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Energy Options for Transport: Deployment and Implications

ERP
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The Energy Research Partnership

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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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Executive Summary

Options for future transport energy

This report provides a high-level perspective on issues that should be considered when making decisions about transport's future energy options, including the implications for the wider energy sector and the steps required for deployment. The report reviews options for reducing transport's greenhouse gas (GHG) emissions, focussing on road transport (the largest contributor to the UK's transport GHG emissions), but noting interactions with other modes (rail, shipping and aviation) including utilising advances in technologies and fuels. The report presents scenarios of possible decarbonisation routes for road transport, focussing on:

- Internal combustion engine vehicles (ICEVs) using liquid fuels (and some gas for HGVs), and transitioning to hybrids; and then plug-in hybrid electric vehicles (PHEVs) that use some electricity;
- Battery electric vehicles (BEVs) being deployed more rapidly;
- Hydrogen fuel cell electric vehicles (FCEVs) being deployed more rapidly.

Strategic considerations

The report does not seek to promote any particular solution. The scenarios highlight the implications of using each energy option, and highlight key steps that would be required to deploy each. Actions could be taken to manage the implications and to reduce the delivery challenges, but issues and risks would remain. Decisions on transport decarbonisation will be a matter of judgement, weighing up the implications and risks alongside other policy objectives. This report brings together strategic considerations to help in this debate, as follows:

Wider decarbonisation

Efforts to decarbonise transport must be seen in the wider context of decarbonising all sectors, so that overall outcomes can be optimised. Different decarbonisation strategies offer differing levels of impact; more ambitious transport options will have to be considered if other sectors face harder challenges. A major example is that decarbonising heavy transport (road freight, rail, shipping and aviation) will likely require liquid fuels with low life-cycle GHG emissions; but sustainable bio-energy resources are limited, and if it was judged that they were better used in other sectors, then heavy transport might need to be given "leeway" through deeper GHG emissions cuts elsewhere.

Primary energy consumption

Each energy option would increase consumption for particular resources (e.g. biomass or natural gas); and uses with high conversion losses could potentially increase the UK's primary energy consumption. There would be logistical challenges in increasing and reconfiguring the supply chains, and potential network operation challenges depending upon the superimposition of energy consumption profiles. There is a strategic risk in the UK relying upon a smaller number of energy vectors (e.g. natural gas) for more of its critical sectors (heat, power, transport), but this risk could be mitigated by diversity of supply sources.

Deployment and performance

Two recurring themes to be weighed up are: challenges of deploying infrastructure (including timing and cost), and performance of vehicles (taking into account potential benefits, and steps that have to occur). Considerations include:

- ICEVs require less new infrastructure, but their impacts could be harder to ensure (via vehicle development and regulation); whereas BEVs and FCEVs require more new infrastructure, but their impacts could be easier to ensure (via regulation of upstream energy processing).
- Impacts include in-use GHG emissions, co-benefits (e.g. air quality with BEVs and FCEVs, and fuel flexibility with PHEVs), and embedded impacts (e.g. batteries and light-weight materials reduce in-use impacts, but increase embedded impacts, so net life-cycle impacts are affected by vehicle mileage and industrial GHG intensity).
- Infrastructure requirements are not mutually-exclusive, but timings differ between scenarios. For example, electrical infrastructure needed for BEVs would also eventually be needed for PHEVs in an ICEV scenario; there could be efficiencies in doing this work earlier (facilitating BEVs) alongside the ongoing programme of network upgrades, or logistical challenges could be reduced by deferring work (facilitating later PHEV uptake). Similarly, BEVs might need liquid fuels for range-extenders (REs), requiring liquid fuel infrastructure for the longer term.
- Whilst total cost is a major consideration, an option with the best chance of success might not be least-cost. To be considered viable, an option must be workable from engineering, financial and customer perspectives: it must be practical and affordable, and consistent with decarbonisation options for other sectors. Successful options will be those that are commercially-viable and marketable. Customer decisions could direct the sector down a particular route irrespective of wider infrastructure requirements. Infrastructure projects would be paid for through combinations of taxes and bills; the financial flows will become more complicated due to changes in models of ownership and use. The allocation of payments will come down to policy judgements about distributional impacts.

Steps to mitigate challenges and implications

Action could be taken to overcome the challenges to deployment, and to manage the implications including the interactions with the wider energy sector. These actions can be grouped as follows:

Research is required to improve energy options:

- Light-weight materials to reduce fuel consumption, with reduced embedded impacts; there are links with aviation.
- New low-carbon liquid fuels (preferably drop-in liquid fuels that would avoid the need for modifications to infrastructure and vehicles), in particular for heavy road transport; there are links with shipping and aviation.
- Improvements in battery performance (range and/or charging time).
- Trials by energy network companies of solutions to address the impacts of transport on the energy networks, with the regulator facilitating third-party project leadership where needed.
- Comparison of transport and energy sector assumptions that underpin scenarios and policies.
- Impacts on demand for transport services due to automation and changes in vehicle ownership, use and logistics.
- Customers' perceptions of light-weight vehicles.

Regulations and incentives are required to drive uptake of options and delivery of their benefits:

- Regulations for GHG emissions are needed to drive ICEV improvements and uptake of alternatives; tests need to be realistic, independently-verified, and should be co-ordinated with air quality tests.
- Incentives would be needed for advanced biofuels (and for bio-methane for HGVs): to significantly increase UK production of bio-energy crops and to divert waste streams to energy production; and to draw in sufficient of those bioenergy resources to the transport sector.
- PHEV operation requires incentives for optimal operation, to avoid the risk of fossil fuels displacing lower-carbon electricity; but by the same token PHEVs offer dual-fuel flexibility for users and systems operators.
- Innovations in communications and commercial arrangements are needed to allow smaller freight operators to engage in logistics efficiency schemes.

Strategic infrastructure decisions are needed to facilitate energy options:

Liquid fuels and (bio-)methane:

- If liquid fuels with high blends of biofuels are used (but not drop-in liquid fuels that closely mimic fossil fuels), then co-ordination will be needed to modify vehicles and fuel distribution infrastructure, and to optimise the selection of fuels at fuelling stations.
- Reduced sales of liquid fuels could threaten the universal coverage of refuelling stations (including in some rural areas), and increase costs for customers that continue to use liquid fuels (that could be mainly hauliers and poorer customers).
- Methane or bio-methane for HGVs would need a strategy to deploy infrastructure for fuelling stations, including extending the networks to the sites and potentially installing compressors on the sites.

Electricity:

- Further grid decarbonisation is needed to deliver GHG benefits of BEVs and PHEVs; higher generation capacity would be needed to support large deployment of EVs and PHEVs; both points apply to FCEVs if using hydrogen from electrolysis.
- Electricity infrastructure changes for transport could be co-ordinated with other changes to the electricity system: undertaking transport changes earlier (to facilitate uptake of BEVs) could offer some cost efficiencies; or undertaking transport work later (to facilitate later use of PHEVs) could reduce logistical challenges.

Hydrogen:

- Hydrogen production by steam methane reforming (SMR) of (bio-)methane would need deployment of centralised SMR facilities and CO_2 infrastructure.
- Hydrogen production by electrolysis would require more low-carbon electricity generation and possibly more electricity network capacity (unless not grid connected).
- Hydrogen distribution from centralised facilities could be most efficiently done by repurposing low-pressure gas distribution networks, with some grid extensions to non-urban fuelling sites and compressors at fuelling sites; repurposing would have to take into account the needs of gas users and the potential for bio-methane.

Carbon Capture and Storage (CCS):

- Deployment of CO_2 pipelines and mapping of CO_2 storage sites are needed to facilitate CCS for various transport options: producing certain liquid fuels, producing hydrogen using SMR, flexible low-carbon power, and reducing industrial emissions for vehicle manufacturing.

Introduction

The UK's transport sector needs to reduce its energy consumption and greenhouse gas (GHG) emissions intensity of its energy, in order to contribute to the UK's overall target of 80% cuts by 2050 (compared to 1990 levels). The level of decarbonisation required in transport will depend upon its options and how they compare with those in other sectors. These challenges are made greater by growth in demand for transport services: central scenarios for UK road transport suggest increases from 1990 to 2050 of ~50% for passenger travel and freight. Furthermore, decarbonisation is taking place in the context of addressing other key priorities, notably air pollution, costs and safety.

The Annex to this report reviews the different energy options for transport, to explain why there is a focus on four main options: liquid fuels, natural gas (and bio-methane), hydrogen and electricity. This main report explores potential GHG emissions cuts, including whether they could approach 80% cuts from 1990. It considers the implications of the options, in particular the interactions with the wider energy sector. It seeks to give a high-level perspective on issues that should be considered when making decisions about the energy options; it does not seek to make a judgement about which is the "best" option. It recognises the relative impacts of different energy options (including the likely extent of changes to vehicles, user experience and infrastructure); but detailed comparison of these factors (e.g. costs) is not in the scope of this report. Both approaches are necessary for making decisions about future energy options for transport: the high-level perspective ensures that all relevant factors are considered; and specific engineering and economic studies are needed for detailed evaluation. Ultimately, the decision is a matter of policy judgement, based on the wider context of transport and energy policy, with their range of objectives.

This report focusses on road transport: light road vehicles (cars and vans) make the largest contribution to the UK's GHG emissions from transport; and heavy road vehicles (freight) make the second largest contribution, and face similar challenges as other heavy transport modes (off-road, rail, shipping and aviation). This report notes opportunities for modes to share advances in technology and fuels (mainly between heavy transport modes, but also with light road transport); it also notes energy requirements from multiple modes (and other sectors) for limited resources. For simplicity, light road transport is used as a proxy for road passenger transport, and heavy road transport as a proxy for road freight transport. Vans face similar issues and opportunities to cars, albeit their use interacts with HGVs; and buses can use a combination of options available to cars and HGVs. Data sets are presented as percentages of 1990 values, the baseline for the UK's target to reduce GHG emissions by 80% by 2050.

This report separates out the GHG impacts of energy vectors and the embedded GHG impacts of vehicles and infrastructure. Whilst these all must be considered for life-cycle assessments, they are addressed by different policies for transport and industrial manufacturing. The report focusses on the GHG impacts of transport energy vectors, including their use in vehicles and their upstream processing.[1] Finally, the report discusses certain wider environmental and social impacts.[2]

The report is structured as follows:

- Section 2 presents future transport scenarios, key demand segments, and historical GHG emissions intensities.
- Section 3 presents three scenarios of future road transport energy, in order to identify key steps required:
  - Internal combustion engine vehicles (ICEVs) using liquid fuels (and some gas for HGVs), and transitioning to hybrids; and then plug-in hybrid electric vehicles (PHEVs) that use some electricity;
  - Battery electric vehicles (BEVs) being deployed more rapidly;
  - Hydrogen fuel cell electric vehicles (FCEVs) being deployed more rapidly.
- Section 4 considers the key steps in the scenarios, in order to identify the challenges that need to be overcome to deliver these steps, and the implications of these energy options (in particular for the wider energy sector).
- Section 5 summarises the main strategic considerations that must be weighed up in decisions about future energy options, and notes actions that could be taken to address the implications of the energy options and the risks to their deployment.
- Annex (separate paper) presents an overview of energy options, explaining the selection of the main energy options presented in this main report.

[1] The terms "in-use", "tailpipe" and "tank-to-wheel" (TTW) are interchangeable, as are "upstream" and "well-to-tank" (WTT).

[2] This report considers tailpipe NO_x emissions, social impacts of fuel distribution, and social inclusion due to mobility. It does not consider other environmental and social impacts e.g. tailpipe particulates, rural land-use, bio-diversity, ambient noise, and resource depletion.

2. Transport services

This section presents examples of data that are useful for developing scenarios of future road transport. It presents historical data (demand for transport services, and GHG emissions intensity) that serve as baselines from which to measure future changes; future scenarios of demand for UK road transport services (a key input to scenarios); and some examples of how road transport segmentation affects energy options.

2.1 Demand for road transport services

Figure 1 shows total demand for road transport services for passengers and freight, measured in passenger-km (p-km) and tonne-km (t-km), and as percentages of the 1990 values.[3] Historically, UK demand for road transport services has risen consistently up until the present, apart from some falls in freight transport during economic downturns. Most commentators anticipate that UK demand for transport services (across all modes) will continue to grow over the coming decades, due to increases in population and wealth. Population growth will increase the overall demand for passenger transport, and will also increase a need for freight transportation for goods and services. Greater wealth would magnify the population effect, and could shift the distribution of passenger transport towards modes with higher costs and in some cases greater impacts.

The key observation is that UK demand for road transport services is expected to grow out to 2040; extrapolation to 2050 of central scenarios suggests ~50% increases from 1990 demand levels for both passengers and freight. However, there is uncertainty about how emerging models for ownership and use will affect demand for transport services.[4] Economic imperatives are acting to change (and blur) the segmentation of demand, potentially playing a major role in reducing the impacts of mobility: in-use impacts could be reduced by higher occupancy under different ownership models; and embedded impacts could be reduced by higher occupancy and utilisation that would require fewer vehicles.

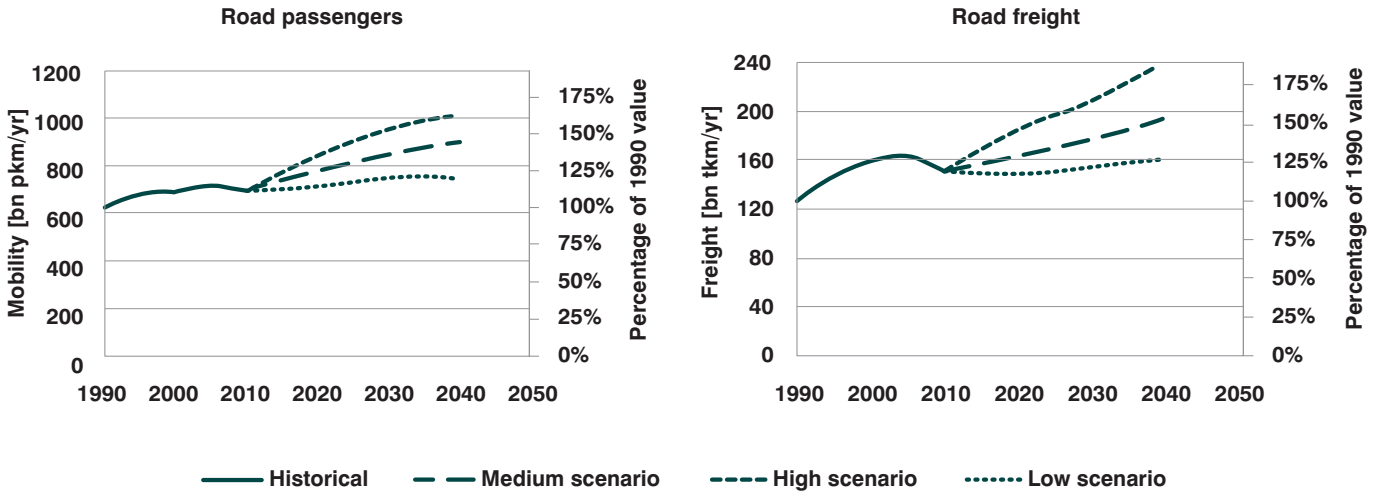

Figure 1: *Historical data and future scenarios for UK road transport: (left) passenger mobility, and (right) freight transportation.[5] Data is for total demand for road transport services (i.e. light road and heavy road transport); passenger travel is mostly by cars, and freight is mostly by HGVs.*

[3] It is interesting to compare passenger transport and freight, and vehicles and their contents. If a passenger and accessories weigh ~100kg, and occupancy is ~1.6, then passenger transport in 1990 of 600billion p-km equated to ~60billion t-km, ~50% that of freight. Vehicle weight is considerably more than the contents being transported: a typical car of 1.2tonnes is ~7.5x that of 1.6 passengers; a typical van of 2tonnes is ~7.5x that of a driver plus average 180kg of contents; and a typical HGV of ~13tonnes is ~2x the driver plus average 6tonnes of freight. Sources include: Tables TSGB0101, TSGB0401 & TSGB0405 (DfT, 2015)

[4] Understanding the drivers of road travel: current trends in and factors behind roads use (DfT, 2015); and: Meeting Carbon Budgets – Progress in reducing the UK's emissions, p126-127 (CCC, 2015)

[5] Based on data from: Road Traffic Forecast 2015 (DfT, 2015) and Table TSGB0101 (DfT, 2015)

2.2. Segmentation of demand for road transport services

Energy options for road transport can be affected by segmentations of the demand for road transport services, some of which are presented in Figure 2. A major segmentation of road freight is between HGVs on trunk routes (motorways and rural A-roads), and vans on urban routes. The majority (~90%) of road freight is by HGVs, but only ~10% of their distances are travelled in urban areas. In urban areas, HGVs account for ~10% of freight vehicle distances, but they transport the majority of the freight.[6] This is relevant when planning logistics schemes such as transferring freight to vans for urban trips: that would require many more vans than at present (unless utilisation was increased form current low levels).

