; rapid (15-20minute) charging technology; battery swapping (limited by lack of standardisation and storage space); range extender combustion engines to recharge batteries on the move; and wireless charging whilst stationary. Hybrid vehicles avoid some or all of these issues. Hybrid electric vehicles (HEVs) use combustion engines for certain conditions, which (along with regenerative braking) recharges batteries. Plug-in hybrid electric vehicles (PHEVs) have the added option of charging from an external source. EVs will affect interactions between the energy and transport sectors, by adding extra electricity demand, shifting demand patterns, and offering some energy storage. These will necessitate combinations of extra network capacity, smarter system management, and new contractual arrangements. GHG emissions depend upon in-use performance, the wider life-cycle (materials, manufacture, and recycling), and factors in the electricity sector (fuel sources, network losses, and whether the energy is marginal load).

Heavy road transport cannot yet realistically use batteries, owing to low energy density, high vehicle mass, and long journeys. Plug-in hybrids have potential, and are being trialled. In the longer term, wired networks could be used: either overhead lines and hybrid diesel engines; or charge on the move from induction coils buried within roads. Such concepts are far from market readiness and would require large infrastructure spending commitments.

Rail already makes use of electricity from networks, primarily for passenger rail. Electric rail can reduce GHG emissions compared to diesel, partly due to more efficient engines, lower mass, and larger carrying capacity, 54 but mainly through decarbonisation of the power sector. GHG emissions reductions also depend upon occupancy levels, and embedded emissions of new infrastructure and stock. 55 Electric rail has lower operating costs than diesel, but higher infrastructure costs. Battery-powered passenger trains 56 and hybrid freight trains 57 are possible, with charging times worked into schedules. More electric rail would increase electricity demand, but this would be more predictable and controllable than for road.

Shipping and aviation cannot use batteries only, but might make use of hybrid technology.

53 See, for example: Lithium-ion based Rechargeable Energy Storage System Safety Research Programs (US NHTSA, 2014)
54 Delivering a Sustainable Railway (DfT, 2007)
55 Comparing environmental impact of conventional and high speed rail (Network Rail, 2009)
56 For the first time in 50years, the UK has a battery-powered timetabled rail service (Harwich to Manningtree).
57 Chinese manufacturer CSR Ziyang has built a diesel-battery hybrid locomotive for use at marshalling yards.
Hydrogen fuel could either be burned in internal combustion engines or used in fuel cells to generate electricity. At point of use, both technologies offer advantages over fossil fuels: greater operational energy efficiency; and much less air pollution, with water being the only by-product. Steam reforming of methane (SMR) (~60-70% efficient) is the most economical method at industrial scale (used in oil refining and fertiliser production), and could be undertaken at small plants for local hydrogen systems. Life-cycle impacts are strongly affected by the production process. The GHG emissions of SMR could be reduced significantly using by using carbon capture and sequestration (CCS), but this has not yet been demonstrated to be cost effective. The lowest GHG emissions are expected from either biomass gasification, or electrolysis using low-carbon electricity. Electrolysis (~60-70%) and has been demonstrated on industrial scales, but is more expensive due to electricity costs. In the longer term, hydrogen could be produced at nuclear power stations via high-temperature electrolysis or thermochemical production. Hydrogen can also be a feedstock for synthetic fuels (see below), and is produced for oil refining processes (e.g. desulphurisation).

Light road vehicles could use hydrogen, in either fuel cells or combustion engines. Hydrogen fuel cell electric vehicles (FCEVs) store hydrogen either as a high pressure gas, or as a gas adsorbed onto a chemical matrix, or as a chemical hydride. Hydrogen fuel cells are already used in some forklift trucks (often seen as a niche for technological development). Widespread adoption would require a refuelling network, supported by: either new pipelines (or repurposed gas networks) to supply hydrogen from central SMR facilities; or electricity and water supplies for on-site electrolysis. One study envisaged 65 refuelling stations situated across the UK early on, increasing to full coverage of 1150 stations.

Heavy passenger road vehicles can use hydrogen. Buses are being trialled in London and Aberdeen. There are currently no commercialised technologies for HGVs: low energy density necessitates bulky storage tanks, and hydrogen is unsuitable for compression ignition (as in diesel engines), but it could be used in turbines, or in dual-fuel hydrogen-diesel engines.