Trip length is relevant for BEVs. Average car occupant mileage is ~20miles per day, and ~90% of car and van distances are in trips of up to 100miles (covering 99% of their trips). Mass-market BEV range is ~100miles; newer models offer ~200miles;[7] and expensive models with larger batteries offer ~300miles.[8] By these measures, mass-market BEVs could be used for most passenger car transport; and they could be charged overnight at home (with no inconvenience to users, and with limited impact upon the electricity system). However, this regime does not work for certain demand segments: the longest 1% of trips (and some others at higher speeds using more energy per km); days with a large total distance; and "contingency charging".[9] In terms of access to charging facilities, cars travel ~40% of their distances in urban areas, and ~45% on trunk roads, both of which have growing networks of charging points. In terms of charging duration, slow charging is an option for regular trips separated by several hours e.g. commuters; and rapid charging is needed for other segments, but it does still require longer breaks during (or between trips) than liquid refuelling of ICEVs.[10] There are examples of vehicle performance and user behaviour "meeting in the middle", e.g. travelling workers with high daily and annual mileages who have made charging into a virtue by scheduling tasks for remote working at service stations.[11] Unless there is a technological breakthrough to reduce charging to just a few minutes,[12] some segments of demand will need alternative solutions: e.g. EVs that are augmented to permit longer distances (e.g. PHEVs or BEV-range-extenders (REs), or dedicated ICEVs for certain trips.

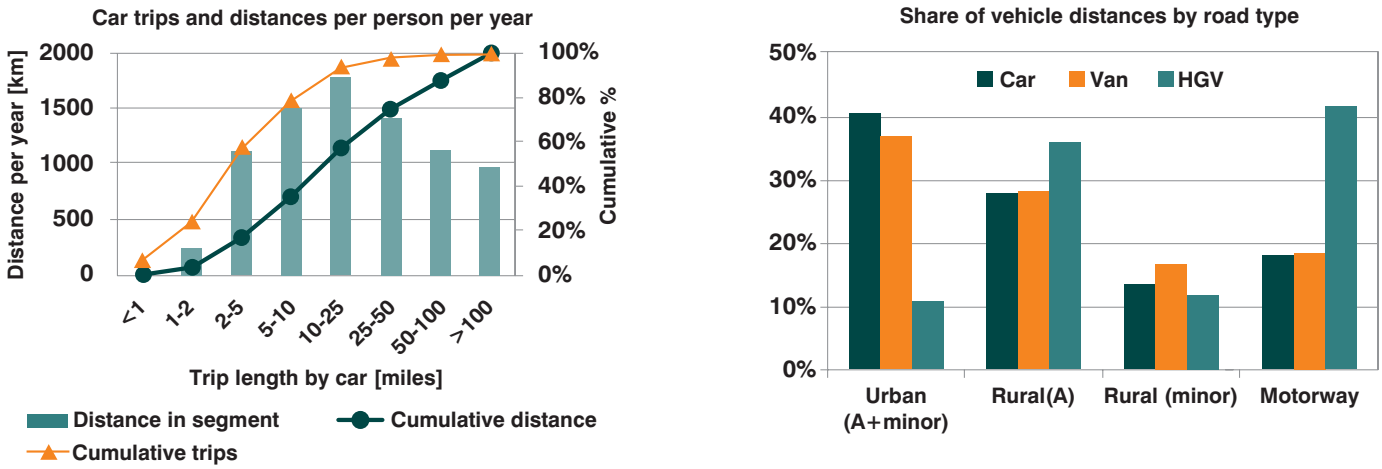

Figure 2: *(left) car and van passenger travel in England in 2014, segmented by trip length:[13] (right) car and freight distances in GB, segmented by road type.[14]*

[6] As noted earlier, average freight carried is ~180kg per van and ~6tonnes per HGV.

[7] See, for example, the Chevrolet Bolt with 200mile range (not available in the UK).

[8] See, for example, the Tesla Model S (stated range over 330miles) and the proposed Porsche Mission E.

[9] Range anxiety is often cited as the biggest issue with BEVs. Anxiety can seem unwarranted by the length of most trips, and what can matter more is the recharging event itself: whether facilities will be available, and the timing (e.g. during a trip) and duration of charging.

[10] The duration of charging scales with the battery capacity; rapid chargers work at several kW, and recharging takes tens of minutes. By comparison, fuel pumps for ICEVs (or FCEVs) have ~10MW flows, and fuelling takes a few minutes.

[11] Rapid Charge Network – Activity 6 Study Report (RCN, 2016)

[12] A plausible option (but still in early stages) is flow-cell batteries, which could be recharged by replacing the liquid electrolytes.

[13] Analysis based on data in Table NTS0308 (DfT, 2015). Trip data is for England only, but is assumed to be similar across the UK. Analysis includes assumptions, e.g. distance travelled is mid-point of each segment (and 125miles for >100miles segment).

[14] Analysis based on data in Table TRA2506a (DfT, 2016). Data is for Great Britain, but is assumed to be similar across the UK.

2.3. Historical GHG emissions intensities

Figure 3 illustrates top-down estimates[15] of the historical energy intensity and GHG emissions intensities for road passenger transport and road freight transport in the UK.[16] The data is presented per p-km and per t-km (e.g. values per passenger are smaller than per car by a factor of 1.6, the average occupancy). Trends for energy and GHG emissions are linked because reductions in the GHG emissions intensity have largely been due to the improved energy efficiency of vehicles. Low-carbon fuels (e.g. certain biofuels) have contributed, but to a small degree thus far; increased use in future would cause GHG emissions intensity to fall more rapidly than energy intensity. Figure 3 shows three key categories of impacts:

- **Tank-to-wheel (TTW):** In 1990 the energy intensity and tailpipe CO_2 emissions were ~0.45kWh/p-km and ~140gCO_2/p-km for road passenger transport (dominated by cars), and ~0.9kWh/t-km and ~270gCO_2/t-km for road freight (dominated by HGVs). Up to 2014 intensities have fallen for passengers by ~20% (to ~0.35kWh/p-km and ~110g/p-km), but have not fallen for road freight.[17]

- **Well-to-tank (WTT):** Typical values for liquid fossil fuels are ~10-20% of the total well-to-wheel energy requirements, i.e. ~0.5kWh/p-km and ~1kWh/t-km in 1990. Assuming that this upstream energy consumption is met by fossil fuels, then well-to-wheel (WTW) GHG emissions intensities were ~160 gCO_2/p-km and 330gCO_2/t-km.[18]

- **Embedded impacts:** This is a new area of research for car manufacturers, and it requires further development. Embedded impacts of ICEV cars have been estimated as ~20% of the life-cycle energy and GHG emissions;[19] in the UK they have reduced since 2005 to ~15% of life-cycle impacts. There is limited data for embedded impacts in 1990; a reasonable assumption might be that they were similar in magnitude to those in 2005 before the industry made specific efforts to reduce the impacts.[20] There is limited data available about HGVs' embedded impacts; a reasonable assumption is that HGVs' embedded impacts constitute a smaller percentage than for cars.[21]

Life-cycle impacts depend upon life-time mileages of vehicles: e.g. in order for BEVs to provide a net benefit compared to ICEVs, they must exceed a critical mileage such that their lower in-use emissions can offset their higher embedded impacts.

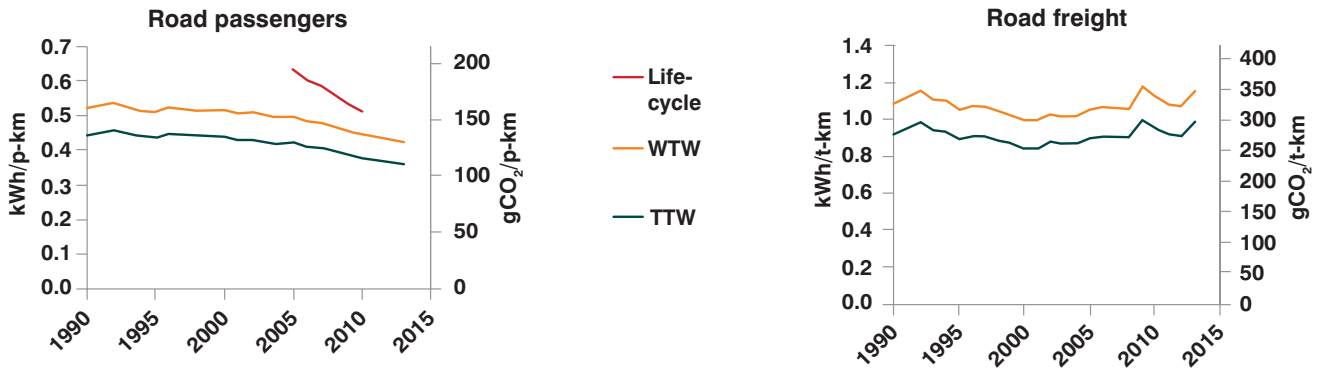

Figure 3: *Energy intensities and CO_2 intensities of road passenger and freight transport,[22] showing TTW, WTW (sum of TTW and WTT), and life-cycle (sum of WTW and embedded) where data is available.*

[15] Emissions intensities can be estimated using a top-down approach (using fuel sales and traffic models) or a bottom-up approach (using vehicle tests). There are discrepancies between these two approaches for UK data, and DfT has a programme of research to improve the evidence; see: Understanding the drivers of road travel: current trends in and factors behind roads use (DfT, 2015)

[16] Some data applies only to GB or only to England, but the main messages apply across the UK.

[17] This more level HGV trend could be because HGVs have always been more efficient than cars (due to financial pressures) and hence have had less potential for improvement. However, it could also be due to models having an inaccurate allocation of fuel sales between passengers and freight, which DfT is investigating. The peak for freight in 2008 was possibly due to the recession causing lower goods demand and hence lower vehicle utilisation.

[18] WTT emissions for fossil fuels include energy consumption for extraction and processing, and GHG impacts of flaring and methane venting. See for example: Methane and CO_2 emissions from the natural gas supply chain – An evidence assessment (SGI, 2015)

[19] Electric Powertrains: Opportunities and Challenges in the U.S. Light-Duty Vehicle Fleet (MIT, 2007)

[20] Embedded impacts are estimated as ~10% for manufacture, and ~5% for disposal and recycling; see, for example: 2015 Automotive Sustainability Report – 16th edition - 2014 data (SMMT, 2015); and End-of-Life Vehicle (ELV) processing (SMMT, 2011)

[21] Compared to cars, HGVs typically have ~10x the mass (hence higher embedded impacts and fuel demand per km), but travel >10x as far over their lifetimes. So, an HGV's embedded impacts could be ~10x that of a car, and its lifetime fuel use would be >10x that of a car, so it is likely that its embedded impacts constitute a smaller percentage of life-cycle impacts.

[22] Data from: Tables TSGB0101, TSGB0401, TSGB0405 (DfT, 2015); Tables 3 & 8, Final UK greenhouse gas emissions national statistics 1990-2013 (DECC, 2013); and 2015 Automotive Sustainability Report – 16th edition - 2014 data (SMMT, 2015)

3. Scenarios of UK road transport options

This section presents illustrative routes for decarbonising transport. The scenarios focus on light and heavy road transport (the largest contributors to transport GHG emissions), and highlights key issues for other transport modes (which have some similarities to heavy road transport). The scenarios explore options for an 80% cut in road transport GHG emissions: the UK does not have sector-specific GHG targets, but it is informative to use this 80% cut as a basis, including to identify aspects of road transport that could potentially exceed it or that could struggle to meet it.

Published scenarios of transport decarbonisation have an apparent consensus that road transport in 2050 will use mainly electricity or hydrogen, with additional options for heavy road transport.[23] The scenarios presented here consider possible routes for getting to that point: each scenario focusses on a greater role for one technology, with less use of the others.

1. **ICEV Evolution:** ICEVs and liquid fuels are used extensively; other vehicle types are used in smaller numbers; ICEVs become increasingly efficient and hybridised; liquid fuels have increasing proportions of biofuels / synthetic fuels, and (bio-) methane is used for HGVs; ICEV-hybrids evolve into PHEVs.

2. **Electric Transition:** BEV uptake is accelerated in the 2020s; grid mix GHG intensity continues to fall; BEV range increases due to battery improvements and/or range extenders (REs); charging duration decreases (or is accommodated by users); freight uses PHEVs for urban trips and eventually charge-on-the-move on main roads.

3. **Hydrogen Transition:** FCEV uptake for light and heavy road transport grows significantly in the 2020s as part of early move to a "hydrogen economy" (including heating, energy storage, etc.).

The scenarios consider three main factors, estimated in terms of their value in 1990 (the baseline year for GHG reductions): demand for road transport services; energy efficiency of technologies; and life-cycle GHG emissions intensity of energy vectors. The scenarios split up the life-cycle GHG impacts, focussing on the impacts of fuels (in-use and upstream) that can be addressed by transport policy and technology, but also noting the embedded impacts (manufacture, disposal and recycling) of vehicles and infrastructure that can be addressed by industrial and construction policy. The scenarios highlight specific improvements that experts have identified; they do not include more general year-on-year improvements that can occur with any technology. The scenarios factor in the ~10-15year lifetime of vehicles:[24] this introduces a lag between improvements being implemented in new vehicles and being seen across entire transport modes.

The scenarios are deliberately narrowly-focussed and ambitious in order to highlight each option's potential for GHG reductions and the key steps that would be required. These key steps are discussed in Section 4, providing more detail about the challenges for delivery, and also the implications including interactions with the wider energy sector and with other sector's decarbonisation options. From these points, judgements can be made about each option; but the report does not seek to promote any particular route, or to predict which route is more likely.