Rail can use hydrogen (“hydrail”), in either internal combustion engines or fuel cells (on which most research has focused). Hydral is seen as a long-term solution, offering advantages over electric rail networks, including: lower costs than electrification; and the ability to produce hydrogen from electricity at off-peak times. Hydral is in a much earlier stage of development than other on-board, lower-carbon fuels (e.g. LNG), but there are examples of research and of light passenger rail being deployed (e.g. the “Dubai Trolley”).

Shipping could possibly use hydrogen fuel cells, drawing on trials of methane fuel cells that have shown advantages (no air pollution, less maintenance), but that are at an early stage.

Aviation has used hydrogen in small aircraft, but it is unlikely to be used for commercial flights due to: low energy density (25% that of jet fuel by volume), the need for extra equipment, costs, embedded GHG emissions, and the climate impacts of water vapour at higher altitude.
5.6. Synthetic fuels

Synthetic fuels can be tailored to mimic existing fuels, and are produced from coal, natural gas or biomass, or by combining hydrogen with atmospheric CO₂. Gas-to-liquid (GTL) processes give fuels that are compatible with existing distribution networks and engines. Synthetic fuels are very pure, and some pollutants are lower (e.g. SOₓ and particulates). GHG emissions depend upon feedstock and processes, and are lower for recycling atmospheric CO₂ (especially with CCS), but coal-to-liquid (CTL) fuels have a high GHG footprint (even with CCS). Synthetic natural gas (SNG) has the in-use impacts of methane. China is producing large volumes of SNG from coal: the SNG is piped to cities where it can be used without adding to urban air pollution, but it has major life-cycle impacts (GHG emissions, water use), although these can be reduced to some extent.

- **Light and heavy road, rail and shipping** can use synthetic fuels. Feedstocks determine the economics; some could be competitive with high oil prices. Life-cycle GHG reductions of ~90% could be achieved using biomass as feedstock and power source, but with low yields.

- **Aviation** could use drop-in synthetic fuels (i.e. with no engine modifications), e.g. Sasol’s CTL fuel (used pure, or blended with kerosene). Kerogen could be an option post-2020.

5.7. Methanol

Methanol is a high-cost liquid fuel, formed from methane, coal or biomass. Compared to ethanol, it has a lower energy density and is more hazardous to handle; compared to LNG, it requires fewer engine modifications. Methanol emits little NOₓ (burns at low temperature), little SO₂ (low sulphur content), and no particulates. GHG emissions depend on feedstock and production methods, and on the use of CCS (although CCS would not fully address GHG emissions for coal-derived methanol).

- **Light road and heavy road** vehicles can use methanol (or blends). It was used widely in the 1990s in the USA, but was withdrawn due to its toxicity, and corn ethanol became popular. It is still used for specialised racing applications (motorbikes and drag cars) due to its purity.

- **Rail** has not considered methanol due to flammability, and because rail has easier options.

- **Shipping** can use methanol, with the same air pollution benefits as LNG, but the advantage of no methane slip. Some scenarios suggest 40-50% market share during 2020-2050.

- **Aviation** cannot use methanol due to its lower energy density and technical challenges, although it could be a feedstock for ketones and alcohols that could fuel aircraft in future.

5.8. Ammonia

Ammonia is made (using the Faber process) for chemical feedstocks and fertilisers (some rural areas have distribution networks). It is gaseous and toxic, its energy density is half that of petrol, and it emits lots of in-use NOₓ. To reduce its upstream GHG emissions requires low-carbon electricity.

- **Light road and heavy road** vehicles can be modified to use ammonia. It can be used neat as a petrol replacement, but only as a blend when replacing (bio-)diesel.

- **Rail, shipping and aviation** have not widely considered ammonia, due to its low energy density and high price relative to conventional fuels.

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67 SBAC Aviation and Environment Briefing Papers: 4: Alternative Aviation Fuels (SBAC)
68 China’s synthetic natural gas revolution (Chi-Jen Yang & Robert B. Jackson, 2013)
69 For example: Improving Process Performances in Coal Gasification for Power and Syntfuel Production (Sudiro et al., 2008)
70 Affordable, Low-Carbon Diesel Fuel from Domestic Coal and Biomass (DoE, 2009)
71 Near-Term Feasibility of Alternative Jet Fuels (RAND, 2009)
72 See, for example: Methanol as a Marine Fuel – The METHAPU project (Lloyd’s Register: Marindagen, 2011)
73 Alternative Shipping Fuels (DNV, 2014)
74 Cost-effective choices of marine fuels under stringent carbon dioxide targets (Grahn et al., 2013)
5.9. Renewables

Renewable energy generation on board vehicles has low energy density and hence limited scope.

- **Light and heavy road transport, rail and aviation** can make limited use of solar power (as per demonstration projects of racing cars and light aircraft, and in Budapest’s “Vill” train), but not for the general transport fleets.

- **Shipping** can use wind to aid propulsion: kites can save ~10-35% on fuel on certain routes.\(^{26}\) Similarly, Flettner rotors are reported to have saved 25% on fuel use for a cargo ship.\(^{26}\)

5.10. Nuclear

Nuclear reactors on board vehicles offer extremely high energy density and hence long range. They can be configured to produce electricity or steam (both have been used for propulsion in military vessels). Wider application is limited due to: capital costs, size (due to operational parameters, economies of scale, and shielding), and risks (radioactive contamination, and weapons proliferation).

- **Light and heavy road transport** cannot use nuclear power, for all of the reasons noted above.

- **Rail** could use small reactors matched to the power needs, and can carry the shielding weight, but concerns remain about the risks. Russia’s RZhD rail company has proposed one project.

- **Shipping** already uses nuclear power for military vessels and ice-breakers. A civilian nuclear-powered cargo-passenger ship (NS Savannah) was launched in 1959, but no more were built due to costs and risks (e.g. due to sinking).\(^{27}\) However, climate change has revived interest in compact nuclear reactors (also called small modular reactors (SMRs)).

- **Aviation** could use small reactors, but the weight of shielding poses a challenge. The USA and Russia conducted stationary trials, but ceased due to risks (to the crews, and in the event of crashes) and lack of success.

5.11. Metals

Burning metals (e.g. iron, boron) can generate sufficient heat to power vehicle engines, including potentially using modified internal combustion engines.\(^{28}\) Given their lower energy density than liquid fossil fuels, metals could require roughly double the weight of fuel. Spent fuel could be regenerated (by applying hydrogen) and re-used, but carrying the spent fuel would use additional energy. These engines operate at very high temperatures and so produce large amounts of NO\(_x\).

- **Light and heavy road transport** could use metals, albeit with the challenges noted above.

- **Rail and shipping** could carry the heavier fuel, but with the associated energy penalty.

- **Aviation** would be less suited to metal fuels, due to the weight and lower energy density.

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\(^{25}\) See, for example: A review of present technological solutions for clean shipping (CNSS, 2011)

\(^{26}\) Rotor sail ship “E-Ship 1” saves up to 25% fuel (Press Release, ENERCON, 2013)

\(^{27}\) Even though safety has improved since 1959, still nowadays — 100 are lost each year (out of — 85,000 ships of at least 100 gross tonnage operating in the world). Source: Lloyd’s List Intelligence Casualty Statistics (data as at January 2015)

\(^{28}\) powdered metal: The fuel of the future (Kurt Kleiner, 2005)
6. Summary and conclusions

There are several energy sources that could replace liquid fossil fuels for transport. From these, the options for each transport mode can be narrowed down by considering key constraints:

- **Technical criteria for each mode**: energy density is important for all modes, but particularly for heavy transport where lower-carbon liquid fuels are likely to be needed.

- **Key priorities for transport sector**: cost, affordability, safety, pollution, and flexibility of operation present complex trade-offs to be weighed-up when considering GHG options.

- **Interactions with wider energy sector**: major energy options could use existing infrastructure (with modifications or repurposing), but all would increase demand for resources.