One challenge with predicting the future route for transport decarbonisation is uncertainty over costs and their role in decisions; this report does not consider costs in detail, but some high-level observations can be made: Firstly, each option would have infrastructure requirements; it is possible to comment on the relative scales, but to specify the costs will require further detailed engineering studies based on the most current information at the time that decisions are to be made. Secondly, studies forecast that the total cost of ownership (TCO) of different vehicle types will become similar around 2030.[25] Whilst upfront vehicle costs can be more important than TCO for some customers, the forecast trends would nonetheless provide increased customer choice that could direct the sector down a particular route irrespective of wider infrastructure requirements. Finally, whilst total cost is a major consideration, an option with the best chance of success might not be least-cost. To be considered viable, an option must be workable from engineering, financial and customer perspectives: it must be practical and affordable, and consistent with decarbonising options for other sectors. Successful options will be those that are commercially-viable and marketable.

[23] See, for example: The Carbon Plan: Delivering our low carbon future (UK Government, 2011); New Lens Scenarios (Shell, 2013); Automotive Council Roadmaps (2013); ERTRAC Roadmaps (2010 to 2015, and ongoing); Transport Energy and CO_2 (IEA, 2009); Bioenergy review (CCC, 2011); and EU Transport Figures (EU Commission, 2012)

[24] See, SMMT data at: *www.statista.com/statistics/299951/average-age-of-cars-on-the-road-in-the-united-kingdom/*

[25] See, for example: A portfolio of powertrains for the UK: An energy systems analysis (UCL, 2013); and An Economic Assessment of Low Carbon Vehicles (Ricardo-AEA, 2013)

3.1. Scenario 1: ICEV Evolution

The attractions of ICEVs include: long range and fast refuelling, familiarity for users, and existing infrastructure. This scenario assumes that: ICEVs and liquid fuels are used extensively; ICEVs become increasingly efficient and hybridised; liquid fuels have increasing proportions of biofuels, and (bio-)methane is used for HGVs; and ICEV-hybrids evolve into PHEVs. Results are shown in Figure 4; assumptions and outcomes are discussed below.

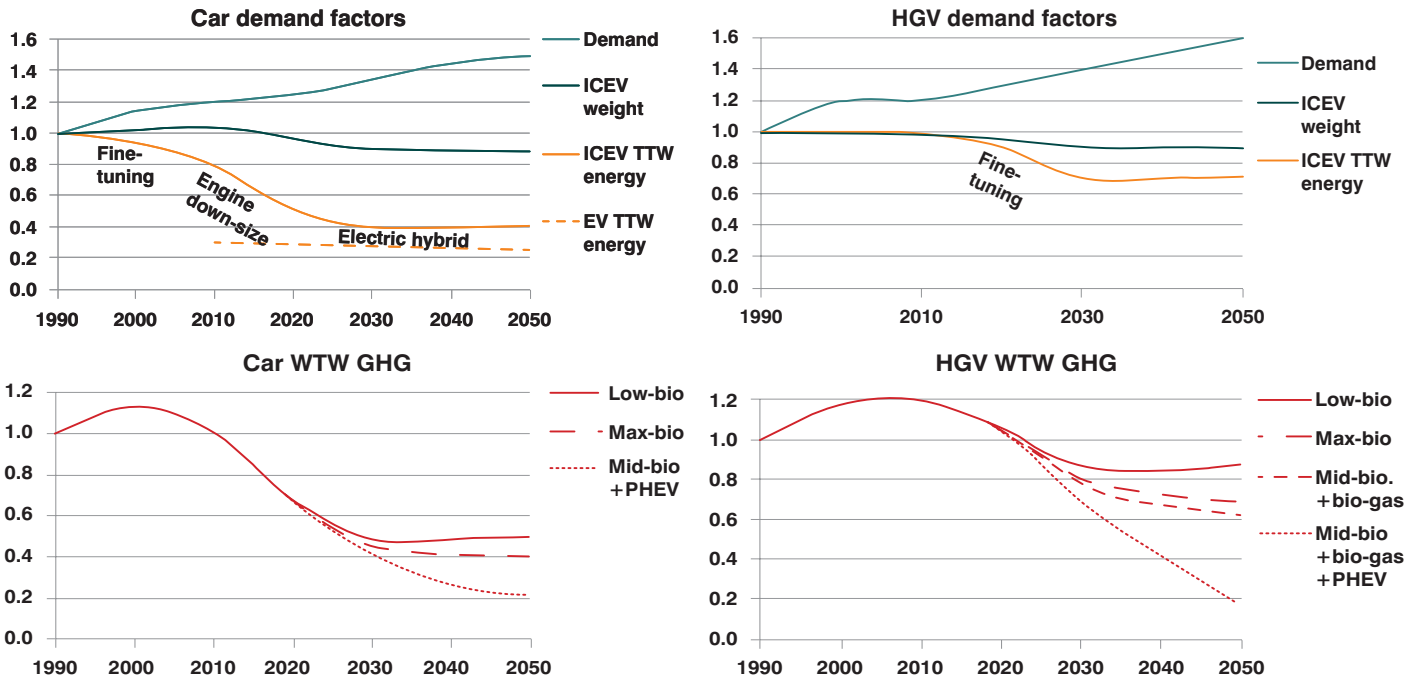

Figure 4: *Future scenario of ICEV Evolution: (left) light road transport and (right) heavy road freight. Values are proportions of the value in 1990. Fuel GHG emissions are well-to-wheel. Weight and energy use are for new vehicles introduced in a year; overall impacts are due to a mix of vehicles of different ages.*

Weight of vehicles can be reduced by integrating components and using lightweight materials:

- ICEV cars' weight could be reduced by ~10-20% by 2030 (from present weight; slightly higher than 1990 value).[26] Battery weight is assumed to make hybrids and PHEVs heavier than ICEVs by ~10% and ~15%, respectively.
- ICEV HGVs' unloaded weight could be reduced by ~5-10% by 2030 (from the present value, which is similar to that in 1990).[27] PHEVs are assumed to be ~15% heavier than ICEVs.

Energy consumption (and hence in-use CO_2) per vehicle can be reduced using energy efficiency measures:

- Energy consumption for an average new car[28] could fall from 2015 levels (~0.65kWh/km, or ~0.4kWh/p-km) by ~40% using engine down-sizing and mild hybridisation,[29] and by ~50% from 2015 (~60% from 1990) by full hybridisation (not plug-in), giving tailpipe emissions of ~70gCO_2/km[30] Most cars would be PHEVs by 2050: their ICE performance would be the same as full hybrids; their electric operation would have GHG emissions of ~10g/km (for gird mix 50g/kWh).
- HGVs could have energy and GHG savings of ~20-30% (similar whether measured from 2010 or 1990) by 2030.[31]

[26] Lightweight vehicle and power train roadmap (Auto. Council, 2013); and Road transport technology and climate change mitigation (Grantham Institute, 2010)

[27] Technical options for heavy duty vehicles (slides for "EU Transport GHG: Routes to 2050", AEA-TNO); and Reducing the energy consumption of heavy goods vehicles through the application of lightweight trailers (Galos, et al., 2015)

[28] A Mid-size car (e.g. VW Golf) is broadly representative of an average car in terms of energy and tailpipe CO_2; although by other measures the average car is smaller, in the super-mini class; see: Motor Industry Facts (2015 (SMMT, 2015).

[29] For examples of downsizing see: mid-sized car (HyBoost: Ricardo, 2013); large car (Ultra Boost: JLR, 2014). See also: Electric Powertrains: Opportunities and Challenges in the U.S. Light-Duty Vehicle Fleet (MIT, 2007). Engine down-sizing naturally reduces vehicle weight.

[30] Source: interviews for this project; and, for example: Ricardo's ADEPT project. Engine down-sizing reduces weight; batteries add weight.

[31] See, for example: Sectoral scenarios for the Fifth Carbon Budget Technical report (CCC, 2015); and Heavy Duty Vehicle (HDV) Efficiency (ETI, 2014)

Forecast demand for road transport services in 2050 (150% of the 1990 level) would give WTW energy consumption compared to 1990 levels of ~40% lower for cars (leaving ~180TWh/yr), and ~15% higher for HGVs (leaving ~110TWh/yr).

Advanced biofuels, synthetic fuels (some using industrial CCS), and some first generation biofuels (depending upon indirect land-use change, ILUC) can provide ~80% reductions in life-cycle GHG emissions, compared to liquid fossil fuels.[32] The trends in the chart are:

- **"Max-bio":** Using most of the UK's forecast bio-energy (~130TWh in 2050)[33] for road transport, would meet ~40% of the energy consumption, reducing GHG emissions from 1990 levels by ~60% for cars, and by ~30% for HGVs.
- **"Mid-bio":** Using ~50% of the UK's forecast bio-energy for 2050 for road transport (e.g. if there was lack of resource, competition with other sectors, etc.), would meet ~20% of road transport's energy consumption, and would reduce emissions from 1990 levels by ~55% for cars, and HGVs' by ~20%.
- **"Low-bio":** If biofuels uptake was limited further to 10% of energy for road transport (e.g. due to blend wall constraints at ~10% blends, competition from aviation, lack of CCS for synthetic fuels, etc.), then GHG emissions would be below 1990 levels by ~50% for cars, and by ~10% for HGVs.

Cars and vans would need to become PHEVs, and would require low-carbon electricity (grid mix assumed to be 50g/kWh from 2030 onwards). The charging regimes needed to maximise the benefits of PHEVs could be best suited to urban freight with short trips and regular schedules. For cars, users might need to modify their usage patterns to optimise charging opportunities. The trend in the chart is:

- **"Mid-bio + PHEV":** PHEVs using low-carbon electricity for 50% of their energy needs (displacing most of the fossil fuel use) could reach an 80% GHG emission cut from 1990.

In order to achieve the remaining GHG emissions reductions, HGVs would require a combination of energy sources: Methane trials are ongoing, and it is being used by some haulage companies,[34] but it gives only a ~15% GHG emissions reduction[35] and it can be eroded by methane leaks (during extraction[36] and from vehicles[37]). Trends on the chart are:

- **"Mid-bio + bio-gas":** Biomethane offers 60-90% reductions,[38] and is being studied further.[39] If HGVs received in 2050 the equivalent of the UK's total present biomethane production (23TWh/yr)[40] for ~20% of their energy consumption, and another 20% of their energy from liquid biofuels, HGV GHG emissions would be ~40% lower than in 1990.
- **"Mid-bio + biogas + PHEV":** Low-carbon electricity could be used in HGVs as PHEVs. Building on the "Mid-bio + bio-gas" trend, if electricity provided 50% of the energy (leaving 10% from liquid fossil fuels) then HGVs could reach an 80% GHG emissions cut from 1990.

Embedded impacts from vehicle manufacture made up ~20% of lifecycle impacts in 1990 for ICEV cars, and ~15% in 2010; battery manufacture makes embedded impacts ~10-25% higher for hybrids (including PHEVs), and ~25-50% higher for BEVs.[41] If the relationship between vehicle ownership and distances travelled remained as they have been, then 2050 would have 150% the number of vehicles (HGVs, vans and cars) as 1990. If most vehicles in 2050 were PHEVs then the embedded impacts would be ~170-190% the 1990 level. In order to have total embedded impacts fall by 80%, manufacturing's GHG emissions intensity would have to fall by ~90%, which is very challenging. New models of ownership and use could be important: if car numbers were 30% of their 1990 level (e.g. due to new models of ownership/rental or ride sharing opportunities), then manufacturing's GHG emissions intensity would need to fall by ~65%. For HGVs (and other heavy transport), embedded impacts would still need to be reduced, by are a lesser challenge than for cars: they are a smaller proportion of the life-cycle impacts of HGVs, because the journeys are more energy-intensive and more frequent, and because a higher proportion of the weight is due to the load (as opposed to the vehicle).

[32] See, for example: Low Carbon Truck and Refuelling Infrastructure Demonstration Trial Evaluation (Atkins & Cenex, for DfT, 2015); and RTFO data at *www.gov.uk/government/collections/biofuels-statistics*.

[33] For example: Bioenergy Review (CCC, 2011); Delivering greenhouse gas emission savings through UK bioenergy value chains (ETI, 2016); Bioenergy Strategy Analytical Annex (DECC, 2012); and The UK bio-energy resource base to 2050- estimates, assumptions, and uncertainties (UKERC, 2010)

[34] Most use gas-diesel hybrids (~30-50% gas); e.g. see: Low Carbon Truck and Refuelling Infrastructure Demonstration Trial Evaluation (Atkins, 2015).

[35] See, for example: Fuels in Transport – Final Report (Ricardo-AEA, 2014)

[36] Methane and CO_2 emissions from the natural gas supply chain – An evidence assessment (SGI, 2015)

[37] See, for example: Report to Parliament (CCC, 2015)

[38] See, for example: Waste and Gaseous Fuels in Transport – Final Report (Ricardo-AEA, 2014)

[39] Gas Well-to-Motion study (ETI, ongoing)

[40] Biomethane for Transport from Landfill and Anaerobic Digestion (Ricardo AEA for DfT, 2015)

[41] Embedded impacts of a mid-sized car have been estimated as ~5tCO_2 for ICEs, and ~8tCO_2 for BEVs; for SUVs as ~10tCO_2 for ICEs, ~12tCO_2 REs, and ~14tCO_2 for BEVs. Sources include: Life Cycle CO_2 Footprint of a LCVTP vehicle (Ricardo, 2012); and End-of-Life Vehicle (ELV) processing (SMMT, 2011)

3.2. Scenario 2: Electric Transition

The attraction of electric vehicles include: zero tailpipe emissions of GHG and air pollutants; low noise; and synergies with automation. There are various published scenarios for uptake of EVs.[42] The scenario presented here is an ambitious uptake of BEVs (and PHEVs), designed to highlight the key requirements of such a strategy. Results are in Figure 5; assumptions and outcomes are discussed below.

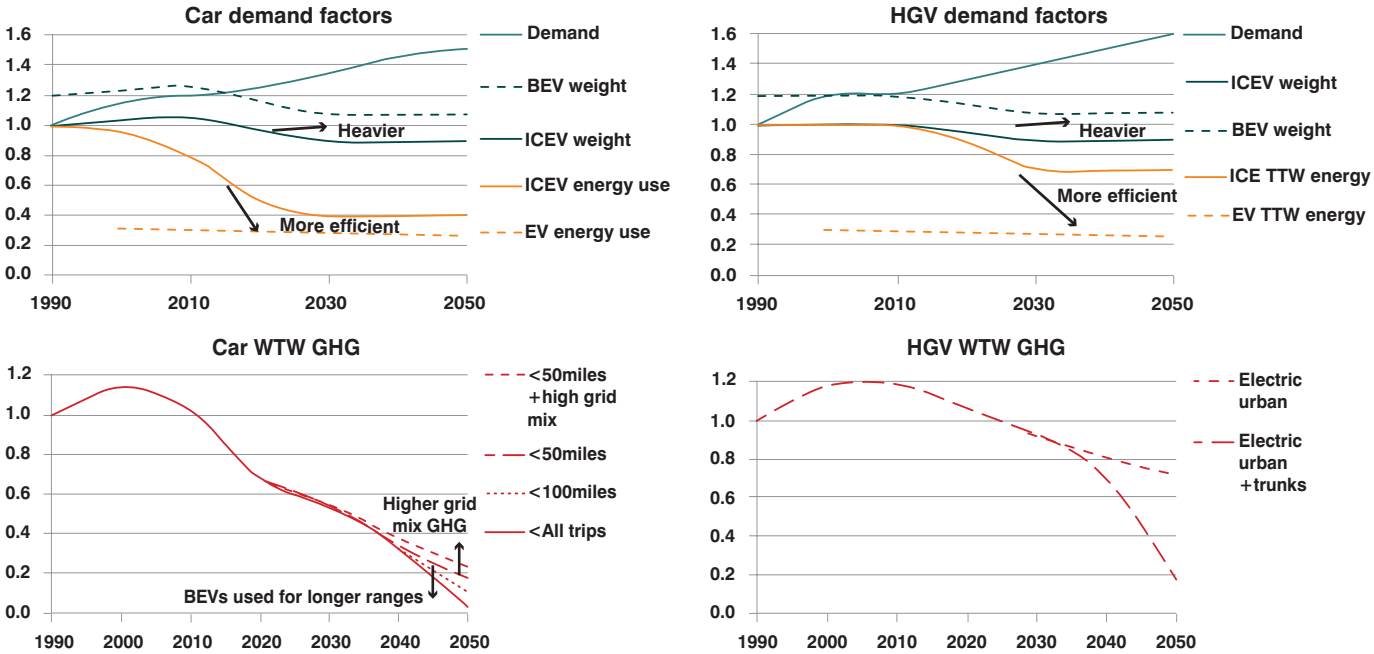

Figure 5: *Future scenario of Electric Transition, for (left) light road transport and (right) heavy road freight. Values are proportions of the value in 1990. Fuel GHG emissions are well-to-wheel. Weight and energy use are for new vehicles introduced in a year; overall impacts are due to a mix of vehicles of different ages.*

Weight reductions for ICEV cars and HGVs are assumed to be as in Scenario 1. BEVs are assumed to be ~20% heavier, and PHEVs 15% heavier, and to follow the ICEV trends (cars losing 10-20% of weight by 2030, and HGVs ~5-10%).