Drawing together points about energy options in this report, a "confidence-impact matrix" can be created (see Figure 6) representing a view of potential GHG emissions reductions (impact), and the level of confidence of delivering that impact. Impact is graded in terms of overall transport GHG emissions: a low impact could result from partially decarbonising a large mode or fully decarbonising a small mode. The confidence is a judgement about the likelihood of delivering those benefits, including technological development and market uptake. Whilst some options are expected to have large impacts, it is important to pursue contributions from small modes (e.g. cycling). Similarly, whilst some options offer high confidence, less promising options should be monitored in case they offer unexpected impacts as circumstances change. Key points to note from this chart are:

- **Advanced biofuels** offer high confidence of delivering high impact for light and heavy road vehicles (the two largest GHG emissions); (bio-) methane offers less impact for heavy road.

- **Electricity** offers high confidence of delivering impact for light road vehicles (the largest GHG emissions), but the size of the impact depends upon the level of grid decarbonisation.

- **Hydrogen** could offer high impact for road vehicles, but with less certainty about deployment.

The main report for this project considers these three lower-carbon energy options in more detail. It presents scenarios of future transport demand and energy efficiency in order to assess:

- extent of GHG emissions reductions that could rely upon lower-carbon energy options;
- steps required to deliver lower-carbon energy options, and risks facing these steps;
- implications of each option, in particular the interactions with the wider energy sector.

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Figure 6: Impact-confidence chart of lower-carbon energy options for transport.
### Annex: Summary table