Energy efficiency of electric powertrains is already high (~80% TTW); there is some (but limited) potential for efficiency improvements in EVs. Energy consumption in 2015 is already low e.g. ~0.2kWh/km for a mid-sized car (~30% of the energy consumption for an ICEV in 1990); modest improvements could lead to TTW energy consumption in 2050 of ~25% that of a 1990 ICEV. Some electric trucks have been developed, but there is less data about performance; for this scenario it is assumed that HGVs too could end up with 25% of the energy consumption of 1990 ICEV equivalents (per t-km).

The UK's grid mix intensity was ~400gCO_2/kWh in 2014,[43] and it assumed to be 50g/kWh by 2030, which amounts to ~10gCO_2km (~5% of an average ICEV's value in 1990). The assumed generation mix is a roughly equal split between nuclear, renewables and natural gas (with CCS); this is consistent with various published scenarios.

[42] For example: Global EV outlook (IEA, 2013); Future Energy Scenarios (National Grid, 2015); and Chapter 4 and Annex 4 of: Reducing emissions and preparing for climate change – 2015 Progress Report to Parliament, p125 (CCC, 2015)

[43] Table 5D of Chapter 5 (Electricity) of DUKES 2015 (DECC, 2015)

Demand for road passenger services can be segmented according to trips, but the reality is complex. BEVs can already achieve ~100miles,[44] battery range in mass-market cars is continuing to increase,[45] and some users have already adapted their regimes to achieve very high BEV mileage.[46] The simpler examples in the chart are illustrative:[47]

- **"All trips":** If BEVs were used for all trips in 2050, total GHG emissions would be ~90% below the 1990 value.
- **"Up to 100miles":** If BEVs were used only for trips up to 100miles in length (88% of distances travelled),[48] cars' total GHG emissions would be ~85% below the 1990 value. ICEVs (either BEV-REs or PHEVs) would be used for longer trips, with low (10%) blends of biofuels (on the assumption it was prioritised for other sectors if BEVs were the focus for road transport). A similar result occurs by using BEVs for all trips with easier access to chargers (urban areas, rural A-roads, motorways), amounting to ~85% of trip distances.[49]
- **"Up to 50miles":** If BEVs were used only for trips up to 50miles (74% of distances travelled),[50] with ICEVs (BEV-REs or PHEVs) for the longer trips, cars' total GHG emissions would be ~80% below the 1990 value.
- **"All car trips + high grid mix":** If the grid mix was not reduced to 50g/kWh by 2030, but instead levelled off at ~150-200g/kWh, then GHG emissions would be ~70% below the 1990 level.

Segmentation by trip is significant for HGVs: the large weights (of vehicles and freight) cause high energy consumption limits range with a reasonably-sized battery.[51] In this scenario, freight uses electrification in two ways, as per the chart:

- **"Electric urban trips":** From 2030, freight transport in urban areas uses small electric HGVs and vans[52] (in part to for air quality), accounting for ~30% of freight distances, and cutting GHG emissions to ~30% below the 1990 level.
- **"Electric urban + rural A-roads + motorways":** From 2040, inductive charge-on-the-move is used on trunk roads (motorways and A-roads routes, covering 55% of freight distances); added to electric vans in urban areas, GHG cuts would be ~80% below 1990.

Embedded impacts from vehicle manufacture made up ~20% of lifecycle impacts in 1990 for ICEV cars; battery manufacture makes embedded impacts ~10-25% higher for hybrids, and ~25-50% higher for BEVs.[53] If the relationship between ownership and distances travelled remained as they have been, then 2050 would have 150% the number of vehicles (HGVs, vans and cars). If most vehicles in 2050 were BEVs then the embedded impacts would be at least 200% the 1990 level. In order to have total embedded impacts fall by 80%, manufacturing's GHG emissions intensity would have to fall by 90-95%, which is very challenging. New models of ownership and use could be important: if car numbers were 30% of their 1990 level, then manufacturing's GHG emissions intensity would need to fall by ~70%.

Mileage is an important factor: BEVs' lower in-use emissions would offset embedded GHG emissions once the vehicle had passed a critical mileage. Embedded impacts are affected by segmentation of demand for transport services. If longer car trips (e.g. over 50miles or over 100miles, as above) used BEV-REs then the additional embedded impacts of RE components would be negligible compared to the BEVs. If longer trips used separate ICEV cars, and if users still had BEVs for shorter trips, then given that longer trips tend to be concentrated (e.g. bank holidays), the worst case would be that users need as many ICEVs as BEVs, giving embedded impacts of ~300% the 1990 value (before mitigating actions discussed above). Alternatives could include "modular cars" to add space and range when needed.

As in Scenario 1, for HGVs (and other heavy transport), embedded impacts are a smaller proportion of the life-cycle impacts than for cars. Embedded impacts of PHEV HGVs are assumed to follow similar trends as for cars. The overall impacts of implementing changes are not clear as they would depend upon the logistics model adopted; e.g. the total number of vehicles could increase if more small vehicles were needed for urban areas. Embedded impacts of HGV charge-on-the-move infrastructure would have to be assessed; reductions would depend upon the energy-intensity of construction processes and upon GHG emissions mitigation (e.g. CCS for cement manufacture).

[44] The Nissan Leaf can achieve ~100mile range.

[45] See, for example, the Chevrolet Bolt has ~200mile range (not available in the UK).

[46] Rapid Charge Network – Activity 6 Study Report (RCN, 2016)

[47] The simple comparison presented here does not segment trips according to the effects of speed upon fuel demand and GHG emissions, but assumes that these are spread equally across each trip type.

[48] Table TRA2506a (DfT, 2016)

[49] Table TRA2506a (DfT, 2016)

[50] Table TRA2506a (DfT, 2016)

[51] For example, BMW has built a 40tonne truck with a range of 100km.

[52] See, for example, electric truck options from EMOSS.

[53] Embedded impacts of a mid-sized car have been estimated as ~5tCO_2 for ICE, and ~8tCO_2 for BEV; for SUVs as ~10tCO_2 for ICE, ~12tCO_2 for RE, and ~14tCO_2 for a BEV. Sources include: Life Cycle CO_2 Footprint of a LCVTP vehicle (Ricardo, 2012); and End-of-Life Vehicle (ELV) processing (SMMT, 2011)

3.3. Scenario 3: Hydrogen Transition

The attractions of hydrogen as a transport fuel include: zero tailpipe CO_2 emissions, quiet operation, long range, fast refuelling, and similarities to present user experience. There are published scenarios for possible future uptake of hydrogen FCEVs.[54] The scenario presented here is an ambitious uptake of FCEVs, designed to highlight key steps in such a strategy. Results are in Figure 6; assumptions and outcomes are discussed below.

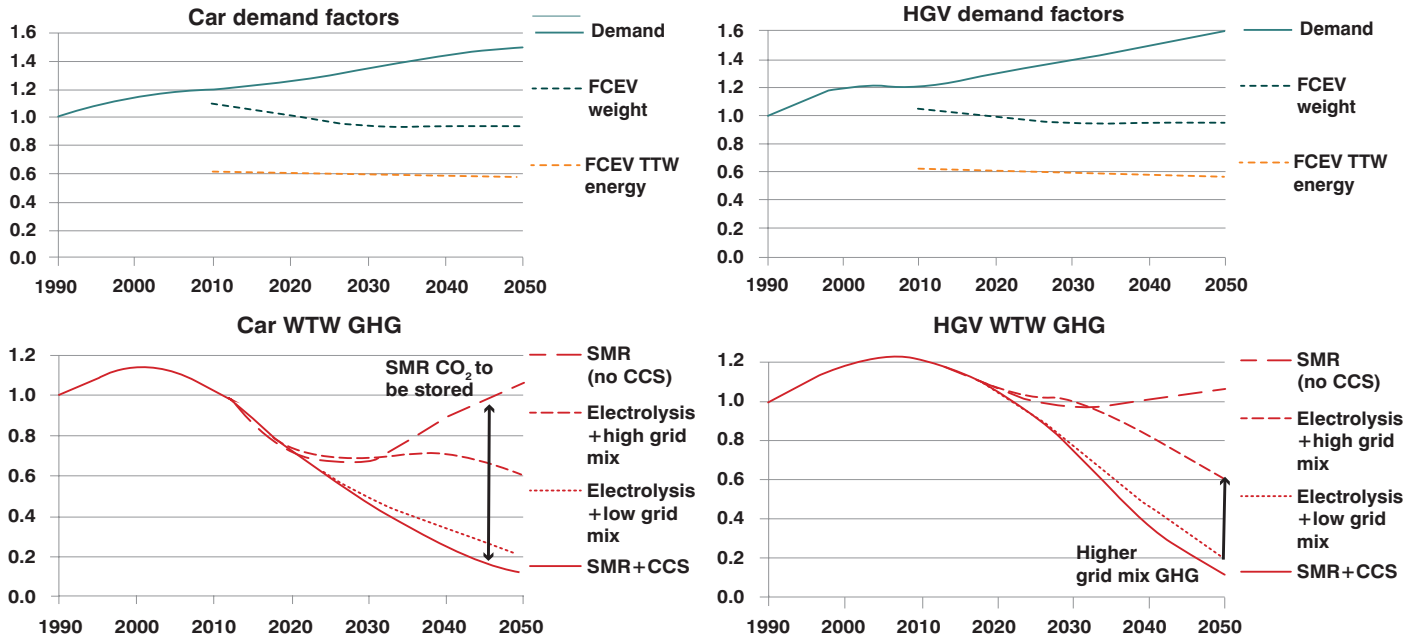

Figure 6: *Future scenario of Hydrogen Transition, for (left) light road transport and (right) heavy road freight. Values are proportions of the value in 1990. Fuel GHG emissions are well-to-wheel. Weight and energy use are for new vehicles introduced in a year; overall impacts are due to a mix of vehicles of different ages.*

Weight reductions for ICEV cars and HGVs are assumed to be as in Scenario 1. FCEVs are ~5-10% heavier than ICEVs, and follow the same trends (cars losing 10-20% by 2030, and HGVs ~5-10%).

Energy efficiency of FCEVs is ~50% from tank to wheel (i.e. using ~0.4kWh/km, which is ~60% of a 1990 ICEV), with some (but limited) potential for efficiency improvements. Modest improvements could lead to TTW energy consumption per km in 2050 of ~50% of 1990 ICEV. It is assumed that FCEV HGVs too could end up with ~50% of the energy consumption of 1990 ICEV equivalents (per t-km).

The scenario illustrates two cases: obtaining all of the hydrogen from steam methane reforming (SMR), and all from electrolysis. Some commentators foresee that initially most of the hydrogen would be produced using SMR, and then later more with electrolysis. It is assumed that CCS is applied to SMR, with a capture efficiency of 60% initially and rising to 90%. The WTT energy efficiency of SMR is ~70%. GHG intensity using electrolysis depends upon the electricity mix: dedicated, on-site renewables could be used; but in this scenario it is assumed that the grid mix electricity is used, with its GHG intensity reaching 50g/kWh by 2030; the WTT energy efficiency is ~70% now, rising to 90% by 2030.

[54] For example: New Lens Scenarios (Shell,2013); and UK H2 Mobility: Phase 1 Results (UK H2 Mobility, 2013)

Demand from passengers and freight for all types of trips could all be met by FCEVs: range is similar to that for ICEVs, so there would be no questions about segmenting transport demand, or requiring changes to user habits or logistics.

The charts illustrate four cases:

- **"SMR with CCS":** If all road transport was fuelled by hydrogen from SMR with CCS, total GHG emissions could be ~90% below the 1990 level.
- **"SMR (no CCS)":** If SMR was used for all hydrogen production, but without CCS, total GHG emissions would be at roughly the 1990 levels. This example illustrates the scale of the challenge of storing CO_2 from SMR for road transport: by 2050, it would be equivalent to roughly road transport's present emissions each year. It also illustrates the importance of developing CO_2 pipelines in a timely manner, in sufficient volumes for transport and any other sectors that plan to use it.
- **"Electrolysis":** If hydrogen was provided by electrolysis, powered by low-carbon electricity (50g/kWh), GHG emissions for cars and HGVs in 2050 would be ~80% below the 1990 levels. (The alternative of dedicated, on-site renewables would have lower GHG emissions intensity, but it not considered in this example.)
- **"Electrolysis + high grid mix":** If the grid mix was not reduced to 50g/kWh by 2030, but instead levelled off at ~150-200g/kWh, then GHG emissions would be ~40% below the 1990 level for cars and HGVs. This illustrates the important of grid decarbonisation; but energy consumption for electrolysis would be in addition to electricity consumption from other sectors, so there would need to be an expansion of generation capacity (whilst maintaining low emissions intensity)

Embedded impacts of FCEVs are modelled as being ~10% higher than ICEVs. They are higher than those for ICEVs due to the manufacture of fuel cells and hydrogen storage tanks, albeit slightly offset by lighter motors; embedded impacts of FCEVs are lower than those for BEVs. If the relationship between ownership and distances travelled remained as they have been, then 2050 would have 150% the number of vehicles (HGVs, vans and cars), and embedded impacts of ~170% the 1990 level. In order to have total embedded impacts fall by 80%, manufacturing's GHG emissions intensity would have to fall by 90%, which is very challenging. New models of ownership and use could be important: if car numbers were 30% of their 1990 level, then manufacturing's GHG emissions intensity would need to fall by ~60%.

Hydrogen could offer flexibility in terms of the longer-term development of road transport energy, potentially offering opportunities to switch between strategies at certain points in the future:

- FCEVs and their infrastructure could develop independently of other vehicle types and energy vectors.
- There could be interplay between energy options for ICEVs and FCEVs: Some synthetic fuel production has similarities to hydrogen production, and bio-methane could be used either directly for HGVs or used to produce hydrogen via SMR; so fuel production methods and supply chains for ICEVs could evolve to support FCEVs.
- There could be interplay between energy options for FEVs and BEVs: FCEVs use essentially the same drivetrains as EVs (differing only in the provision of electricity), and hydrogen production from electrolysis would use much of the same electricity infrastructure as for charging BEVs; so the either option could emerge from the other.

4. Implications and deployment

This section discusses the implications of each energy option, including interactions with the wider energy sector and with decarbonisation in other sectors. This section also discusses the key steps that would be necessary for the deployment of each energy option (grouped as vehicles, infrastructure, and energy resources, as summarised in Figure 7), and highlights challenges facing deployment at each of these steps. The main themes about implications and deployment and then drawn together in Section 5 (Summary and Conclusions).

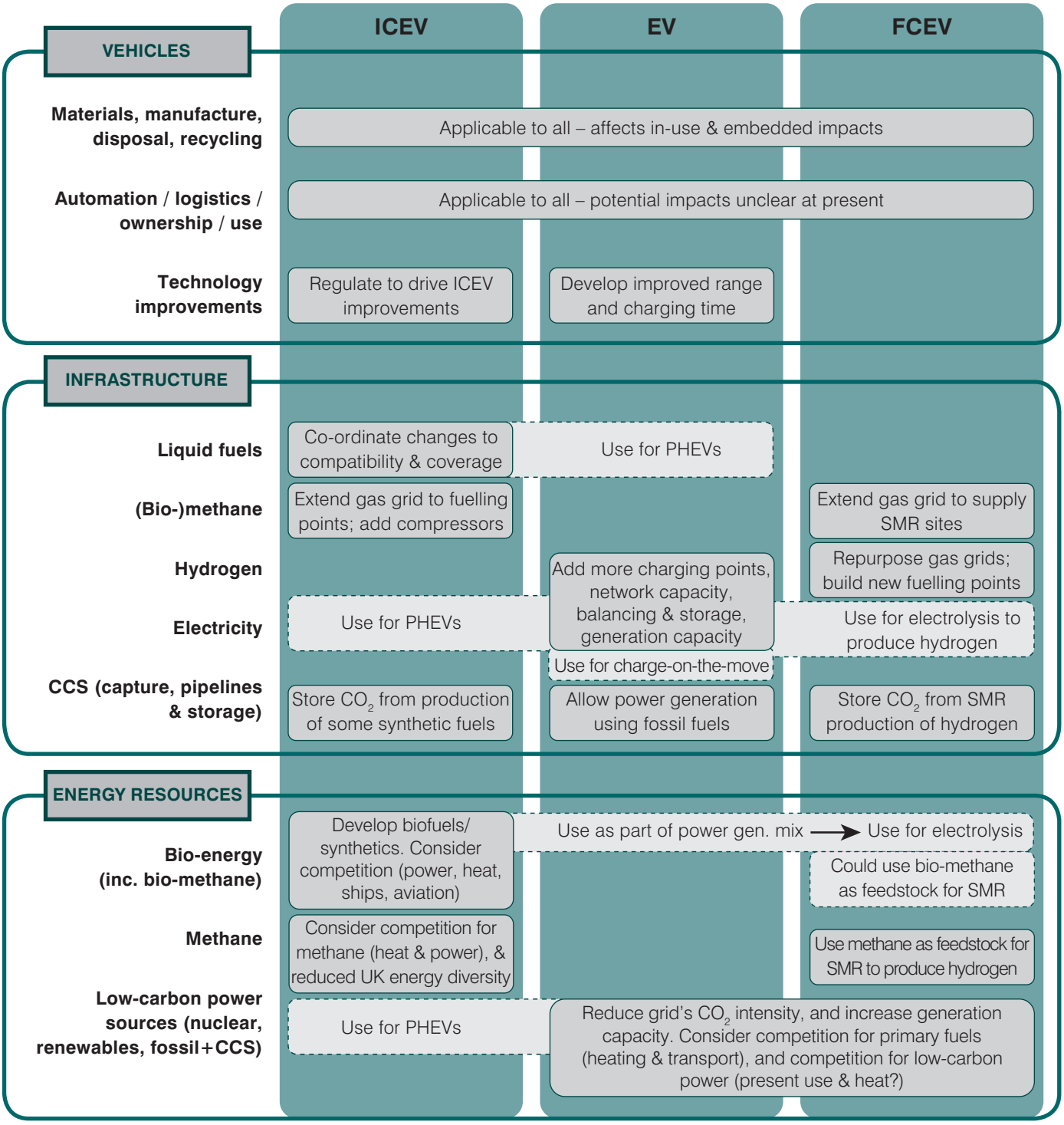

Figure 7: *Key steps for the possible routes to decarbonising road transport. Comments summarise key steps required; steps marked with pale boxes and dotted lines are less critical, but would still be needed for fully realising the benefits. The last grouping (energy resources) does not include hydrogen as a separate row, but notes its interactions with the other three energy resources listed.*

4.1. Vehicles

In each scenario, forecast growth in demand for transport services is the main driver for changes in energy consumption and GHG emissions. This sub-section considers the potential mitigating actions to meet that demand for transport services in more efficient ways: how we use vehicles; how they are manufactured, disposed of and recycled; and technological improvements to reduce fuel use per unit of demand for transport services.

User interactions: automation, logistics, ownership and use

The scenarios highlight that demand for transport services is a major factor in determining GHG emissions due to both fuel use and vehicle manufacture. Some reductions in GHG emissions could be achieved through developments that occur partly for reasons unrelated to GHG emissions, including changes in automation, logistics, ownership, use and behaviour. Taken together, these options offer opportunities for developing mobility as a service to meet specific needs, but there is uncertainty about their evolution and their net impact on GHG emissions.

Automation in transport covers a range of options, from smoothing vehicles' response to driver's actions, through to driverless vehicles; it could have a range of GHG outcomes, some of which are potentially conflicting. Smoother driving could allow efficiency savings; and driverless vehicles could allow efficiency savings (e.g. through platooning[55] of HGVs, with reduced drag and more efficient changes in speed). However, full automation could also make travel so much easier for users that demand for transport services increases more than forecast; whilst this would be a positive development for people who are unable to drive, it would increase the challenge of GHG emissions reductions.

Logistics for freight have changed in recent years, with many more vans and smaller HGVs being used, particularly for deliveries of online shopping orders. Electronic navigation can reduce fuel use by preventing failed delivery attempts. The electric vehicle scenario sees a need to co-ordinate freight for urban areas, to allow deliveries by smaller electric vehicles; and in all scenarios there are benefits from greater co-ordination to increase utilisation of vehicles. Large haulage operators have more opportunity to engage in both of these changes; the greater challenge is co-ordinating the many smaller operators (similarly for switching to lower-carbon fuels).

Vehicle owners have assets that are unused for an average of 95% of the time, and that contribute to embedded impacts; the aggregate impacts of all vehicles will grow if extra demand for transport services results in more vehicles. However, the phenomenon of "peak car" suggests that this link is weakening, and most commentators foresee different models of ownerships and use that will weaken the link still further.[56] There is scope for more car rental and alternative car-sharing models, facilitated by online services, especially in large urban areas (with high populations, many short distance trips, and the additional motivation of limited parking); if so, they would reduce the numbers of cars needed to provide the required mobility, and hence contribute to reducing embedded GHG emissions.

Vehicle use is clearly related to all of the developments discussed above. Shared use of vehicles can be defined as people (or freight) undertaking a trip together, as opposed to using the same vehicle for different trips. Shared use could potentially be the largest single means of reducing energy use and the associated GHG emissions (especially in urban areas where it is more likely to operate). If all urban car journeys in 2050 had double the current occupancy rate, this could reduce car vehicle distances by 10% from 1990;[57] savings of energy and GHG emissions would depend upon speed and congestion, but would also be of this order. Digital technologies and increased connectivity (between vehicles, online services, smart phones, etc.) will be important facilitators of these developments, having a significant impact on the evolution of mobility; however, as noted for automation, increased access to mobility could have as-yet uncertain impacts upon demand for transport services and hence energy consumption and GHG emissions.

Users' behaviour can affect the GHG impacts of PHEVs, via the relative mix of refuelling and recharging. However, this is also a benefit of PHEVs, that they can easily switch between fuels, allowing use of whichever is available (e.g. liquid fuels when in rural areas with fewer charging points), and to respond to price signals (e.g. due to constraints in liquid fuel supply or constraints on electricity networks).

[55] Platooning is the practice of vehicles travelling in convoy with all being controlled by one operator.

[56] See, for example: Understanding the drivers of road travel: current trends in and factors behind roads use (DfT, 2015)

[57] Assumes 50% demand growth from 1990, and 40% of car distances are urban as today; see: Table TRA2506a (DfT, 2016)

Materials, manufacturing, disposal and recycling

There are many opportunities to reduce vehicles' weight, by addressing each of its components.[58] Weight can be reduced by using lighter-weight materials, by assembling them into integrated units with less joining material, or by using stronger versions of existing materials and so enabling less material to be used. Light-weight materials allow weight reductions, but most have more intensive manufacturing requirements and hence have higher embedded energy (and GHG emissions). There are synergies in light-weighting between sectors: advances from motorsports have been applied to road vehicles; and the road and aviation sectors could share some further advances.[59] There are questions amongst some experts about how customers might perceive lighter-weight vehicles: it would be a reversal of the upward trend in vehicle weight that has been described as an "arms race" in which customers have wanted larger (and hence generally heavier) vehicles to increase their (actual or perceived) safety.[60]

More generally, embedded impact reductions rely on decarbonising manufacturing: this will require low-carbon power, low-carbon heat, and industrial CCS. However, even if manufacturing's GHG intensity is reduced, it will still have a significant energy consumption, contributing to the overall issue of primary energy consumption (in the UK and globally). Solutions to these issues will require action across transport and manufacturing policy, and also co-operation with other vehicle manufacturing countries to ensure life-cycle decarbonisation.

Once life-cycle impacts are considered, there can be a benefit in leaving some older vehicles in-use for longer, to maximise the benefits of their embedded impacts before causing further embedded impacts by manufacturing replacement vehicles (especially those with large batteries and other advanced components). In this way, transport has more constraints than some other sectors where scrappage schemes (e.g. for heating boilers) have had rapid positive impacts that easily outweigh the embedded impacts. These complex trade-offs support the need for life-cycle assessments (as discussed below about regulations) to stimulate technology and market change. There are already examples of novel end-of-use practices. For example, car batteries can be re-used as energy storage at service stations (to address grid constraints by charging overnight and then supplying cars during the day).[61] This reduces the embedded impacts per unit of energy provided over a battery's lifetime; and it can reduce the costs that are allotted to the initial cars' owners, hence improving their affordability.

Technology improvements

The scenarios highlighted specific improvements that experts have identified. There are two particular aspects where improvements are important: battery range and/or charging time; and ICEV energy efficiency and tailpipe CO_2 emissions.

EV batteries and charging

As discussed in Section 2, the applicability of EVs to passenger and freight transport depends upon the interplay between battery range, charging duration, access to charging points, and the time at which charging occurs. The relative importance of battery range and charging duration depends upon the mobility needs of the vehicle users. It is possible that a sufficient improvement in one or both of these factors could make the user experience close enough to that of ICEVs that users are willing to "meet in the middle" and adopt BEVs more widely. For example, it could be speculated that, even if battery range remained at ~100-200miles (as for current and new mass-market models), there could be a tipping point in user acceptance if charging duration fell to a certain level (i.e. number of minutes to reach 80% charge using a rapid charger).[62] Or, it could be speculated that, even if charging duration remained at ~30minutes for 80% charge with a rapid charger, there could be a tipping point in user acceptance if range increased.

Further research is required by the public sector and established vehicle manufactures, alongside the large research programmes of new entrants. As well as improving BEV performance, there is some evidence that technology advancements in electric mobility for road applications (energy storage, electrical machines and power electronics) could have applications in other transport modes including shipping and possibly aviation.[63]

ICEV efficiency and tailpipe emissions

Targets for GHG emissions are important for future scenarios of road transport, by driving the adoption of available improvements for ICEVs, growing the market share of EVs and FCEVs, and encouraging R&D for further improvements in all of the technologies. There are regulations requiring lower-carbon fuels.[64] The main regulatory instrument for energy efficiency is EU tailpipe CO_2 emission targets for new cars;[65] EU targets will be introduced for new vans from 2017, and there is growing pressure for the introduction of HGV targets.[66] The EU is developing the VECTO model of HGVs' life-cycle GHG emissions;[67] this will hopefully assist in designing life-cycle assessment for light road vehicles.

[58] See, for example: The potential for mass reduction of passenger cars and light commercial vehicles in relation to future CO_2 regulatory requirements (Ricardo-AEA, 2015)

[59] Aviation is seeking energy savings of 20-40% (from 2015 levels), including through light-weighting; see: proposed "stringency options" for civil aviation (ICAO, 2016)

[60] Source: Interviews for this project.

[61] See details of Evalu8 project at: *http://evalu8-ti.org/*

[62] To protect batteries, charging above 80% must take place more slowly; hence 80% of battery capacity is a benchmark for rapid chargers.

[63] Source: Interviews for this project.

[64] Renewable Energy Directive (RED) (EU Directive 2009/28/EC, 2009);and Fuel Quality Directive (FDQ) (EU Directive 2009/30/EC, 2009)

[65] Setting emission performance standards for new passenger cars as part of the Community's integrated approach to reduce CO_2 emissions from light-duty vehicles (EU Regulation 443/2009, 2009)

[66] See, for example: Sectoral scenarios for the Fifth Carbon Budget – Technical report (CCC, 2015)

[67] VECTO stands for Vehicle Energy consumption Calculation Tool. See: Development and validation of a methodology for monitoring and certification of greenhouse gas emissions from heavy duty vehicles through vehicle simulation (TUG, et al., 2014)

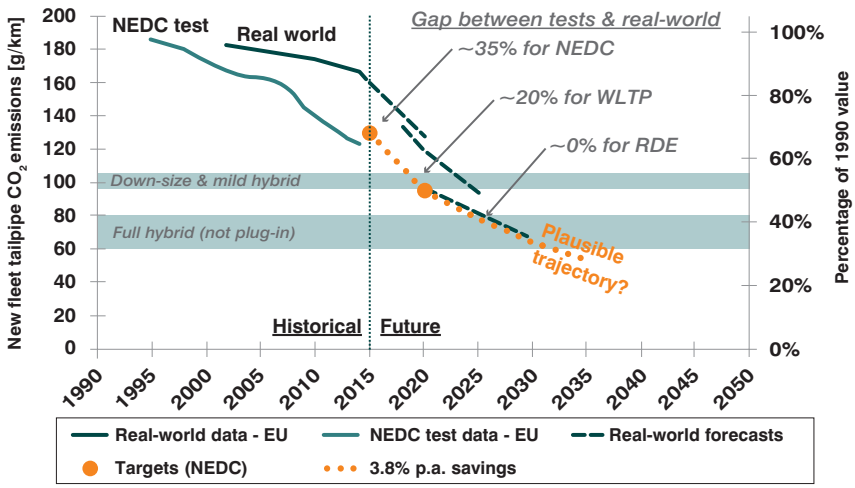

Figure 8: *Tailpipe CO_2 emissions for UK's new car fleet, from 1990 onwards.*[76]

Figure 8 illustrates tailpipe CO_2 emissions intensity for new cars. The data is shown per vehicle-km (left axis), but occupancy rates have been fairly constant at ~1.6, so the percentages of the 1990 values (right axis) apply to passenger-km as well. Key points include:

- Tailpipe CO_2 emissions intensity of new cars in the UK has fallen since 1990, from ~190gCO_2/v-km to ~124gCO_2/v-km in 2014 (according to the NEDC test),[68] a reduction of ~35%.