<table>
<thead>
<tr>
<th>ENERGY SOURCE</th>
<th>Liquid fossil fuels</th>
<th>1st gen. biofuels</th>
<th>2nd gen. biofuels</th>
<th>3rd gen. biofuels</th>
<th>Synthetic fuels</th>
<th>Methanol</th>
<th>Ammonia</th>
</tr>
</thead>
<tbody>
<tr>
<td>REPORT SECTION</td>
<td>5.1</td>
<td>5.3</td>
<td>5.3</td>
<td>5.3</td>
<td>5.6</td>
<td>5.7</td>
<td>5.8</td>
</tr>
<tr>
<td>TRANSPORT MODE</td>
<td></td>
<td></td>
<td></td>
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<td></td>
<td></td>
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</tr>
<tr>
<td>Road (light)</td>
<td>High energy density; rapid refuelling</td>
<td>High energy density; rapid refuelling</td>
<td>High energy density; rapid refuelling</td>
<td>As fossil fuels; but R&amp;D at early stage</td>
<td>As fossil fuels; but R&amp;D at early stage</td>
<td>Enough energy density; rapid refuelling</td>
<td>Enough energy density; rapid refuelling</td>
</tr>
<tr>
<td>Road (heavy)</td>
<td>High energy density; rapid refuelling</td>
<td>High energy density; rapid refuelling</td>
<td>High energy density; rapid refuelling</td>
<td>As fossil fuels; but R&amp;D at early stage</td>
<td>As fossil fuels; but R&amp;D at early stage</td>
<td>Enough energy density; rapid refuelling</td>
<td>As light road &amp; must be blended</td>
</tr>
<tr>
<td>Rail</td>
<td>High energy density; rapid refuelling</td>
<td>As fossil fuels; &amp; long storage degrades fuel</td>
<td>High energy density; rapid refuelling</td>
<td>As fossil fuels; but R&amp;D at early stage</td>
<td>As fossil fuels; but R&amp;D at early stage</td>
<td>Enough energy density; rapid refuelling</td>
<td></td>
</tr>
<tr>
<td>Shipping</td>
<td>High energy density; rapid refuelling</td>
<td>Technical issues limit use</td>
<td>As fossil fuels, but R&amp;D at early stage</td>
<td>As fossil fuels; but R&amp;D at early stage</td>
<td>As fossil fuels; but R&amp;D at early stage</td>
<td>Enough energy density; rapid refuelling</td>
<td></td>
</tr>
<tr>
<td>Aviation</td>
<td>High energy density; rapid refuelling</td>
<td>As fossil fuels; &amp; long storage degrades fuel</td>
<td>As fossil fuels; &amp; ongoing R&amp;D</td>
<td>As fossil fuels; but R&amp;D at early stage</td>
<td>As fossil fuels; but R&amp;D at early stage</td>
<td>Too low energy density</td>
<td>Too low energy density</td>
</tr>
<tr>
<td>INTERACTIONS</td>
<td></td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Availability of fuel</td>
<td>Abundant, but climate action could limit use</td>
<td>Limited arable land; limited waste sources</td>
<td>Limited land area; large waste sources</td>
<td>Large potential (but small scale now)</td>
<td>Large potential (but small scale now)</td>
<td>Small current manufacturing capacity</td>
<td>Produced in large volumes currently</td>
</tr>
<tr>
<td>Competition for fuel</td>
<td>Limited (transport is main user)</td>
<td>Potential food competition</td>
<td>Land &amp; wood use; waste for heat &amp; power</td>
<td>Water use; land use (unless at sea)</td>
<td>Alternative use of fuels</td>
<td>Alternative use of fuels</td>
<td>Chemical industry &amp; agriculture</td>
</tr>
<tr>
<td>Use of infrastructure</td>
<td>Uses current manufacturing &amp; distrib'n</td>
<td>Uses current manufacturing &amp; distrib'n</td>
<td>Use current distrib'n; new manufacturing</td>
<td>Use current distrib'n; new manufacturing</td>
<td>Use current distrib'n; new manufacturing</td>
<td>Use current manufacturing; new distrib'n</td>
<td></td>
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<tr>
<td>TECHNICAL REQUIREMENTS FOR MODES</td>
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<tr>
<td>Cost &amp; Affordability</td>
<td>Fuel price volatility</td>
<td>Price is volatile &amp; higher than fossil fuels</td>
<td>High fuel price currently</td>
<td>High fuel price currently</td>
<td>High fuel price currently</td>
<td>High fuel price currently</td>
<td>High fuel price currently</td>
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<tr>
<td>Safety</td>
<td>Flammability &amp; toxicity are managed</td>
<td>Flammability &amp; toxicity are managed</td>
<td>Flammability &amp; toxicity are managed</td>
<td>Flammability &amp; toxicity are managed</td>
<td>Toxic &amp; highly flammable</td>
<td>Toxic</td>
<td></td>
</tr>
<tr>
<td>Pollution</td>
<td>In-use SO₂ &amp; NOx &amp; particulates</td>
<td>In-use part.s, organics &amp; NOx; lower SO₂</td>
<td>In-use part.s, organics &amp; NOx; lower SO₂</td>
<td>In-use as 2nd gen.; &amp; NOx from fertilisers</td>
<td>Low levels in-use</td>
<td>Very low levels in-use</td>
<td>High in-use NOx</td>
</tr>
<tr>
<td>Climate (life-cycle GHG)</td>
<td>High in-use CO₂; some from refining</td>
<td>Depends on method (some high)</td>
<td>Depends on method (some very low)</td>
<td>Low (but early R&amp;D)</td>
<td>Low (but with complex processing)</td>
<td>Low (if use bio / waste or have CCS)</td>
<td>High in-use NOx; some upstream</td>
</tr>
</tbody>
</table>

**Figure 7:** Table of energy options for transport modes, summarising points from this report about key criteria: technical requirements for each mode (primarily energy density to allow sufficient range); key priorities for transport sector (Section 3); and interactions with wider energy sector (Section 5). The interaction of “life-cycle energy efficiency” is not noted in this table; it is studied in more detail in Phase Two of this project. Energy options are grouped according to shared characteristics.
if substantive issues are addressed; (red) is not satisfied and hence the fuel is not an option for that mode.

Colours indicate for each fuel whether a criteria: (green) is satisfied with only minor issues; (orange) could be satisfied (e.g. liquid fuels); in Section 5 the main options are listed first, followed by options that appear to be less viable or impactful. Colours indicate for each fuel whether a criteria: (red) is not satisfied and hence the fuel is not an option for that mode.