- There are options for reducing tailpipe CO_2 emissions further, in line with confirmed (and possible) targets.[69] Energy consumption could be cut by ~40% from the 2010 level (~50% cut from 1990) for cars[70] using engine down-sizing and mild hybridisation (i.e. for functions other than motion),[71] and some of these measures are now used in production models.[72] Energy consumption could be reduced by ~50% of the 2010 level (~60% from 1990), using full hybridisation (i.e. electricity for motion);[73] some observers expect these gains by 2030,[74] whereas others foresee year-on-year progress that could reach the 60% reductions by 2025.[75]

Figure 8 illustrates issues with the present test procedures for tailpipe CO_2 emissions. Studies show that real-world driving tailpipe CO_2 emissions are higher than NEDC test results, and that this discrepancy has grown to as much as 35% in 2014.[77] This implies that real-world new cars' tailpipe CO_2 emissions could have been ~170gCO_2/v-km in 2014, a reduction of 12% since 1990.[78] The discrepancy results from several issues,[79] and there is broad consensus on the need for tests that are more realistic and that are independently verified. The EU intends to implement the more realistic World harmonised Light vehicles Test Procedure (WLTP) laboratory test from 2017,[80] at which time the Real Driving Emissions (RDE) test (conducted on public roads) could also become a requirement. Figure 8 illustrates the smaller gaps between real-world results and the WLTP and RDE tests and; a reconciliation will be needed in order to account for the differences between tests.[81] Some experts contend that the agreed target for 2020 (95gCO_2/v-km) can be met under the WLTP conditions (or with a comparatively small difference),[82] but this has yet to be proven by all manufacturers so there is the risk that ICEVs might not be able to deliver the expected savings in real-world conditions. Ultimately, tests should include GHG impacts of

[68] NEDC stands for New European Drive Cycle, the laboratory test used by car manufacturers to measure tailpipe CO_2.

[69] The EU target for 2025 is likely to be ~70gCO_2/km. Source: Interviews for this project.

[70] Sectoral scenarios for the Fifth Carbon Budget – Technical report (CCC, 2015).

[71] For examples of downsizing see: mid-sized car (HyBoost: Ricardo, 2013); large car (Ultra Boost: JLR, 2014). See also: Electric Powertrains: Opportunities and Challenges in the U.S. Light-Duty Vehicle Fleet (MIT, 2007). Engine down-sizing naturally reduces vehicle weight.

[72] See, for example, the Ford Focus Ecoboost.

[73] Source: interviews for this project. See also, for example: Road transport technology and climate change mitigation (Grantham Institute, 2010)

[74] See, for example: Sectoral scenarios for the Fifth Carbon Budget – Technical report (CCC, 2015)

[75] Targets for 2015 and 2020 amount to 3.8% p.a. reductions, which could plausibly continue. Source: interviews for this project.

[76] Data from: Europe's Automotive Industry on the Move: Competitiveness in a Changing World (2006); SMMT annual CO_2 reports; Table VEH0256 (DfT, 2015); Road transport technology and climate change mitigation (Grantham Institute, 2010); Sectoral scenarios for the Fifth Carbon Budget – Technical Report (CCC, 2015)

[77] Studies include: Travelcard Nederland BV data source document: fuel consumption of Dutch passengers cars in business use 2004-2012 (TNO, 2013); Test cycle vs. real-world: Preparing for a Life Cycle CO_2 Measure (Ricardo, 2011); and Impact of real world-driving emissions for UK cars and vans (Element Energy, 2015)

[78] It is assumed that the discrepancy was zero in 1990, given that this was before tailpipe CO_2 tests were introduced. This assumption is supported by the convergence of datasets back towards 1990 in Figure 8.

[79] See, for example, discussion in: Impact of real world-driving emissions for UK cars and vans (Element Energy, 2015)

[80] See, for example: EU Memo 15-5705 (2015)

[81] Discrepancies would be seen in vehicles' tailpipe CO_2 emissions, but less so in DECC's GHG inventory based on overall fuel sales.

[82] Source: interviews for this project. For example, Ricardo's ADEPT project aims for emissions <70gCO_2/km, which would meet at least the 2020 target even with some adjustments to the target under the WLTP test.

upstream energy production and vehicle manufacture (each constituting ~15% of an ICEV car's life-cycle impacts, and larger shares for EVs and FCEVs). The sector recognises the value of life-cycle assessments, but it will take several years for a methodology to be developed, agreed and implemented.

Efforts to reduce tailpipe CO_2 emissions have been undertaken alongside similar efforts to reduce tailpipe air pollutants, including SO_x and particulates, with a focus on NO_x (a mixture of NO and NO_2) due to its impacts around busy roads especially in urban areas. EVs emit zero tailpipe CO_2 and NO_x, and FCEVs emit zero tailpipe CO_2 and virtually no NO_x; indeed, NO_x emissions are one of the main drivers of interest in these powertrains. To deliver these benefits using EVs and FCEVs would require more radical transitions including infrastructure investments. By contrast, some benefits could be delivered using ICEVs, allowing an incremental approach with fewer infrastructure requirements. However, for ICEVs there are technical interactions between the production of CO_2 and NO_x; but perhaps more-so there have been complications due to interactions between the policies and regulations for CO_2 and NO_x, and also there have been issues with the implementation of these policies and regulations.

On a technical level, there are some mutual solutions for CO_2 and NO_x, e.g. weight reduction reduces fuel consumption that in turn reduces emissions of both CO_2 and NO_x. But some solutions for ICEVs are conflicting, e.g. higher engine temperature increases efficiency and hence reduces CO_2 emissions, but also increases NO_x. Similarly, NO_x emissions can be addressed by a range of different technologies, but some options require energy from the vehicle and hence add to CO_2 emissions.[83]

On a policy and implementation level, there have been trade-offs. Most notably, incentivising use of diesel ICEVs (in favour of petrol ICEVs) should reduce CO_2 emissions,[84] but without mitigating measures it would tend to raise NO_x emissions.[85] This trade-off between CO_2 and NO_x was perhaps made in the belief that NO_x emissions were improving significantly: according to manufacturers' published test data, NO_x emissions for new vehicles have fallen consistently and in line with EU limits,[86] and should now be 90% lower than in 1993. Independent regulatory verification of emissions has a reduced role in the UK now.[87] Other studies have found that many newer diesel cars have higher real-world NO_x levels than are expected;[88] not just higher than the tighter Euro 6 regulations, but also higher than previous regulations.[89] Overall, the impact of real-world NO_x emissions upon air quality remains a major policy issue.

The discrepancy between NO_x test results and real-world emissions is essentially due to lack of incentives for manufacturers to apply the available technology in a way that is appropriate to real-world conditions. In an extreme example, "defeat device" software was used to modify performance in order to pass NO_x tests, but allowing higher NO_x emissions at other times (to reduce the impact on other aspects of vehicle performance).[90] This practice has added pressure for realistic test that are properly enforced; but by harming public trust, the practice has potentially made it harder to gain public acceptance about genuine challenges with testing. More generally, appropriate technology can be applied, but are not necessarily calibrated optimally for real-world conditions. The incoming Euro 6 regulations include a "conformity factor" that allows new cars to exceed the limits by a tolerance that will reduce over coming years to give manufacturers time to incrementally introduce improvements; but this has been perceived by some as a weakening of regulations, and there is also a risk that it could be treated as a target to be hit rather than as a backstop to be exceeded wherever possible.

Finally, in the studies of real-world NO_x emissions, there are examples of new diesel cars that do meet the required level in real-world operation, showing that the technology is available and can be calibrated for real-world operation (as opposed to test conditions).[91] Therefore, the problem of high NO_x emissions could be a transitory issue, but will only be resolved if manufacturers have clear guidance on how to treat CO_2 and NO_x,[92] and if manufacturers have strong incentives to make appropriate use of the available technology and to conduct R&D into further improvements. Addressing the issues with tests for NO_x and CO_2 would improve the value of information that is available for manufacturers, for customers, for researchers, and for the formulation and evaluation of policy. To deliver improved performance and data would require the following steps:

- Regulations should be co-ordinated for CO_2 emissions and air quality to provide clear direction for manufacturers;
- CO_2 and NO_x tests should closely reflect real-world usage to increase the uptake of improvements;
- Tests should be independently verified in real-world usage to provide confidence in the results.

[83] For example, some NO_x reduction measures can incur fuel penalty equating to an extra ~5-10% CO_2.

[84] Compared to petrol, diesel has: 8% more energy/litre, 16% more CO_2/litre, 20% lower fuel demand/km, and ~10% less CO_2/km. This benefit of diesel ICEVs is being reduced by gains in the efficiency of petrol ICEVs.

[85] Diesel engines operate with excess air ("lean" combustion), i.e. there is more oxygen present than is needed to burn all of the fuel, and hence there is oxygen to react with nitrogen in the air to form NO_x. During the period since 2000, the NO_x limit for new diesel cars (i.e. what would have been expected) has three been times that for new petrol cars (but the difference was larger in reality).

[86] Limits are named Euro 1, 2, .. 6. Note that Euro 1 & 2 included NO_x and hydrocarbons together.

[87] The UK's Vehicle Certification Agency (VCA) ceased its spot checks of emissions in 2011. Independent testing by government agencies as a means of identifying higher than expected emissions is used in Sweden, Germany and the USA.

[88] See, for example: Real-world exhaust emissions from modern diesel cars (ICCT, 2014)

[89] There are also questions about the impacts of changing proportions of NO and NO_2 in NO_x. See, for example: Primary NO_2 Emission Factors for Road Vehicles (note by Ricardo-AEA for NEAI, 2013)

[90] See press coverage in late 2015 and in 2016 about VW's defeat device in diesel cars.

[91] See, for example: Real-world exhaust emissions from modern diesel cars (ICCT, 2014)

[92] This could be aided by the recently-formed alliance including the Low CVP and the Clean Air Alliance; see press release (2016).

4.2. Infrastructure

Infrastructure for transport sector energy includes energy processing facilities, distribution networks, and supply points. Each energy option would require modifications or extensions to existing infrastructure, or new infrastructure. Some of the investments are common to more than one option, but with different timings, e.g. focussing on BEVs would require electrical infrastructure soon, but focusing on ICEVs will require it later for PHEVs. Some options would require many small interventions (e.g. to vehicles and energy supply); whereas others would require a small number of large interventions (e.g. new refineries and power stations). Both types of intervention pose risks that can prevent delivery of expected benefits: e.g. small interventions are harder to monitor, whereas large projects concentrate the risks. Both types of intervention have long timescales: e.g. the smart meter roll-out and the first new nuclear power plants were originally proposed in the early 2000s, and may not now be achieved until well into the 2020s.

Each of the energy options would require large capital investments. Whilst total cost is a major consideration, an option with the best chance of success might not be least-cost. To be considered viable, an option must be workable from engineering, financial and customer perspectives: it must be practical and affordable, and consistent with decarbonising options for other sectors. Successful options will be those that are commercially-viable and marketable.

The energy sector faces challenges that limit its available capital and its appetite for risk, including: profitability relies upon customers accepting the new option and buying vehicles; new technologies must compete with incumbents that might adapt to the challenge; and projects can face lengthy planning processes. Major infrastructure projects require political will, long-term commitments, and co-ordination between key actors, more so for cross-sectoral projects.

Infrastructure projects would be funded by different mechanisms. Greatest certainty is provided by regulated investments (e.g. rail, gas and electricity networks), and Government projects (e.g. roads); market conditions will determine the success of other investments (e.g. power plants and refineries). Ultimately, all projects would be paid for by citizens and businesses, through a combination of transport costs, energy bills, personal taxes, road taxes, and business taxes. The financial flows and distribution of payments will become more complicated due to changes in ownership and use. The allocation of payments will come down to policy judgements about distributional impacts.

Infrastructure contributes the life-cycle impacts of an energy option; these are not included in this report's scenarios. They depend upon the carbon intensity of the manufacturing and construction sectors (determined partly by the energy intensity of key materials, e.g. steel, aluminium and concrete), that require ongoing decarbonisation policies.

Liquid fuels infrastructure

Biofuels / synthetics would use existing liquid fossil fuels distribution infrastructure for, but modified production equipment. 'Drop-in' fuels are chemically similar to fossil fuels, and would require minor changes to infrastructure, even if used at high concentrations; but commercially-viable processes and supply chains need to be developed. The majority of present biofuels are not 'drop-in' fuels; beyond the ~10% "blend wall" they pose a material operational risk necessitating modifications to infrastructure and vehicles. Moving to higher blends would require long lead-times and industry-wide agreement: engine manufacturers would need several years to develop new models; owners of existing vehicles would need incentives for replacing them; and fuel suppliers would need to decide on which fuels to supply.[93] These changes to vehicles and infrastructure could be harder to address for smaller hauliers and fuel suppliers.

It is likely that liquid fuels (of whatever sort) will provide less transport energy in future than they do at present, with implications for the infrastructure. Reduced sales could affect the "universal coverage" of refuelling stations, especially in rural areas (where total demand for transport services is lower, but can be high per user), such that car users and freight hauliers would incur additional time and expense travelling to remaining refuelling stations. The costs of the infrastructure would be charged to remaining customers, hence increasing their fuel prices. For car users, these are likely to be poorer customers using older, less efficient cars (less likely to have new more efficient ICEVs, or EVs, hybrids, etc.). These two issues would combine in those rural areas with longer trips and lower incomes, and a strategy would be required to manage the impacts. If in the longer term cars primarily moved away from liquid fuels, but HGVs did not (e.g. used fossil-biofuel mixes), the freight sector would be increasingly affected by the lower numbers of fuelling stations and higher prices at those that remained.

[93] Most forecourts sell only two versions of each fuel (e.g. petrol and premium petrol). They could be faced with two new options (e.g. high bio-blend petrol, and premium high bio-blend petrol), and would still need to offer a lower blend fuel for ~10years for older vehicles.

Methane and bio-methane infrastructure

Natural gas and bio-methane for HGVs could use some existing gas infrastructure, but would require further investments. The feasibility is dependent upon wider decisions about the future of the low pressure gas distribution grids, e.g. whether they should be retained for methane and bio-methane, decommissioned if heating is to be electrified, or repurposed for transporting hydrogen.

- Liquefied natural gas (LNG) would use liquefaction and import facilities,[94] and would then be transported by road tankers without the use of the gas pipe networks.
- Compressed natural gas (CNG) could be supplied through the gas networks to fleet depots or public refuelling stations, but the supply pressure for vehicles (300bar) is at present only in used the national transmission system (NTS) and the local transmission systems (LTS, located only in the Midlands). If CNG (including bio-methane) was to be used extensively, there would be merit in developing a strategy to extend the NTS in a less incremental manner than at present, and / or for installing compressors and storage at depots on low pressure grids.[95]
- Bio-methane production technology can be built at small scales or up to industrial scales, and does not need to be large to achieve break-even economies of scale (although larger plants tend to be more economical, and the economics are affected by any incentive payments). If made locally (e.g. on farms where some resource is found), it could be co-ordinated with local transport depots without the need for gas networks.[96]

Increased consumption of gas would have to be managed at the system operational level:

- The fuelling of HGVs could, depending upon superimposition with other sectors' gas consumption profiles, add to the challenges of intra-day balancing; or potentially HGV depots could provide useful storage for the gas network.
- Network companies are working with scenarios suggesting that HGVs could use perhaps 1.5% of UK gas consumption by 2030.[97] A more rapid uptake of gas (whether driven by commercial decisions, or by policy) would require co-ordination with network companies to plan investments and operational strategies.[98]

Hydrogen infrastructure

There are different views about how hydrogen could best be produced: SMR is proposed for early large-scale production;[99] but there would be a need to move to other sources, e.g. electrolysis from low-carbon electricity (or perhaps hydrogen from waste, or processes at nuclear power plants). Hydrogen could be distributed to fuelling stations by using existing low pressure gas distribution networks repurposed for hydrogen; then the logistics and customer interactions with the fuelling infrastructure could function very much as they do for liquid fuels. Significant changes (or additions) would be need to other infrastructure, in one of two ways:

- Hydrogen could be produced locally at fuelling stations (most likely by dedicated electrolysers),[100] requiring a water supply and electricity grid reinforcements (or on-site renewables).
- Hydrogen could be produced at central locations (e.g. by SMR) and taken to refuelling points by tankers or pipelines. A new hydrogen pipeline system would be a major infrastructure undertaking; some gas network companies propose an alternative of repurposing parts of their low pressure urban gas distribution networks to transport hydrogen. It raises trade-offs with use for (bio-)methane, and with the needs of gas customers.[101] Repurposing would make hydrogen supply more widespread, requiring less network development for transport (except on non-urban routes beyond the repurposed urban grids). Fuelling stations would compression and purification equipment.[102] Hydrogen from SMR would require CO_2 capture, and would depend upon strategic development of CO_2 pipelines and storage (see below).

[94] For example, National Grid has LNG tanker loading facilities are available at Avonmouth and (since 2015) Isle of Grain LNG terminal.

[95] Compression of gas to give CNG incurs a ~10% energy penalty.

[96] As for CNG from natural gas, there would be a ~10% energy penalty for compression.

[97] Future Energy Scenarios (National Grid, 2015)

[98] The UK will be preparing infrastructure plans for alternative transport fuels; see: Directive 2014/94/EU (2014)

[99] See, for example, plans for hydrogen supply in Leeds using SMR.

[100] Alternatively, electrolysers could use only cheap curtailed intermittent renewable generation, but this is concentrated in a small number of time periods each year; see, for example: Managing Flexibility on the Electricity System (ERP, 2015). This would necessitate high capacity (and costs) of electrolysers and storage; this business case is challenging, but that could change if there was a wider "hydrogen economy".

[101] Part of the high-pressure networks would have to supply gas to SMR sites.

[102] Fuel cells need higher purity hydrogen than do boilers; it would probably be more efficient to treat only transport's hydrogen than all of the hydrogen before injection into the networks.

Electricity infrastructure

Providing electrical energy for cars and vans (and possibly HGVs) would require additional generation capacity, additional network capability (capacity and balancing abilities), and charging infrastructure. Ultimately, millions of charging points (mostly slow chargers) could be required, including at homes, businesses, and public locations. Deployment is progressing under Government schemes and private initiatives, and would have to see consistent rapid pace.[103] Beyond the charging points, transport sector scenarios tend to assume that the required infrastructure will be available; but this deployment is a matter for network companies and the energy regulator. Similarly, the energy sector uses assumptions about the transport sector: network companies are forecasting the impacts on peak energy consumption,[104] but more rapid uptake of EVs (whether driven by customer interest in particular models, or perhaps Government policy e.g. on air quality) could require different investments and network operation strategies.

Charge-on-the-move would be a major infrastructure project on a similar scale to the rail or motorway networks. There would be significant embedded impacts, disruption due to installation, and extra power consumption during operation.[105] It is being trialled on a short section of motorway,[106] and technological improvements and cost reductions might be achieved through its emerging application in stationary charging. It would need Government funding, co-ordinated with regulated energy network investments and market-based investments in power production.

A major concern has been managing power flows. Trials (including joint energy-transport sector projects) are suggesting that the necessary tools are available (e.g. network reinforcements, network storage,[107] charging point storage,[108] EV storage,[109] user engagement,[110] etc.). Energy network companies should continue trialling transport solutions, with the regulator facilitating third-party project leadership where beneficial. A challenge is how to fund the deployment of significant numbers of measures through regulated energy network charges, given future uncertainty.

The other major concern is meeting overall energy consumption. Some in the power industry are concerned about meeting existing energy consumption let alone transport energy consumption.[111] Investment in most new power stations presently requires incentives to offset the high financial risks, and projects are subject to lengthy timelines. These challenges affect all of generation technologies, including gas, nuclear and renewables. Alternative approaches could reduce some of these challenges; e.g. GW-scale nuclear plants have particularly long time-scales and high costs, and there is increasing interest in small modular reactors (SMR, not to be confused with steam methane reforming) that have different siting requirements and draw upon a broader UK supply chain.[112]

There are opportunities to co-ordinate policy and scenario assumptions about vehicle uptake and energy consumption, to facilitate investment planning. Change in the electricity sector is ongoing for other reasons (e.g. asset replacement, local generation, smart metering, etc.); there could be efficiencies in undertaking transport-related changes at the same time (on timescales that could facilitate BEV uptake), or there could be reduced logistical challenges in deferring transport-related changes until later (on timescales to facilitate later PHEV uptake under the ICEV scenario).

CCS infrastructure

CCS would be needed for key components of transport energy options: low-carbon production of some synthetic liquid fuels; steam methane reforming for hydrogen production; flexible fossil fuel power plants; and low-carbon manufacturing and construction to reduce embedded impacts. CO_2 capture can be applied to individual projects, but they depend upon strategic decisions to support the deployment of CO_2 pipelines and the mapping of CO_2 storage sites. There needs to be a critical mass of projects to justify research and investment; changes to the strategy for CCS in the power sector have left uncertainty about how these strategic developments will be led.

[103] See: DfT's Electric Vehicle Homecharge Scheme; and Ecotricity's Our Electric Highway

[104] See, for example: Future Energy Scenarios (National Grid, 2015); and Sectoral scenarios for the Fifth Carbon Budget – Technical report (CCC, 2015)

[105] See for example: Wireless Electric Charge-On-The-Move: An Economic Appraisal of the Potential for the UK Transport Application (Nicolaides & Miles, 2015); and Feasibility of using Dynamic Wireless Power Transfer for EVs (slides by TRL for FABRIC project, 2016), presentation related to: Feasibility study – Powering electric vehicles on England's major roads (Highways England)

[106] Feasibility study: Powering electric vehicles on England's major roads (Highways England, 2015)

[107] See, for example, use of Energy Storage and Management Units (ESMU) in SSE's Thames Valley Vision project, funded under the LCNF.

[108] See details of Evalu8 project at: *http://evalu8-ti.org/*

[109] Benefits of flexibility from smart electrified transportation and heating in the future UK electricity system (Appl Energy, 2015)

[110] See details of SSE's My Electric Avenue project, funded under the LCNF.

[111] Source: Interviews for this project.

[112] Source: Interviews for this project.

4.3. Energy resources

Energy consumption includes the energy used in the vehicles (TTW) and the energy used to process fuels upstream (WTT), as well as the embedded energy of vehicles and infrastructure. This section focusses on resources for transport energy vectors (in-use and upstream energy), and not on embedded energy since (which involves industrial energy vectors).

A central issue for transport energy vectors is the primary energy consumption, i.e. the total energy that must be put in at the start of the upstream process (resource extraction / harvesting) in order to meet transport's energy consumption. Primary energy consumption includes all of the conversion losses at each step. For example, road transport is presently ~15-25% efficient overall, taking into account ICEV efficiency of ~20-30% and upstream fuel efficiency of ~80-90%; so primary energy consumption is presently about five times the energy used for useful motion.

Another key issue regarding transport energy vectors is that many of them can have alternative uses in other sectors; so use of an energy resource for transport can prevent its application (sometimes as a different energy vector) in another sector. Given limitations on low-carbon energy resources, there will be limitations on their use; but care must be taken to avoid constraining sectors that have no better option and would hence resort to options with higher GHG impacts. Ultimately, the aim should be to optimise use of energy resources to minimise the overall GHG emission reductions across all sectors. At present, there is insufficient certainty about impacts of some options (in particular some bio-energy options) to make definitive points on this topic.

Finally, decarbonisation strategies for each sector are linked also by each other's success (or challenges). At present, it seems that all sectors will face challenges in decarbonising, in particular in the latter stages towards UK-wide 80% cut. But if one sector was to make particularly good progress, then this could allow another sector to defer some of the more challenging steps.

Bio-energy and synthetic fuel resources

There are various estimates of bio-energy resources globally, including those that could be used in the UK (domestic and imported);[113] a typical estimate is ~10% of UK energy consumption in 2050, i.e. ~130TWh,[114] although there have been concerns about the limited number of primary research projects to assess resource potential.[115] There are estimates specifically for transport energy, e.g. that biofuels from European waste could provide 16% of European road transport energy by 2030;[116] and the UK Government is assessing the scale of UK waste resources.[117] There are forecasts for the output of advanced biofuel refineries,[118] and the UK Government is funding demonstration projects.[119] Synthetic fuels are liquid fuels (some can be made as drop-in fuels that mimic fossil fuels and hence require no alternations to vehicles or infrastructure) produced from coal, methane or biomass; CCS is needed if some synthetic fuels are to provide GHG emissions reductions.

Decisions about use of bio-energy depend upon which impacts are being considered, and which are to be optimised. There of different uses (in transport and other sectors) for bio-energy resources, which fall into three types: oily sources (e.g. palm oil) provide heavy fuels (e.g. bio-diesel) and can be used for heating; starchy sources (e.g. maize) provide lighter fuels (e.g. ethanol to blend with petrol); and cellulosic sources (e.g. wood) and other solid wastes can be processed to provide a range of transport fuels, or used for heating or power generation. The application of each resource could shift in future, e.g. due to cost reductions in biofuel production or for other power generation options.

[113] See, for example: UK Bioenergy Strategy (UK Government, 2012); UK and Global Bioenergy Resource (AEA, 2011)

[114] See, for example: Bioenergy Review (CCC, 2011); Delivering greenhouse gas emission savings through UK bioenergy value chains (ETI, 2016); Bioenergy Strategy Analytical Annex (DECC, 2012); and UK bio-energy resource base to 2050- estimates, assumptions, and uncertainties (UKERC, 2010).

[115] The UK bio-energy resource base to 2050: estimates, assumptions, and uncertainties (UKERC, 2010)

[116] An assessment of advanced biofuels from wastes & residues (ICCT, IEEP & NFCC, 2014). Waste is municipal organic waste and forestry residues, although GHG impacts depend upon counterfactuals (e.g. leaving some forestry residues as carbon sinks).

[117] Ongoing project by DfT.

[118] For example: New Lens Scenarios (Shell,2013); Boosting the Contribution of Bioenergy to EU Climate and Energy Ambitions (EIBI, 2014)

[119] See announcement in 2015 for funding for three projects under the Advanced Biofuels Demonstration Competition.

There can be conveniences in matching energy vectors to end-use sectors of a similar size, allowing economies of scale and easier replacement (e.g. most heating systems use gas boilers); hence HGVs could be well-suited to using available bio-energy, but this is only one consideration. Using biofuels / synthetics for transport would affect the energy options available to other sectors, some of which could achieve larger GHG emissions reductions, e.g. bio-hydrogen and bio-electricity (but these could supply BEVs and FCEVs, illustrating some of the complexity of the considerations)[120].

It will be challenging to provide large volumes of bio-energy resources to road transport, requiring the development of large supply chains and supporting infrastructure:

- Bio-energy crops are now being chosen so as to reduce land-use competition with food crops and ILUC,[121] but could still face sustainability challenges as they still require land and still have impacts.[122]
- UK production of bio-energy crops would start from a low base and would need to attempt huge growth. It would also need to learn from previous incentive schemes[123] that have had difficulty meeting targets. Reasons include that biofuels can be a complex undertaking, requiring contracts between farmers and manufacturers; by contrast, the resources can instead be used on farms to produce biogas by simpler processes.[124]
- Municipal waste resources vary throughout the year, but advanced biofuel production generally works most efficiently when optimised for a particular feedstock composition.
- Municipal waste is mostly dealt with by large operators on long-term contracts; whilst some are moving into energy projects, overall progress is slow, and it is difficult for new entrants to enter the market.
- Resources for road transport would be subject to competition from other sectors (heating, power, shipping, aviation), and also from international markets[125] (and other countries' incentive schemes).[126]
- Different biomass sources have different applications (replacing petrol or diesel); there is believed to be sufficient flexibility in supply chains,[127] but any limitations could necessitate switching between engine types.
- Advanced biofuels / synthetics production is at an early stage when ordinarily producers would focus on low-volume/ high-price markets (e.g. reagents for the chemicals industry), but they are instead facing significant risks in investing in high-volume/low-price fuel production.[128] It had been hoped that the aviation sector would lead the development of such fuels (its only apparent low-carbon energy option), that would in turn lead to development of fuels for shipping and HGVs. But aviation investment has been limited due to uncertainty over how aviation will be treated in climate change agreements; the industry has only just released its proposals for consideration.[129]
- Some biofuel/synthetic fuel processes would need to use industrial CCS. CO_2 capture can be applied to individual projects, but they depend upon strategic decisions to support the deployment of CO_2 pipelines and the mapping of CO_2 storage sites. There needs to be a critical mass of projects to justify research and investment; changes to the strategy for CCS in the power sector have left uncertainty about how these strategic developments will be led.

WTW energy efficiency of biofuels / synthetics should be considered, which will affect UK primary energy consumption:

- Assuming that a future ICEV has a TTW efficiency of 40%, the lower WTT efficiency for advanced biofuels (typically ~50%) compared to liquid fossil fuels (~80-90%) would give WTW efficiency of ~20% compared to ~35% (for pure fossil fuels). That is, primary energy consumption would be ~75% higher in the bio-energy supply chain than for liquid fossil fuels. The 40% biofuel sensitivity ("Max-bio") in Scenario 1 would give an aggregate WTW efficiency of ~25-30%.
- Transport fuel is not the most energy efficient use of bio-energy. Biomass for heating has higher upstream efficiency, and boilers are highly efficient, giving overall ("WTW") efficiency of ~80-90%. Power production is currently the UK's largest use of biomass; upstream energy consumption depends upon the source location, but power plant efficiency of ~25% places an upper bound on overall ("WTW") efficiency.

[120] Delivering greenhouse gas emission savings through UK bioenergy value chains (ETI, 2016)

[121] Impact Assessment (ref. SWD(2012) 343 final) relating to amendments to Directives 98/70/EC and 2009/28/EC (EU Comm., 2012)

[122] Studies are ongoing e.g.: The sustainability of liquid biofuels – a collaborative metastudy (RAEng, for UK Gov., 2015 onwards); and ETI call for partners for Carbon Life Cycle Assessment Evidence Analysis (2016 onwards)

[123] Energy Crops Scheme started in 2000; reports include: Domestic Energy Crops; Potential and Constraints Review (NNFCC, 2012)

[124] Source: Interviews for this project. See also: Request for Proposals – Bioenergy Programme: Biomass Logistics in the UK (ETI, 2016)

[125] Technology Roadmap – Biofuels for Transport (IEA, 2011)

[126] For example, North American wood pellets are primarily sold overseas to Drax power station in the UK.

[127] Source: Interviews for this project.

[128] See, for example, the challenges faced by a BA-backed, £340M waste-to-fuel project in London.

[129] Aviation aims for energy savings of 20-40% (from 2015 levels); see, the ICAO's proposed "stringency options", published in 2016.