<table>
<thead>
<tr>
<th>Gaseous fossil fuels</th>
<th>Electric hybrid</th>
<th>Plug-in hybrid</th>
<th>Battery</th>
<th>Charge-on-the-move</th>
<th>On-board renewables</th>
<th>Other energy sources</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hydrogen</td>
<td>Hydrogen</td>
<td>Hydrogen</td>
<td>Battery</td>
<td>Lower energy density; slower charging</td>
<td>High energy density; needs no refuelling</td>
<td>Solar &amp; wind not practical in most cases</td>
</tr>
<tr>
<td>Gaseous fuels</td>
<td>(Part) electric</td>
<td>(Part) electric</td>
<td>Battery</td>
<td>Charge-on-the-move</td>
<td>Sun &amp; Wind</td>
<td>Nuclear</td>
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<td>5.2</td>
<td>5.5</td>
<td>5.4</td>
<td>5.4</td>
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<td>5.10</td>
</tr>
<tr>
<td>5.11</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Metals</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Fuel price volatility</th>
<th>High fuel price currently</th>
<th>High vehicle cost</th>
<th>High vehicle cost &amp; charging infrastructure</th>
<th>High vehicle cost &amp; charging infrastructure</th>
<th>High cost of new infrastructure</th>
<th>Networks are impossible</th>
<th>Wind can give meaningful energy savings</th>
<th>Very high energy density</th>
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<th>Very high energy density</th>
<th>Enough energy density</th>
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</thead>
<tbody>
<tr>
<td>Flammable &amp; pressurised</td>
<td>Flammable &amp; pressurised</td>
<td>Low risk from battery fires &amp; high voltages</td>
<td>Low risk from battery fires &amp; high voltages</td>
<td>Low risk from battery fires &amp; high voltages</td>
<td>Manageable, similar to electric rail</td>
<td>No particular issues</td>
<td>Radiation risk &amp; weapons proliferation</td>
<td>No particular issues</td>
<td>No particular issues</td>
<td>No particular issues</td>
<td>No particular issues</td>
<td>Enough energy density</td>
</tr>
<tr>
<td>Low levels in-use</td>
<td>Very low levels in-use</td>
<td>Low in-use; toxicity in battery manu.</td>
<td>Low in-use; toxicity in battery manu.</td>
<td>Low in-use; toxicity in battery manu.</td>
<td>Low in-use; toxicity in battery manu.</td>
<td>None in-use</td>
<td>Radiation risks</td>
<td>High NOx in-use</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>In-use CO₂, &amp; methane slip; refining</td>
<td>Low (with CCS, low-C elec. &amp; biogas)</td>
<td>Depends on fuel &amp; elec. generation</td>
<td>Depends on fuel &amp; elec. generation</td>
<td>Depends on fuel &amp; elec. generation</td>
<td>Depends on electricity generation</td>
<td>None in-use; low embedded</td>
<td>None in-use; some upstream</td>
<td>In-use NOx; some upstream</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Abundant, but climate action could limit use</td>
<td>Large sources (methane, water)</td>
<td>Could use range of fuels</td>
<td>New elec. generation needed</td>
<td>New elec. generation needed</td>
<td>New elec. generation needed</td>
<td>Wind on some sea routes (but not all)</td>
<td>Limited mineral resources</td>
<td>Abundant mineral resources</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Heat &amp; power generation</td>
<td>Refining; other sectors in future maybe</td>
<td>Less competent due to higher efficiency</td>
<td>Power customers</td>
<td>Power customers</td>
<td>Power customers</td>
<td>No competition</td>
<td>Power sector, medical uses, military uses</td>
<td>Many uses, but abundant</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Use current sources; adapt networks</td>
<td>New / adapted networks; new manufacturing</td>
<td>Use current manufacture &amp; networks</td>
<td>Need some extra / smarter distribution</td>
<td>Need much extra / smarter distribution</td>
<td>Need much extra / smarter distribution</td>
<td>No need for infrastructure</td>
<td>Expand current manufacture &amp; distribn</td>
<td>Use current manufacture, new distribn</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

(e.g. liquid fuels); in Section 5 the main options are listed first, followed by options that appear to be less viable or impactful. Colours indicate for each fuel whether a criteria: (green) is satisfied with only minor issues; (orange) could be satisfied if substantive issues are addressed; (red) is not satisfied and hence the fuel is not an option for that mode.

Annex: Summary table

21
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