Methane and bio-methane resources

Fossil natural gas cannot offer sufficient GHG emissions reductions to meet 2050 targets for decarbonising HGVs. In addition, even if used in just the medium term, there are potential risks associated with using natural gas for HGVs in addition to using it for most heating and a for significant amount of power generation.[130] Firstly, there could potentially be operational challenges in supplying HGVs, depending upon their total energy consumption, and how their fuelling patterns superimposed upon those of other users. Secondly, there could be a strategic risk if another critical sector (road freight, in addition to heating and power generation) relies upon natural gas: whilst there are potentially more diverse sources of gas than of oil, using gas for HGVs would place more reliance upon gas imports and anticipated UK shale gas production.

Bio-methane offers significant GHG emissions reductions, and so could be useful in the longer-term, either directly in HGVs (or potentially as a feedstock for hydrogen production via SMR). Bio-methane has certain practical appeals: production by anaerobic digestion is a natural production process (albeit encouraged in engineered systems), without the need for pure feed-stocks or complex processing. Bio-methane is currently produced in comparatively small quantities in the UK (~23TWh in 2013). Of this, only 0.1% was used for transportation, meeting only 0.006% of road transport's energy consumption.[131] Now, none of this is used for HGVs since the UK's only supplier ceased production; some fleet operators claim to use bio-methane, but this is not counted in UK totals due to issues with EU regulations.[132] The present low usage for transport is primarily because financial incentive schemes are stronger to use biogas for heating or power generation than for transport. Given that HGVs have limited options for low-carbon fuels, there could an argument for encouraging the use of bio-methane for HGVs. That said, the potential impact could be small: if all of the present resource was diverted to HGVs, it could meet just ~20% of their forecast energy consumption in 2050 (as per the "Mid-bio + biogas" sensitivity in Scenario 1). If this was attempted, it could best be done as part of an expansion of the sector, so that HGVs would not divert biogas from other sectors such as heating and power production that use biogas more efficiently (especially with CHP) and in so doing displace methane.

Low-carbon electricity resources

Low-carbon electricity will be needed for road transport; in this respect, the major difference between scenarios is when that electricity consumption will become significant. For rapid uptake of EVs, this could begin in the 2020s; for a prolonged use of ICEVs/PHEVs, or for FCEVs using mainly electrolysis, the extensive use of electricity would be postponed (but still required). The ability to generate electricity from a range of sources offers opportunities but also poses risks. It can make use of diverse energy resources, hence increasing resilience; but it can therefore also be in competition for energy resources that could be used elsewhere. As discussed for bio-energy and (bio-)methane, it is necessary to weigh up the different impacts across the sectors, against the key criteria to be satisfied.

Apart from in the case of bio-energy, there are few constraints on energy resources for low-carbon electricity. Non-biological renewable sources are abundant; the questions are about the challenges of harnessing them and integrating them into the system. Nuclear fuels are also abundant, especially if alternative fission pathways are considered. Natural gas is abundant (but it would need to use CCS), and is available from several sources. However, similar to the issue raised for HGVs using methane, there could be risks in using natural gas to meet increasing electricity consumption for transport. Transport would become another critical sector (in addition to power and heating) that is dependent upon natural gas; and the extra gas consumption would increase the UK's reliance upon gas imports and anticipated UK shale gas production. However, using natural gas for electricity generation has merits, including that it can be partly decarbonised using CCS, more easily than some other sectors (e.g. heating) that cannot use CCS. Indeed, if the challenges of decarbonising gas use in some other sectors mean that they have to stop using natural gas, then overall UK gas consumption could fall, and the security of supply concerns raised by transport using gas could diminish.

BEVs WTW efficiency depends upon modelling of non-biomass renewables and nuclear power. They can be viewed as 100% efficient in the sense that the renewables have no waste heat, and the nuclear fuel has no other use in the energy sector. If so, most forecast grid mixes using renewables, nuclear and natural gas (with CCS) would give WTT efficiencies of ~70-80%. BEVs have TTW efficiencies of ~80%, giving WTW efficiencies of ~60%. The main consideration is that the energy consumption is being switched to different feed-stocks, which will have to adapt their supply chains.

[130] The UK uses 300TWh/yr of gas for heating and 200TWh/yr for power generation; HGVs would add up to 100TWh/yr.

[131] Waste and Gaseous Fuels in Transport (Ricardo-AEA, 2014)

[132] Source: Interviews for this project.

Hydrogen resources

Hydrogen is a raw material for various sectors, e.g. presently most hydrogen is used in oil refining (accounting for 2% of UK energy consumption), produced from methane using SMR (without CCS, and hence with high GHG impacts). There are different views about the potential future role of hydrogen in the wider energy sector; these are being considered in the ERP's project about hydrogen.[133] Hydrogen could be an intermediate step until low-carbon electricity develops further; or it could be useful only in niche applications; or it could be used in heat, power and transport to power a "hydrogen economy" that could emerge on its own or could evolve out of an electrified energy sector. Indeed, one of its appeals is that it can be used in (and between) multiple markets.[134] Linkages between energy vectors offer opportunities to make better use of resources: e.g. producing hydrogen via electrolysis using surplus renewable electricity;[135] storing energy (with more flexibility than batteries) up to inter-seasonal scales; and regenerating electricity later at times of peak consumption or for supplying remote locations.[136] In another example, hydrogen can be combined with atmospheric CO_2 to produce low-carbon methane or methanol (which would probably only be done with hydrogen produced from electrolysis rather than from SMR which would be somewhat circular processing). However, linking between markets adds complexity and risk (e.g. fuels could be unavailable in the absence of sufficient contractual arrangements or price signals).[137]

The TTW efficiency of a FCEV is ~50%. The upstream efficiencies are estimated to be: ~80% for compression and piping of hydrogen, and ~70% for SMR; and ~70-90% for electrolysis, and ~70-80% for electricity generation (see under low-carbon electricity resources). These together give a WTT efficiency of ~60% (whether using SMR or electrolysis), and overall WTW efficiency of ~30%. This compares with future estimates of WTW efficiency of ~25-30% for ICEVs (using a fossil-biofuel mix) and 60% BEVs (under a variety of low-carbon grid mixes). Adding this consumption to the gas or electricity sectors would require considerable planning.[138] As discussed for other options, there could be implications for security of supply in relying upon a smaller number of energy resources to supply a larger number of critical sectors; these concerns could be reduced if energy resources were supplied from a range of sourced. Bio-methane produced from waste could be a feedstock for hydrogen via SMR; this would offer large GHG emissions reductions from a domestic energy source, but with competition from other uses of bio-methane (see above).

SMR's requirement for large volumes of CO_2 pipeline and storage capacity would require significant co-ordination with that new sector. Indeed, due the SMR's gas consumption and CO_2 storage requirements, if hydrogen was to be used widely in the longer-term, there would need to be a plan to transition to other sources (e.g. electrolysis or nuclear facilities).

[133] Hydrogen report (ERP, to be published in 2016)

[134] See, for example, discussion in: New Lens Scenarios (Shell, 2013); and Wind-hydrogen systems in Scotland (St Clair-Ford, 2014)

[135] As noted in the section about hydrogen infrastructure, using surplus renewable power generation might be a challenging business case for hydrogen production. However, it could work better in local energy systems with high renewable resources and low demand.

[136] Transferring between energy vectors reduces the overall energy efficiency (e.g. using electricity to produce hydrogen via electrolysis, and then using hydrogen fuel cells to generate electricity). However, it could possibly be cheaper than building peaking power plants that would be used for just a few hours each year.

[137] Such risks are also seen with existing fuels, e.g. see reports about UK diesel supplies (RAC Foundation, 2015).

[138] There could be opportunities for starting this co-ordination around the formulation of infrastructure plans for the EU in 2016; see: Directive 2014/94/EU on the deployment of alternative fuels infrastructure (European Commission, 2014)

5. Summary and conclusions

This report has presented illustrative scenarios of future energy options, and has identified the implications of each option, including the interactions with the wider energy sector. This report has also highlighted the key steps that would be required for delivery of each energy option, including the main challenges. This summary section brings together the report's main messages about actions that could be taken to manage the implications and to reduce the challenges for delivery. However, even with mitigating actions, issues and risks will remain. Decisions on transport decarbonisation will be considered alongside other policy objectives, and will include an element of judgement about which issues and risks are preferable. This summary section brings together strategic considerations that can stimulate this debate.

Strategic considerations

Wider decarbonisation

Efforts to decarbonise transport must be seen in the wider context of decarbonising all sectors, so that overall outcomes can be optimised. Also, different decarbonisation strategies offer differing levels of impact: e.g. more ambitious transport options will have to be considered if other sectors face harder challenges. A major example is that decarbonising heavy transport (road freight, rail, shipping and aviation) will likely require access to liquid fuels with low life-cycle GHG emissions; but sustainable bio-energy resources are limited, and if they were better used in other sectors, then heavy transport might need to be given "leeway" through deeper GHG emissions cuts elsewhere.

Primary energy consumption

Each energy option would increase consumption for particular resources (e.g. biomass or natural gas); and uses with high conversion losses could potentially increase the UK's primary energy consumption. There would be logistical challenges in increasing and reconfiguring the supply chains, and potential network operation challenges depending upon the superimposition of energy consumption profiles. There is a strategic risk in the UK relying upon a smaller number of energy vectors (e.g. natural gas) for more of its critical sectors (heat, power, HGVs), but this risk could be mitigated by diversity of supply sources.

Deployment and performance

Two recurring themes for each of the energy options are: challenges of deploying infrastructure (including timings and costs), and the performance of vehicles (taking into account the potential benefits, and the steps that have to be taken). In brief, ICEVs require less new infrastructure, but performance could be harder to ensure; whereas BEVs and FCEVs would require more new infrastructure, but performance would be easier to ensure. To expand upon this point:

- **Deployment challenges:** ICEVs offer an easier deployment route for incremental improvements; whereas BEVs (and to a lesser extent FCEVs) would incur higher costs and disruption for more significant infrastructure changes.
- **Potential benefits:** ICEVs (moving into PHEVs) could deliver the necessary GHG emissions reductions, and some improvements in other impacts (e.g. tailpipe pollutants and noise). BEVs could deliver the necessary GHG benefits (with PHEVs or REs for some segments of travel), almost total reduction of tailpipe pollutants (but with upstream impacts), and quieter operation. Hydrogen could deliver the necessary GHG benefits for all segments of travel, reduced tailpipe pollution, and quieter operation.
- **Steps to deliver benefits:** All options rely upon securing sufficient low-carbon energy sources. The delivery of benefits by ICEVs depends upon regulations being effectively applied and enforced across all manufacturers and vehicles. Successful delivery of the benefits by BEVs and FCEVs does not depend upon the individual vehicles, but upon regulations being effectively applied and enforced across a smaller number of upstream energy facilities.

The challenges of deployment can be explored further:

- **Timings of deployment:** Both ICEV and BEV scenarios could eventually end up using PHEVs (either to reduce the GHG emissions of ICEVs, or to increase the range of BEVs). Hence both scenarios would require electrical charging infrastructure; the difference is that BEVs would require early deployment of widespread infrastructure, whereas ICEV-PHEVs would require it later. The electricity sector is undergoing major changes for a range of reasons, so there is a question about whether it could be more efficient to undertake transport-related changes at the same time, or whether it could reduce logistical challenges to defer these transport-related changes until later. Finally, road transport could benefit from future developments in other transport modes; but it should not defer action for too long, in particular because other modes are hoping to benefit from developments in road transport.
- **Costs of deployment:** Whilst total cost is a major consideration, an option with the best chance of success might not be least-cost. To be considered viable, an option must be workable from engineering, financial and customer perspectives: it must be practical and affordable, and consistent with decarbonising options for other sectors. Successful options will be those that are commercially-viable and marketable. Customer decisions could direct the sector down a particular route irrespective of wider infrastructure requirements. Infrastructure projects would be paid for through combinations of taxes and bills; the financial flows will become more complicated due to changes in models of ownership and use. The allocation of payments will come down to policy judgements about distributional impacts.

Steps to mitigate challenges and implications

Action could be taken to overcome the challenges to deployment, and to manage the implications including the interactions with the wider energy sector. These actions can be grouped as follows:

Research is required to improve energy options:

- Light-weight materials to reduce fuel consumption, with reduced embedded impacts; there are links with aviation.
- New low-carbon liquid fuels (preferably drop-in liquid fuels that would avoid the need for modifications to infrastructure and vehicles), in particular for heavy road transport; there are links with shipping and aviation.
- Improvements in battery performance (range and/or charging time).
- Trials by energy network companies of solutions to address the impacts of transport on the energy networks, with the regulator facilitating third-party project leadership where needed.
- Comparison of transport and energy sector assumptions that underpin scenarios and policies.
- Impacts on demand for transport services due to automation and changes in vehicle ownership, use and logistics.
- Customers' perceptions of light-weight vehicles.

Regulations and incentives are required to drive uptake of options and delivery of their benefits:

- Regulations for GHG emissions are needed to drive ICEV improvements and uptake of alternatives; tests need to be realistic, independently-verified, and should be co-ordinated with air quality tests.
- Incentives would be needed for advanced biofuels (and for bio-methane for HGVs): to significantly increase UK production of bio-energy crops and to divert waste streams to energy production; and to draw in sufficient of those bioenergy resources to the transport sector.
- PHEV operation requires incentives for optimal operation, to avoid the risk of fossil fuels displacing lower-carbon electricity; but by the same token PHEVs offer dual-fuel flexibility for users and systems operators.
- Innovations in communications and commercial arrangements are needed to allow smaller freight operators to engage in logistics efficiency schemes.

Strategic infrastructure decisions are needed to facilitate energy options:

Liquid fuels and (bio-)methane:

- If liquid fuels with high blends of biofuels are used (but not drop-in liquid fuels that closely mimic fossil fuels), then co-ordination will be needed to modify vehicles and fuel distribution infrastructure, and to optimise the selection of fuels at fuelling stations.
- Reduced sales of liquid fuels could threaten the universal coverage of refuelling stations (including in some rural areas), and increase costs for customers that continue to use liquid fuels (that could be mainly hauliers and poorer customers).
- Methane or bio-methane for HGVs would need a strategy to deploy infrastructure for fuelling stations, including extending the networks to the sites and potentially installing compressors on the sites.

Electricity:

- Further grid decarbonisation is needed to deliver GHG benefits of BEVs and PHEVs; higher generation capacity would be needed to support large deployment of EVs and PHEVs; both points apply to FCEVs if using hydrogen from electrolysis.
- Electricity infrastructure changes for transport could be co-ordinated with other changes to the electricity system: undertaking transport changes earlier (to facilitate uptake of BEVs) could offer some cost efficiencies; or undertaking transport work later (to facilitate later use of PHEVs) could reduce logistical challenges.

Hydrogen:

- Hydrogen production by steam methane reforming (SMR) of (bio-)methane would need deployment of centralised SMR facilities and CO_2 infrastructure.
- Hydrogen production by electrolysis would require more low-carbon electricity generation and possibly more electricity network capacity (unless not grid connected).
- Hydrogen distribution from centralised facilities could be most efficiently done by repurposing low-pressure gas distribution networks, with some grid extensions to non-urban fuelling sites and compressors at fuelling sites; repurposing would have to take into account the needs of gas users and the potential for bio-methane.

Carbon Capture and Storage (CCS):

- Deployment of CO_2 pipelines and mapping of CO_2 storage sites are needed to facilitate CCS for various transport options: producing certain liquid fuels, producing hydrogen using SMR, flexible low-carbon power, and reducing industrial emissions for vehicle manufacturing.

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